Resource Characterization to Estimate Potential for Electricity Co-Production at Blackburn Oil Field, Nevada

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ABSTRACT

The U.S. Department of Energy estimates that an annual average of 25 billion barrels of hot water are produced from oil and gas wells within the United States. The thermal energy available in the co-produced water stream is usually discarded, as the produced waters are considered an inconvenience by the operators and are disposed of using injection wells. However, utilizing organic Rankine cycle (ORC) generators, a vast amount of thermal energy can be captured and converted into electricity (albeit at relatively low efficiency due to the low temperatures). The National Renewable Energy Laboratory (NREL), in collaboration with Transitional Energy and Grant Canyon Oil & Gas, evaluated the feasibility of geothermal co-production of electricity by utilizing existing oil wells in Blackburn oil field in Nevada. The once prolific Blackburn oil field is located in Pine Valley, approximately 45 miles east-southeast of Elko, Nevada. Currently, the wells targeting the highly fractured Devonian Nevada dolomite reservoir are operating at a water cut ratio of more than 99%, with individual fluid (oil and water) production rates reaching 7.4 L/s (4,021 BBL/day). Analysis of publicly available data showed that the combination of the suitable wells' maximum historical production rates reached 22.90 L/s. The production from these wells occurs naturally and the wells are choked (and even shut down) by the operator to mitigate excessive water production, indicating a strong reservoir recharge and future opportunity to increase the water production for geothermal electricity generation. The main goal of this study was to evaluate the productivity of the existing wells, the performance of the reservoir, the surface network, and the operational constraints in order to achieve 1 MW_e of electricity production from the field's water production. Utilizing the GEOPHIRES tool, we have determined that a twofold to threefold increase in the total fluid production, compared to the historical production under artificial restraint (choke), is required to reach a 1-MW_e net target output for a low-temperature ORC system with air-cooled condensers. Lower flow rates would be required when utilizing water-based condensers instead of air-cooled condensers. However, that would require a constant supply of cold water, which may be challenging given the arid environment of the project site.

1. Introduction

Blackburn Field is an oil field located within Sections 7 and 8 of Township 27N Range 52E of northern Eureka County, Nevada. Geographically the field is in Pine Valley, 45 miles east-southeast of Elko, Nevada. The field location is shown in Figure 1.

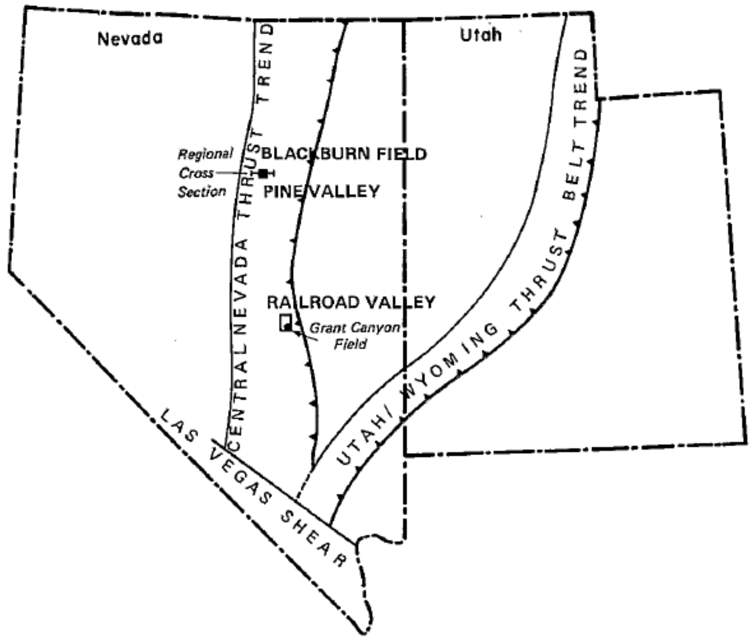

Figure 1: Geological map showing the location of the Blackburn Field. Adapted from Scott and Chamberlain (1988).

The first exploration well in the Blackburn Field, Blackburn 1, was completed August 16, 1980, and was followed by Blackburn 2, completed March 6, 1981. Both wells were dry holes. The Blackburn 3 well, completed April 6, 1982, encountered oil pay in Tertiary Indian Well formation, Mississippian Antler Basin sandstones, and fractured Nevada Formation dolomite. A drill stem test (DST) in Blackburn 3 showed flowing oil (Scott and Chamberlain, 1988) in the Nevada Formation. The well had a relatively high water cut of 78% (200 BO and 700 BW).

According to the Nevada Division of Minerals (NDOM), a total of 17 wells with the “Blackburn” name designation were drilled in the field (2023). Additionally, on the west-northwest edge of the field, two wells named “Mary Kay Federal 1”, and “Stream 1-7” were drilled. Most of the drilling operations occurred during the 1980s and early 1990s. The last addition to the field was Blackburn 22, which was completed March 1, 2017.

The historical production data (NDOM, 2023) shows that the Blackburn Field produced 4,356,115 barrels of oil and 43,547,058 barrels of water between 1982 and 2022 (inclusive), resulting in an overall cumulative water cut of 90.91%. In 2022, the annual water cut was 98.98%. The cumulative oil production and the annual water cut history of the field is shown in Figure 2. The steep increase in the water cut is characteristic of the naturally fractured reservoir with a strong water drive (hydraulic recharge). In fact, the wells penetrating the fractured Nevada dolomite pay zone were historically completed in the shallowest (top) portion to avoid water encroachment from the bottom.

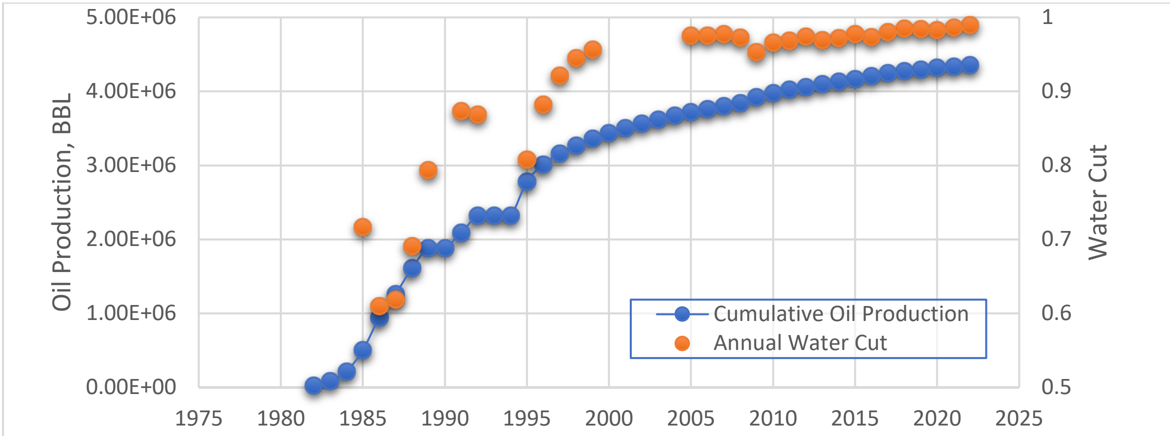

Figure 2: Cumulative oil production and annual averaged water cut for Blackburn Field. Prepared using the data gathered from the NDOM database. Gaps in the calculated water cut are due to the gaps in the water production data, mainly from '00 to '04 (inclusive), having missing entries in the database.

2. Blackburn Field Data Analysis

We gathered a plethora of publicly available data and documentation in preparation for the future reservoir modeling studies in the subsequent project tasks. This dataset includes but is not limited to well logs, completion reports, well locations, well deviation surveys, annual production going back to 1982, monthly production going back to 2016, scientific papers, satellite imagery, and surface digital elevation model (DEM) for the Blackburn Field location.

2.1 Overview of the Blackburn Field Wells

We identified 17 wells with the "Blackburn" name designation and 2 proximal wells (Stream 1-7 and Mary Kay Federal 1) in and around the Blackburn Field location. Table 1 presents the completion dates, usage designations, and the operational status specified in the NDOM database. Out of the 19 wells, 10 were reported as plugged. Initial analysis of the drilling reports of the plugged wells indicated that they were dry holes when considering oil production potential. We decided to eliminate the plugged wells from the list of candidate wells for geothermal production and reinjection as the field operations required for re-activating these wells would be costly, even if they are connected to the hydrothermal system. However, stratigraphic, structural, and drilling data acquired from these wells' records were implemented in the overall analysis.

Table 1: Table summarizing the Blackburn Field and proximal well entries in the NDOM database. Active (not plugged) wells are highlighted in tan. The last column represents the current operational state reported within the project proposal document (Transitional Energy, 2022).

Well Name	Completion Date	API No.	Original NDOM Classification	Current State	
				NDOM	Transitional Energy Data
Blackburn 1	8/16/1980	27-011-05205	Production	Plugged	-
Blackburn 2	3/6/1981	27-011-05207	Production	Plugged	-
Blackburn 3	4/6/1982	27-011-05210	Injection	In Use	Shut-In
Blackburn 4	8/18/1982	27-011-05212	Production	Plugged	-
Blackburn 6	9/15/1982	27-011-05214	Production	Plugged	-
Blackburn 10	7/6/1983	27-011-05216	Production	In Use	Producer
Blackburn 5	10/11/1983	27-011-05213	Production	Plugged	-
Blackburn 12	12/28/1983	27-011-05218	Injection	In Use	Injector
Blackburn 14	7/10/1985	27-011-05230	Production	In Use	Producer
Blackburn 15	11/18/1985	27-011-05231	Production	Plugged	-
Blackburn 16	12/21/1985	27-011-05232	Production	In Use	Producer
Mary Kay Federal 1	5/14/1987	27-011-05233	Production	Plugged	-
Blackburn 17	7/12/1987	27-011-05234	Production	Plugged	-
Blackburn 18	11/20/1992	27-011-05269	Production	In Use	Producer
Blackburn 19	5/20/1994	27-011-05285	Production	In Use	Shut-In
Blackburn 20	5/20/1996	27-011-05289	Production	Plugged	-
Blackburn 21	9/7/1997	27-011-05292	Injection	In Use	Producer
Stream 1-7	9/27/2001	27-011-05301	Production	Plugged	-
Blackburn 22	3/1/2017	27-011-05315	Production	Shut-In	Shut-In

Figure 3 presents the locations of wells of interest in the Blackburn Field. The two earlier exploration wells, Blackburn 1 and Blackburn 2, are not shown in this figure as they reside away from the active part of the field to the south and east, respectively. A quick glance at this figure shows that the active (not plugged) wells are centralized around the section line separating Sections 7 and 8 of Township 27N Range 52E.

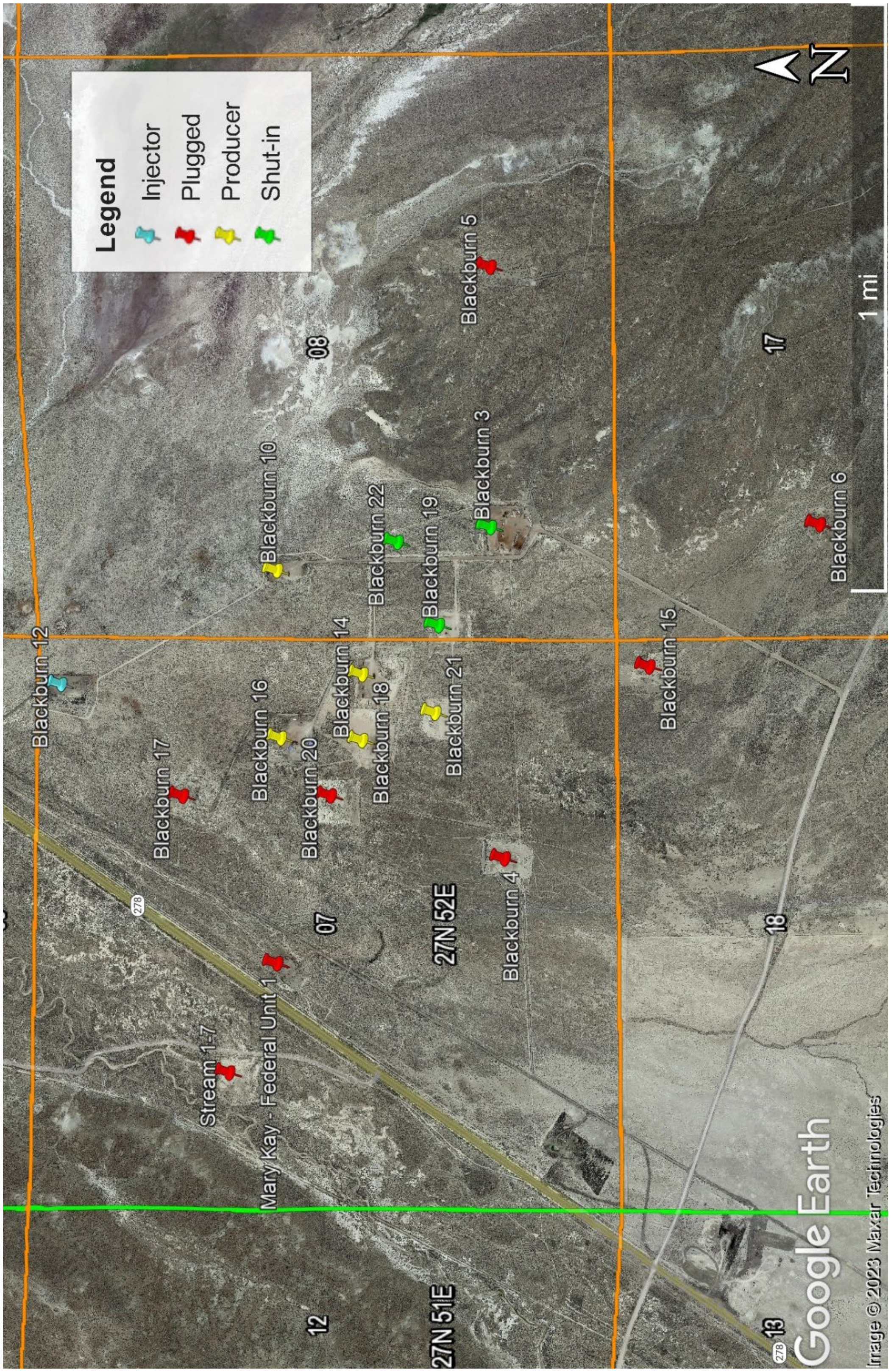

Figure 3: Map showing the location of the Blackburn Field and proximal wells. The orange lines and green line represent the section and range borders, respectively.

2.2 Historical Production Data Analysis

The nine active wells listed in Table 1 and shown in Figure 3 are Blackburn 3, 10, 12, 14, 16, 18, 19, 21, and 22. The yearly fluid (oil and water) production history for these wells, excepting Blackburn 12, which has likely been an injection well since its completion, is shown in Figure 4. Considering the production data after 2006, we observed that some wells were more prolific (Blackburn 18, 19, 21) as they produced at much higher rates compared to other low-energy wells (Blackburn 10, 14, 16). The annual production volume difference among these could be explained by the low-energy well set extracting fluids from:

i) compartmentalized sections within the Nevada dolomite, or
ii) the overlying relatively low permeability Chainman and/or Indian Wells formations.

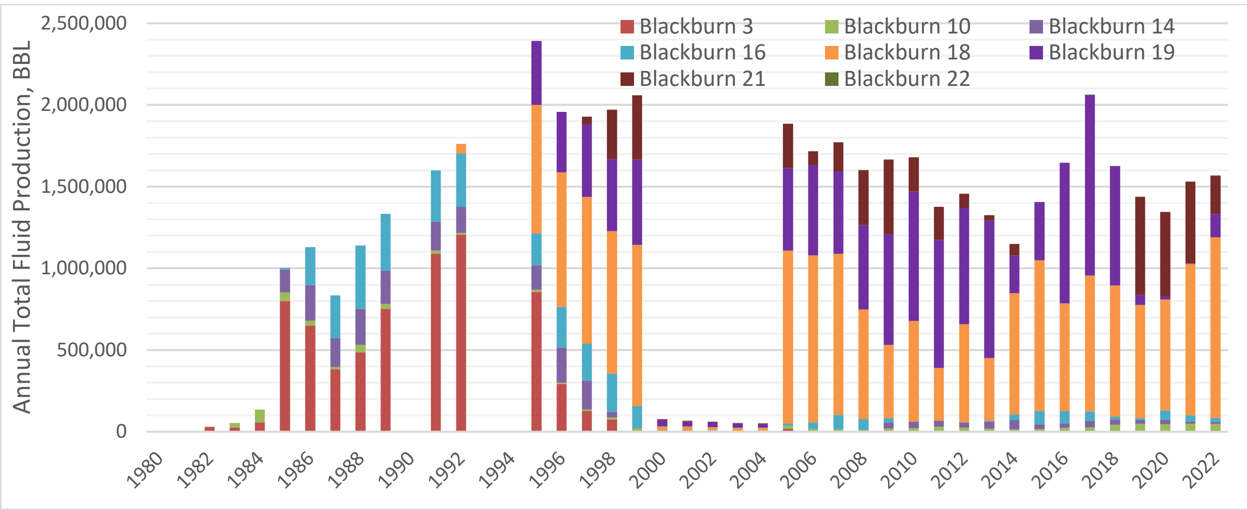

Figure 4: Historic total annual fluid (oil and water) production at the Blackburn Field. It should be noted that the dataset had missing production volume entries for some years. The production volumes reported in the NDOM database between 2000 and 2004 likely included oil production only; it is estimated that the total fluid production for these years was in the range of 1.9 to 2.1 million barrels.

Using satellite imagery, we determined that the prolific wells (Blackburn 18, 19, 21) are likely to be producing naturally (without pumping assistance), as no wellhead pumping equipment, i.e., pumpjacks, was visible. In contrast, all low-energy wells (Blackburn 10, 14, 16) had pumpjacks visible. This observation led us to conclude that these two sets of wells are producing from different intervals (or formations) with no pressure communication in between. This conclusion was also later confirmed by Transitional Energy.

Figure 5 presents the average monthly production rates for the wells of interest. The data for this figure was obtained from the monthly production reports published by NDOM and allowed us to examine the recent flow behavior at a higher resolution compared to annual reports. The difference in the production rates between the prolific and the low-energy wells can be observed more clearly. The low-energy wells produce at most 0.2 L/s, whereas the prolific wells can reach 3 to 7 L/s.

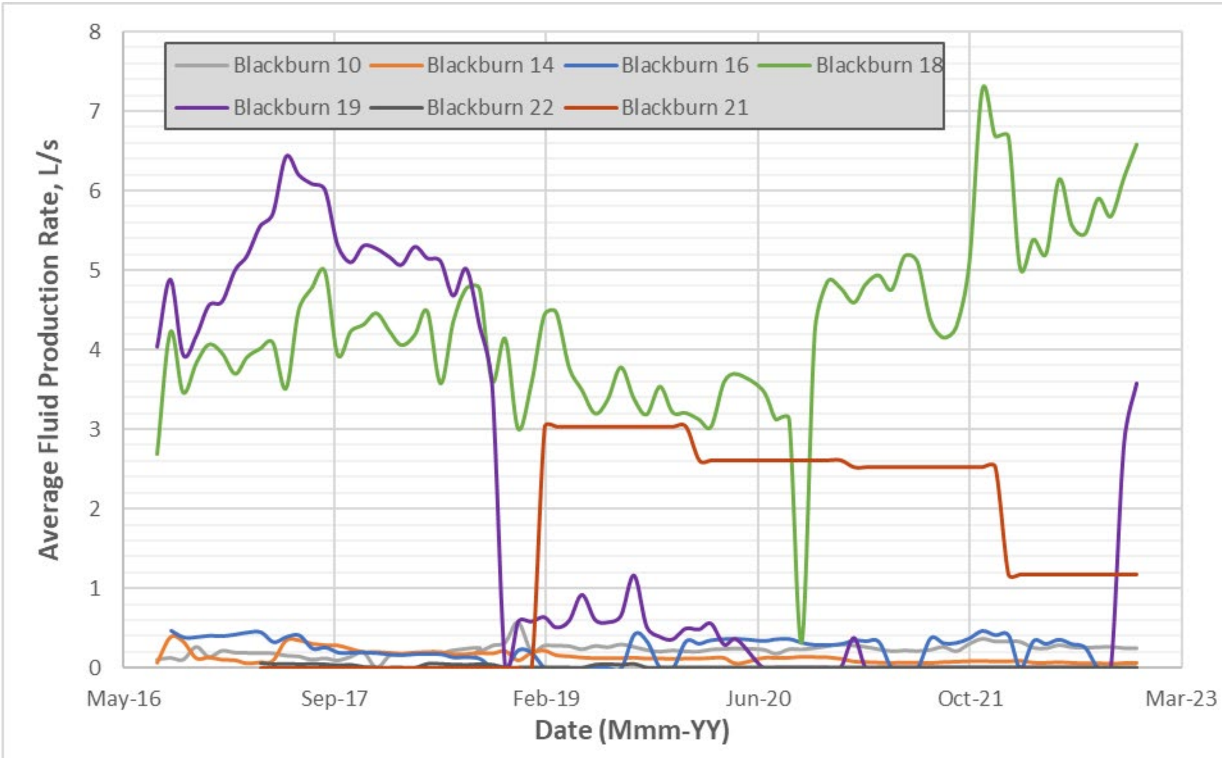

Figure 5: Average monthly production rate for selected wells between July 2016 and November 2022. Blackburn 21's rate data was estimated from annual production, as monthly production rate was unavailable.

Flow rate analysis of the prolific wells (Blackburn 18, 19, and 21) led us to conclude that there is a strong recharge present within the Nevada dolomite reservoir, given that a distinct and characteristic natural flow rate decline was not observed in the production data. Transitional Energy staff stated that during a site visit on May 4, 2021, they observed that Blackburn 18 and 21 were flowing naturally on 26/64 and 20/64 chokes, respectively (Transitional Energy, 2022). While there is no direct evidence in the gathered data, we concluded that any reduction in the flow of the prolific Nevada dolomite wells is artificial and not due to a natural decline in the reservoir pressure energy. In other words, these wells were choked to slow down the flow rate or were shut in completely to mitigate against excessive water production.

Examining the annual production data before the year 2000 (Figure 4), we determined that Blackburn 3 can also be considered a prolific well for geothermal production. This well is currently shut in (Transitional Energy, 2022). However, it was historically produced at rates feasible for geothermal production until 1996.

Table 2 summarizes the maximum observed production rates, and Figure 6 presents the annual production profiles for the wells with geothermal production potential. If these wells can operate simultaneously at their historically observed maximum capacity, there is potential for up to 22.90 L/s of total fluid production. However, the following technical points should be noted:

- The publicly available production datasets do not contain pressure and operational (choke and pump configurations) data. Flow capacity analysis without these parameters is only preliminary.
- The fluid volume handling capacities of the surface facilities and injection wells are not known. These capacities may be exceeded if all prolific wells are operated at the same time.
- Productivity of the prolific wells did not show a distinct natural decline, and thus we estimated that the Nevada dolomite reservoir had enough permeability and hydraulic recharge to support the historical production. For instance, between 2005 and 2022, the prolific wells' (excepting Blackburn 3) total production averaged 7.47 L/s, with no observable decline in productivity. Because the determined historical total capacity of 22.90 L/s poses a threefold increase in the total flow rate, additional reservoir modeling is required to determine whether the reservoir can support the increased production demand.

Table 2: Historical maximum flow rates observed for wells of interest. The rates, calculated from the annual production, do not include non-productive time. The actual values for these entries are likely higher.

Well Name	Maximum Observed Flow Rate, L/s	Water Cut, %	Data Source	Date
Blackburn 3	6.07	96.95	Annual Production	1992
Blackburn 18	5.34	98.67	Annual Production	2005
Blackburn 18	7.26	99.77	Monthly Production	Nov. 2021
Blackburn 18	4.81	99.42	Transitional Energy Field Observation	May 2021
Blackburn 19	5.57	98.86	Annual Production	2017
Blackburn 19	6.43	99.00	Monthly Production	May 2017
Blackburn 21	3.14	99.65	Transitional Energy Field Observation	May 2021
Blackburn 21	3.03	99.52	Annual Production	2019

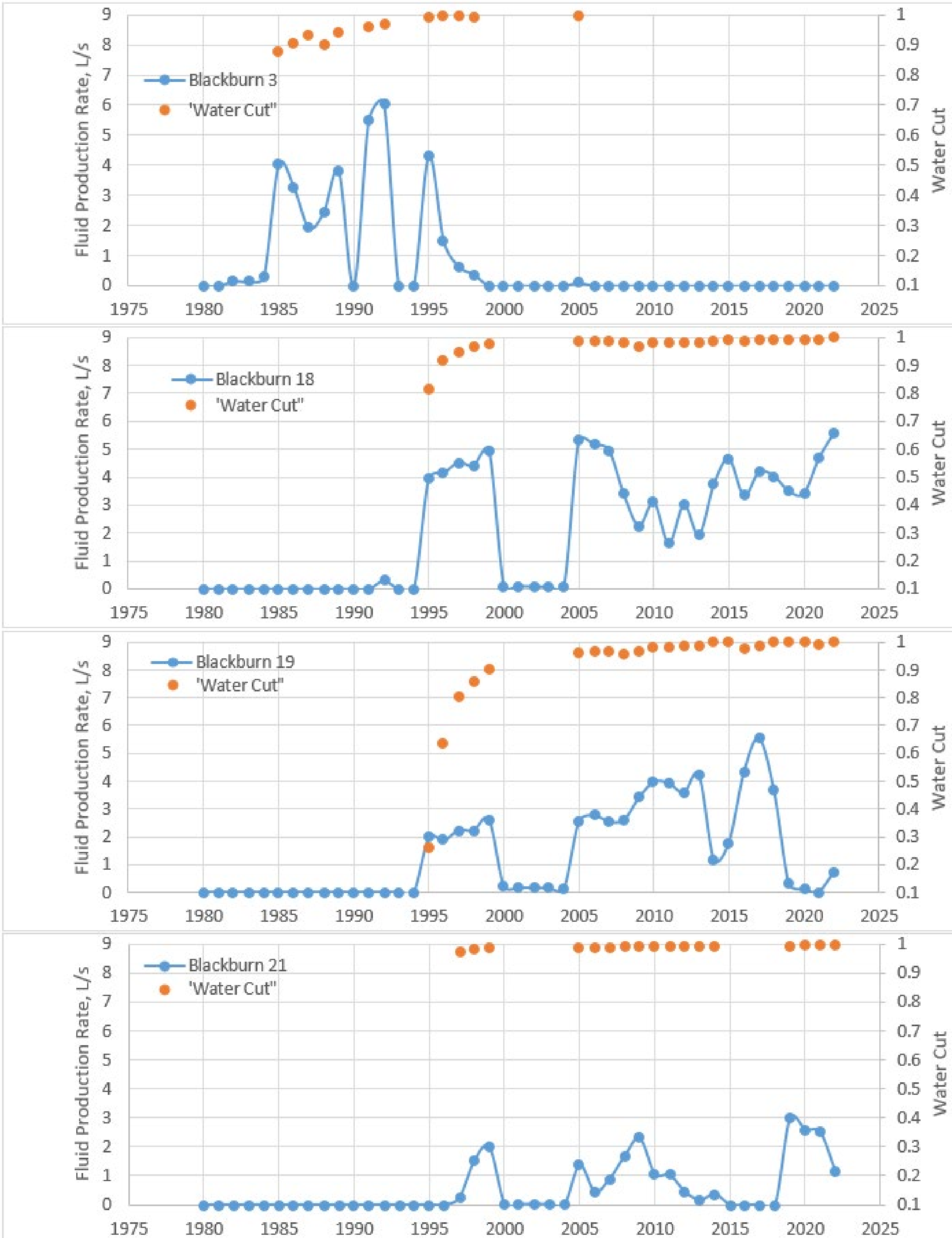

Figure 6: Annual averaged production rates of the identified prolific wells Blackburn 3, 18, 19, and 21. The fluid production rate was calculated from the annual production and does not include non-productive time. The flow rates between 2000 and 2005 represent the oil flow rate only, as the water production for this time interval was unavailable in the database.

2.3 Temperature Data Analysis

We acquired four well logs of temperature for Blackburn 3, 4, 6, and 10 from the public database (NDOM, 2023). These well logs were then digitized for plotting, as shown in Figure 7 alongside the drill stem test (DST) temperature results from seven Blackburn wells. DSTs are more reliable records of temperature because they sample the temperature of reservoir fluids. Conversely, the well logs are affected by the drilling induced cooling, which varies in magnitude depending on the seasonal surface ambient temperature.

The DST documents for Blackburn 3, 18, and 21 report temperatures of 246.3°F, 250°F, and 251°F, respectively. The DST temperature for Blackburn 19 was significantly lower than the rest of the prolific wells at 222°F; however, other records (well log headers) indicated a maximum measured temperature of 259°F for this well. While the reason behind this discrepancy is unknown, we have decided to use the higher temperature for Blackburn 19 for further calculations.

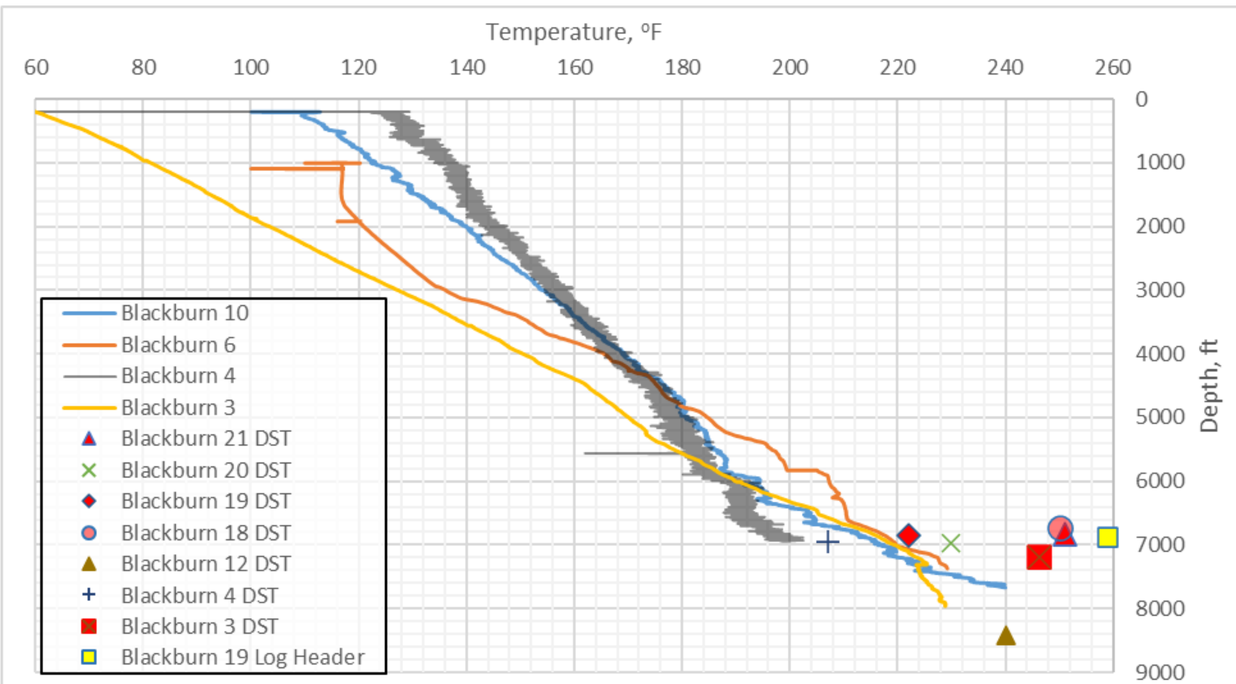

Figure 7: Digitized temperature logs (solid lines) and reported drill stem test temperatures of various Blackburn wells. DSTs of the prolific wells identified earlier are shown using red markers. Additionally, the maximum log header temperature for Blackburn 19 is shown with a yellow square marker.

Using an average ambient surface temperature of 44.6°F (7.0°C) for Elko County, Nevada (National Oceanic and Atmospheric Administration, 2023), we estimated the average geothermal gradient for the prolific wells as 30.0°F / 1,000 ft (54.7°C/km).

On their visit to the Blackburn Field site, Transitional Energy staff observed wellhead producing temperatures of 244°F for Blackburn 18 and 219°F for Blackburn 21 under sunny conditions and an ambient temperature of 72°F (Transitional Energy, 2022). We completed a wellbore heat transfer modeling study to compare the original bottomhole temperature of these wells to the reported observations and concluded that the Blackburn 18 did not cool down significantly during its operational lifetime. However, the observed wellhead temperature for the Blackburn 21 well indicates that this well has undergone cooling.

Determining the cause of the cooling in Blackburn 21, and whether it indicates cooling of the Nevada dolomite reservoir, requires a more detailed analysis of the operational conditions of this well and the wellhead producing temperatures. Our literature and public database review on field-wide historical wellhead producing temperatures was not fruitful. Additional field temperature testing is planned for late Fall 2023 to determine the production temperatures of the prolific wells.

3. GEOPHIRES Power Production Simulations

In order to predict the power co-production alongside the existing oil production operations, we completed a preliminary GEOPHIRES (Beckers and McCabe, 2019) simulation study. We prepared and analyzed two cases. The first case uses the recently measured wellhead production temperature of Blackburn 18 at 244°F as fluid inlet temperature. The second case imposes a temperature drop at the surface network and utilizes a fluid inlet temperature of 210°F. Both cases utilized a flow rate of 22.9 L/s, which was the sum of the individual historically observed maximum rates of the prolific wells.

Table 3 presents the results of the two simulation cases. The higher, or "base," geofluid temperature case analysis showed that power co-production up to 393.6 kW_e is possible. The case with the reduced geofluid temperature resulted in 214.8 kW_e. In order to reach 1 MW_e net power co-production (with air-cooled condensers), the total geofluid production rate will have to be increased to 58.2 L/s (154% increase) and 106.6 L/s (366% increase) for the base and the reduced temperature GEOPHIRES cases, respectively.

Table 3: GEOPHIRES simulation results for power co-production at Blackburn Field

	Base Temperature	**Reduced Temperature**
Geofluid Inlet Temperature, °F	244	210
Fluid Inlet Rate, L/s	22.9	22.9
ORC Efficiency	6.03	4.58
Power Production, kW	393.6	214.8
Flow Rate Needed to Reach 1 MW_e, L/s	58.2	106.6

Historically, the Blackburn Field wells were choked to reduce excessive water production and optimize oil production. At the time of writing, the maximum unchoked productivity of the prolific wells is unknown. We expect a significant increase if these wells are allowed to flow with less restraining choke settings. Field testing (nodal analysis and well testing) at the Blackburn site is currently being planned by Grant Canyon Oil & Gas and Transitional Energy for late Fall 2023 to determine the productivity and absolute open flow properties of the targeted wells.

The organic Rankine cycle (ORC) efficiencies for the GEOPHIRES runs were determined by the built-in functions of GEOPHIRES, and they are in good agreement with the efficiencies published by Augustine (2009). However, if favorable wet-bulb temperature and ambient temperature conditions exist, intermittent ORC efficiencies as high as 9% can be expected. If encountered, this high, albeit intermittent, efficiency can provide 49% to 196% of the increase required (154% to 366%) to reach the 1-MW_e power co-production for the base and reduced temperature cases, respectively.

4. Preliminary Geological and Reservoir Performance Analysis

During our literature survey, we were able to locate two publications discussing the geology of the Blackburn Field (Hulen et. al, 1990; Scott and Chamberlain, 1988). According to Scott and Chamberlain (1988), Devonian units were superimposed over Mississippian source rocks, which conceivably occurred during the Devonian-Mississippian Antler orogeny, indicating an ancient structural past of thrust faulting in the older formations of the system. As a result of the Antler orogeny, the Nevada dolomite reservoir is sealed by the overlying Chainman shale. The field is divided by complex, extensional NNE-striking normal faults and at least one ENE-striking fault; both NNE-striking and ENE-striking faults could be induced by historic extension in the Great Basin and oblique-slip faulting in the Humboldt Structural Zone, respectively, as similar extensional fault structures are present in these regions (Faulds et al., 2006). Figure 8 presents a geological map and two cross sections of the Blackburn Field. To the east of the Blackburn Field is the Sulphur Spring Range. This range most importantly contains surface expressions of Devonian to Mississippian-age formations. Units expressed in the mountain range include the Nevada dolomite formation and the Chainman shale (Figure 9). A gas seep is located close to the dolomitic formations. The exposed units in the mountain range are located approximately 4 miles from the Blackburn Field.

From a reservoir performance perspective, two aspects of the geological setting were determined as critical for the success of the project. The first is the sealing properties of the faults, for instance, the fault separating the injection well Blackburn 12 from the rest of the productive wells to the south. If this fault is sealing, then it is likely that the reinjection fluids are diverted away from the reservoir. Conversely, if it is non-sealing, the reinjected fluids can short-circuit to the production wells, which especially can become a detriment if the field-wide production rate (and therefore the cold-water reinjection rate) is increased to reach the 1-MW_e target, which would amplify the short-circuit cooling of the produced fluids. Field sampling and testing of naturally occurring and artificial tracers are currently being planned. These tests will indicate the magnitude of flow feedback from the injection well to the production zone.

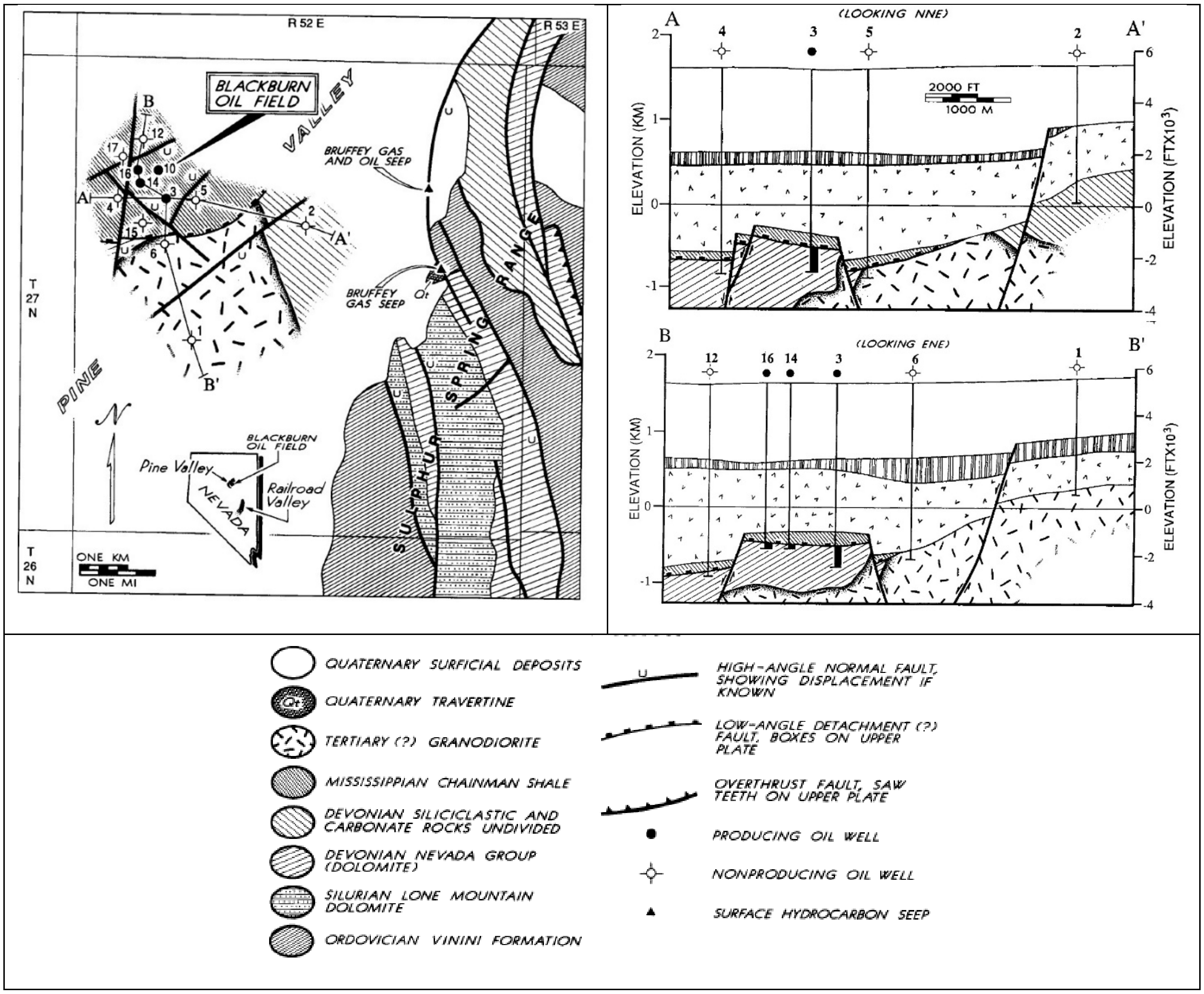

Figure 8: Map showing the Blackburn Field and its wells in relation to the subsurface geology (left). Two cross sections of the conceptualized geology prepared in approximately east-west (top right) and north-south (bottom right) directions. The legend is given in the bottom figure. Adapted from Hulen et. al., 1990.

The second geological aspect critical to project success is the hydraulic recharge of the Nevada dolomite. As discussed earlier, there is evidence in the public production data that the wells targeting this reservoir are not undergoing natural decline and the reservoir has strong hydraulic recharge. Hulen et. al. (1990) discuss the hydrothermal system and mention that because there are no young magmatic heat sources in the vicinity of the field, the relatively high temperature gradient reaching to 60°C/km is likely due to the upward flow of geothermal waters through the faults at the western margin of the Sulphur Spring Range (Figure 8), hinting at the likelihood of a bottom-drive water recharge in the Nevada dolomite reservoir. Planned tracer testing will also aid in determining the magnitude of hydraulic recharge of the Nevada dolomite reservoir. The Bruffey gas seep and exposed Nevada dolomite formation in the Sulphur Spring Range may be indirectly connected to the Blackburn Field through a system of complex normal faults and fractures, indicating recharge to the system from the east.

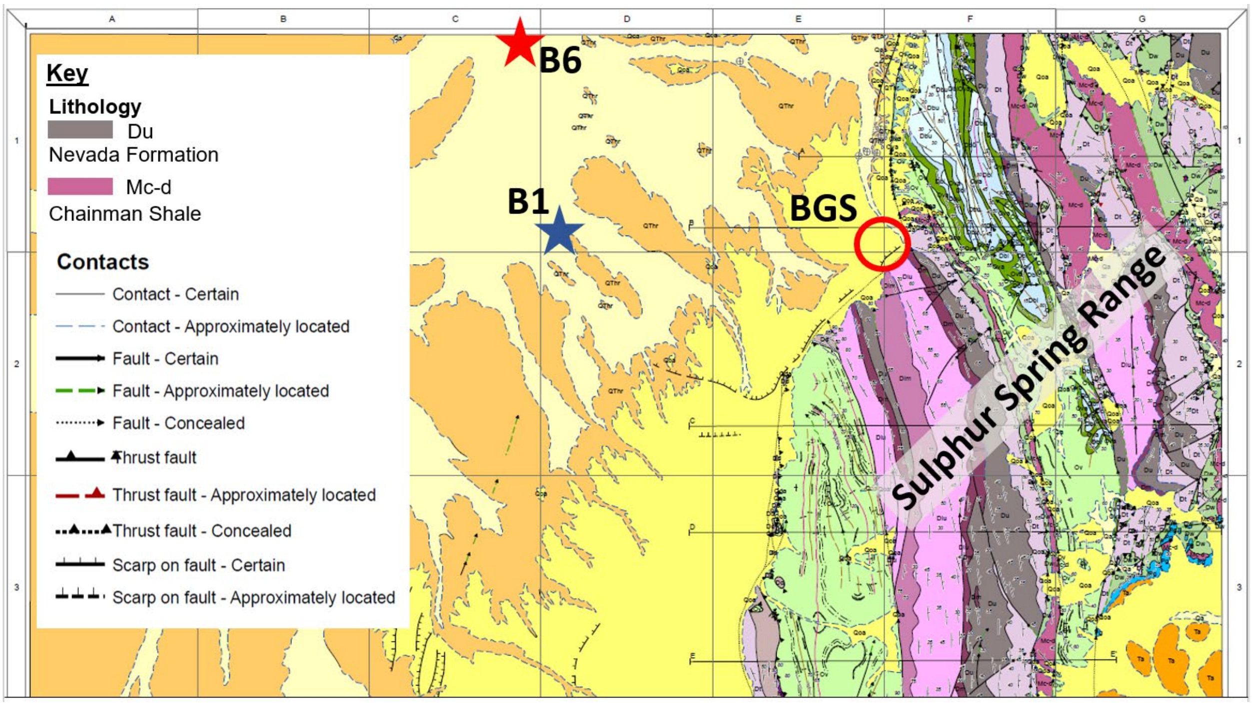

Figure 9: Regional geological map around the project area. Approximate locations of Blackburn Field wells 1 and 6 (B1 & B6, respectively) and the local Bruffey gas seep (BGS) are highlighted. Adapted from Carlisle and Nelson, 1990.

To address the thermal short circuiting and the hydraulic recharge uncertainties of the Nevada reservoir, a static conceptual geological model has been developed in Leapfrog. Publicly available well data has been utilized to suggest surface contacts between the formations present in the system (Figure 10; Nevada Bureau of Mines and Geology, 2023). Faults from the interpretive subsurface structure from the cross sections in Hulen et al. (1990) and fault trends in the basement structure proposed in Scott and Chamberlain (1988) have been imported to provide a basic 3D understanding of the east and west fault boundaries. The general trend of the intrusive basement layer has been assumed based on two downhole well log surfaces and cross sections from Hulen et al. (1990). The modeled subsurface expression is more accurate where wells are centralized; in areas where downhole well data is not available, Leapfrog superimposes the subsurface expression by extrapolating trends generated by clusters of wells. Therefore, some contacts may not be accurately represented in areas where no downhole well data is available. In the future, a numerical reservoir model will be constructed. This work is currently in progress, and the results will be published in subsequent publications. The model will incorporate the field flow and tracer testing results. Furthermore, commercially available legacy 3D seismic survey data was recently acquired by Transitional Energy. This dataset will be reprocessed using contemporary processing techniques and then implemented in the models to determine the geometry of reservoir contacts and faults.

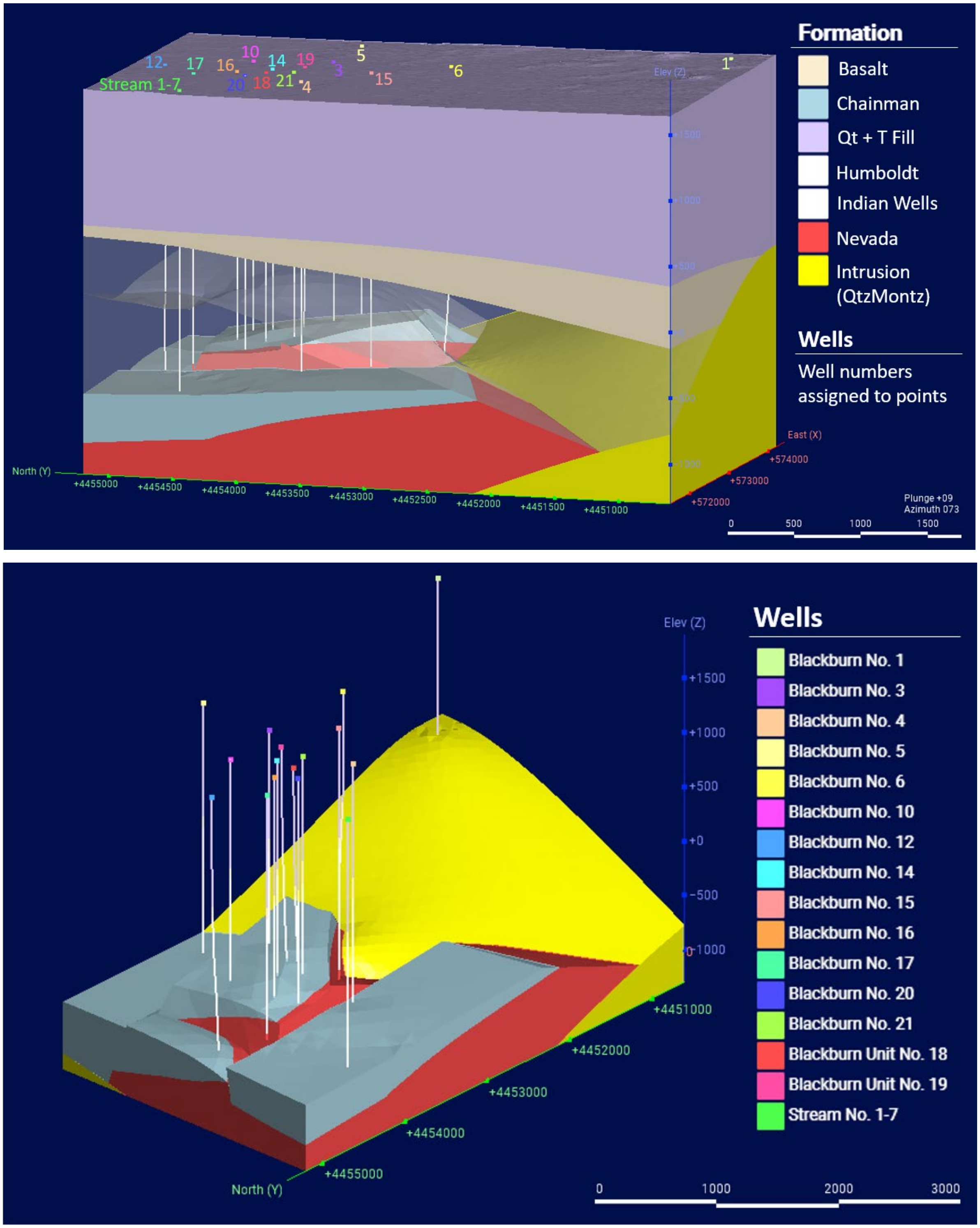

Figure 10: (Top) Conceptual Leapfrog model (looking NE) created with public data of the Blackburn Field subsurface with a focus on the structure bounded by faults at depth in the Chainman and Nevada formations (Qt – quaternary; T – tertiary, primarily alluvial; QtzMontz – quartz monzonite). (Bottom) Isolated focus (looking SE) on simplified structural interpretation of the Chainman shale and Nevada dolomite resting on the QtzMontz bedrock. The modeled subsurface expression is more accurate where wells are centralized; some contacts may not be accurately represented where no wells are present.

5. Conclusions

In collaboration with Transitional Energy and Grant Canyon Oil & Gas, the National Renewable Energy Laboratory prepared a preliminary resource characterization and evaluation. The data used in this study was primarily obtained from publicly available sources. Analysis of the historical production data showed that the Blackburn Field may possess field-wide aggregate production rates as high as 23 L/s. The most recent production temperature measurements indicated that flowing temperatures as high as 244°F can be expected. GEOPHIRES power production modeling, based on the historical performance of the reservoir, indicated that net power co-production up to 394 kW_e can be possible with air-cooled condensers. We are investigating pathways to increase the electricity output to ~1 MW_e (gross), including increasing the field-wide production rate beyond 23 L/s and considering condensers based on evaporative cooling instead of air-cooled condensers. Additional field flow and tracer testing is planned, and results will be implemented in numerical reservoir simulations to determine the ultimate power co-production potential at the Blackburn Field.

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