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# Deep Direct Use Geothermal Energy in the North Dakota Clean Energy Transition Strategy

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## Keywords

*geothermal, sedimentary basin, deep direct use, DDU, CHP, ORC*

## ABSTRACT

The geothermal heat in the Williston Basin is an energy giant that can provide sustainable, renewable, and ecologically sound heat and power for the state of North Dakota (ND). We have known of this resource for decades, but development has been delayed for reasons which can be summed as economic competition from existing fossil fuel energy sources. With the “seismic” shock of the Covid-19 pandemic reverberating through the state’s carbon-centric economy, the timing is ideal for acting quickly to develop this energy resource.

Coincidentally, the State Energy Research Center (SERC) within the Energy & Environmental Research Center (EERC), has recently embarked on an analysis of ND’s energy future, and the availability and sustainability of resources for the state and the citizens of ND. Thus, the opportunity to examine the case for including geothermal energy in the strategy is at hand.

The option we examine here is Deep Direct Use (DDU) geothermal energy, in multiple applications and in conjunction with Advanced Energy Storage technology. DDU can reduce and replace demand on energy supplies in two applications: direct use heat and electrical power. While in grid energy terms each DDU unit is relatively small, hundreds of these units would have a significant impact and merit consideration in the energy strategy. Realizing that DDU development is not currently market-driven, we are framing the analysis for potential early adopters and energy policy advisors based on a reference design and using that design to examine the project economics. The purpose of this paper is to get an early indication of whether the early stage project economics indicate “stop now”, or “proceed with caution”.

## 1. Introduction

The western half of the State of North Dakota (ND) is situated over the Williston Basin, a large geothermal energy giant that can provide sustainable, renewable, and ecologically sound heat and power. We have known of this resource for decades, but development has been delayed for reasons which can be summed as economic competition from existing fossil fuel energy sources.

Given the extreme continental climate of the north central United States, there are high demands for heating year-round. The mean annual temperature in central North Dakota is 4.3°C and temperatures in the winter (December – March) average -12.4 °C. Annual heating degree-days average approximately 4000°C (8600 °F). Average summer temperatures (June-September) are less than the base temperature, thus cooling degree-days are negative. The potential for meeting these heating needs with direct-use geothermal energy is excellent in North Dakota.

There is also a need for reliable, 24/7 electric power for industrial and commercial applications, especially in the oil sector. These applications have sites that are typically distant from existing grid facilities, requiring an expensive new electric service to be installed

Figure 1 provides a comprehensive view of the available geothermal energy compared to state energy demand, which is approximately 0.6EJ ( $6 \times 10^{17}$ J). In this chart, Available Energy assumes a DDU Combined Heat and Power (CHP) plant with a power conversion rate of 12%, which is multiplied by the 0.1% of the total reservoir energy in the temperature range shown. For example, the total energy in the eight aquifers with a temperature range of 130-140°C is  $5.5 \times 10^{21}$ J; the recoverable portion of that energy while maintaining the reservoir in a sustainable condition is 0.1% of the total or  $5.5 \times 10^{18}$ J. The available energy, assuming 12% power conversion efficiency, is  $6.6 \times 10^{17}$ J. Energy coverage in this temperature band is

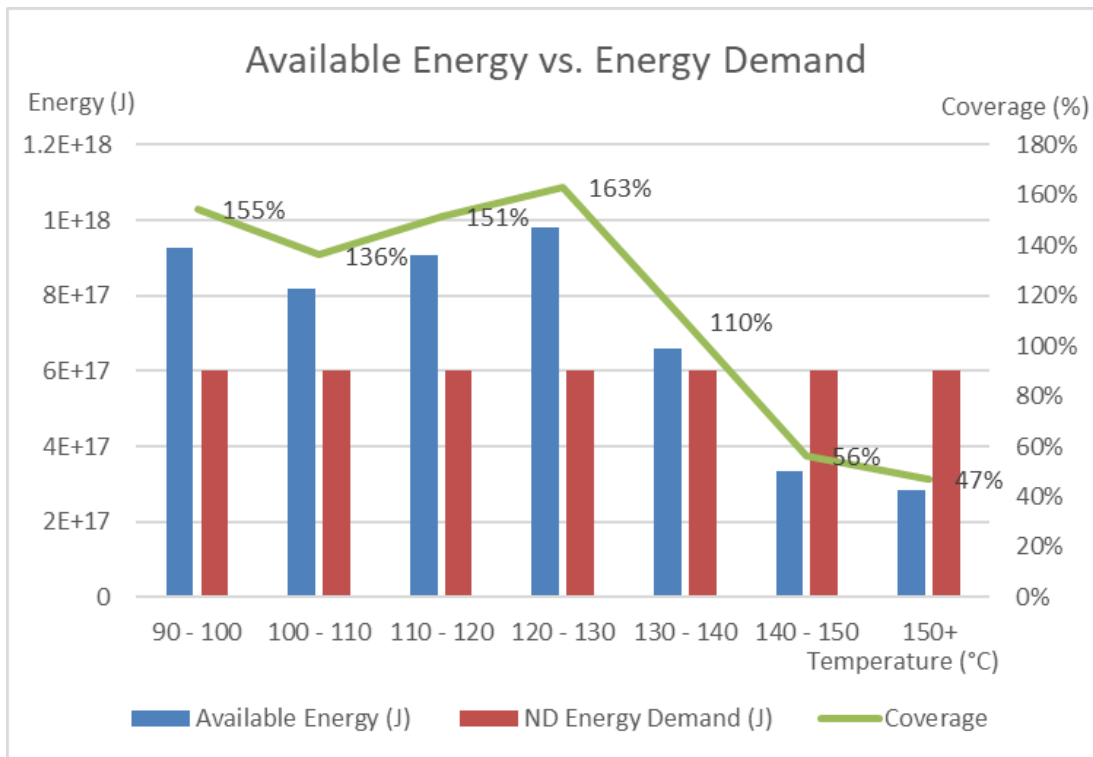


Figure 1: Available Energy vs. State Energy Demand. Coverage (Available Energy/Energy Demand) is shown as a percentage (right axis)

$$6.6 \times 10^{17} \text{J} / 6 \times 10^{17} \text{J} = 110\% \text{ (Crowell, 2011).}$$

From this chart we can readily see the vastness of the geothermal resource. For example, in the wildly optimistic case that the state future energy strategy decided to maximize geothermal power, in theory 47% of the state demand could be met – sustainably – from just part of the five

aquifers where the temperatures exceed 150°C. Clearly this is not realistic, but it does show that the geothermal energy is there, it is substantial, and it does merit consideration in the future energy strategy.

In section 2 we describe a reference design to be used as a template for DDU CHP projects and serves as a baseline for an initial review of the geological, technical and economic factors. In section 3 we provide a high-level economic assessment based on the CREST model. Section 4 states the conclusions from this work.

## 2. DDU CHP Reference Design

In this paper we use a high-level reference design of a DDU CHP plant that is configured for cascaded heat & power operation. While Enhanced Geothermal Systems (EGS) have greater potential for grid-level electricity production and might typically be a better geothermal option for an energy transition strategy (Tester, 2016), the scarcity of high temperature (>150°C) geothermal resources in the Williston Basin precludes their use here. The abundance of medium temperature (90°C to 150°C) resources in the basin, however, make DDU-based heat and power generation well suited for building a large number of smaller, distributed energy systems as part of a future energy strategy.

The distributed energy approach increases grid resilience while improving upon and adding to technology supporting the state's move toward sustainable and ecologically benign energy. Realization that DDU development is not currently market-driven with typically investor-funded projects leads to understanding that government and community entities likely will assume the role of "early-adopters." Therefore, we are preparing the case, aimed at these early adopters as well as investors and energy policy advisors, based on geological feasibility, proven technology, and positive economic benefits.

Development of DDU geothermal energy in multiple applications in conjunction with Advanced Energy Storage technology can reduce and replace demand on energy supplies in two applications: direct use heat and electrical power. The applications identified at this time are:

- industrial: oil wells, manufacturing, and processing plants
- commercial: multi-tenant commercial complexes
- municipal: small communities or subdivisions
- educational: campuses

To make an impact on a scale necessary for inclusion in a future energy transition strategy we envision hundreds of such DDU-CHP units being installed. In this section we consider the geological and technical requirements; in the following section the economics are examined.

The general configuration of the geothermal system envisioned for the North Dakota energy strategy is shown in Figure 1 below.

The reference design is essentially a 'back of the napkin' sketch used to start the discussion of whether DDU CHP makes sense.

Figure 2 shows the reference design. It includes innovative features that capitalize on opportunities and address challenges unique to this geography. The hydrostratigraphy of the Williston sedimentary basin with ten major aquifers at varying depths for production, injection, and storage reservoirs, is of particular interest.

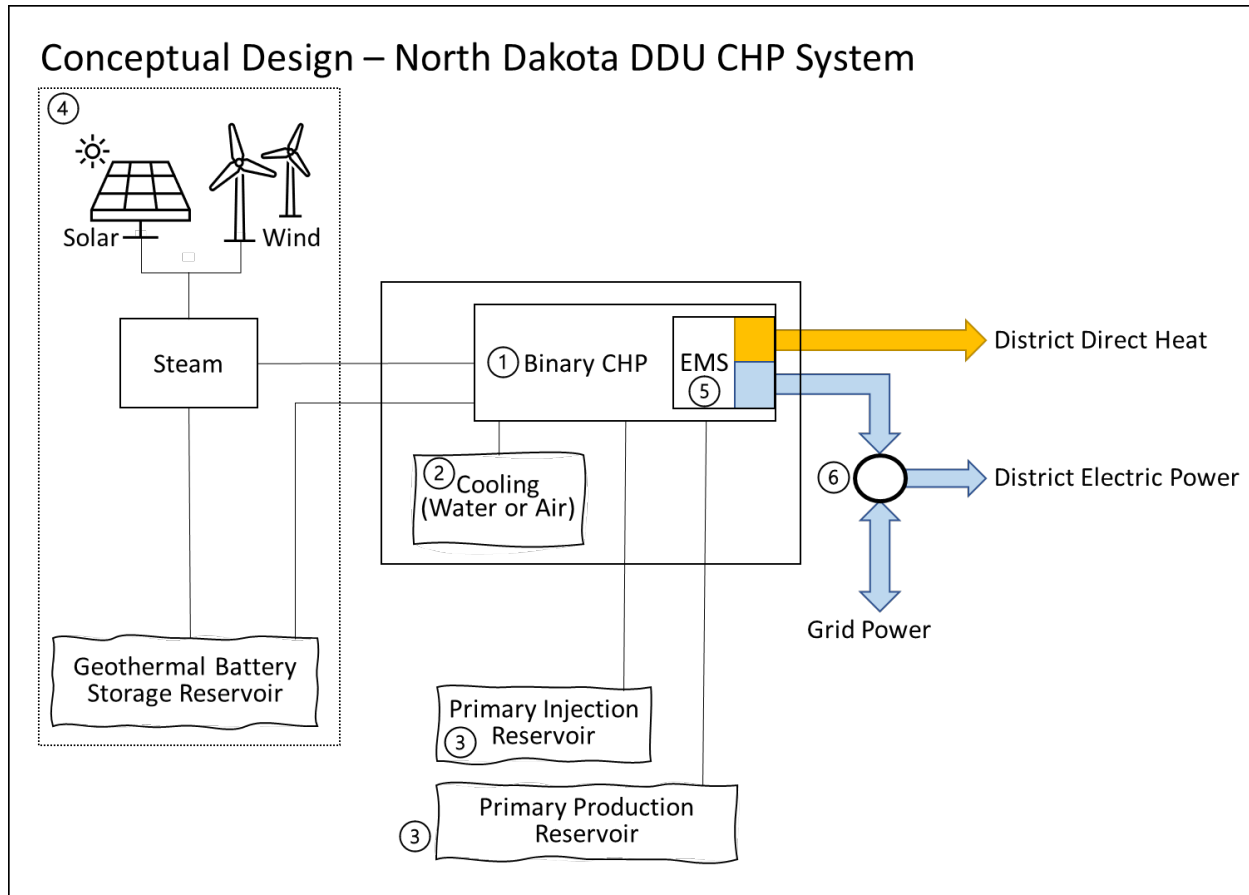


Figure 2: Reference Design

While the detailed design for any specific project will depend on the constraints and requirements for that project, we envision that each will consider the following common elements from this general configuration:

Major sub-systems of the reference design:

(1) Binary Cycle CHP plant. The plant will be configured for both district direct heat and district power. No specific plant design (Organic Rankine vs. Kalina cycle, single versus double flash) has been chosen at this time; these decisions are taken during detailed design. Recent studies will inform these decisions. For example Van Erdeweghe et al (2017) investigate four Organic Rankine Cycle (ORC) CHP plant configurations, examining different heat/power balances and concluding that the optimal plant for a given configuration will have higher exergetic efficiency and equal or better electric power generation than an electric-only power plant. Dawo et al (2019) compares approaches for modeling a Kalina cycle CHP plant to optimize the plant for part load configuration. Both types of plants are proven, commercially available technology.

In several areas the proximity of rivers makes water cooling an attractive option for the condenser to increase thermal efficiency and will be investigated. If problems caused by heavy ice build-up during extremely cold winters cannot be eliminated air cooling will be used.

(2) Primary Production and Injection Reservoirs. The Williston Basin has ten different dolomitic limestones with temperatures of 130°C to 150°C at depths of 3.5 to 4.3 km. These formations have been extensively drilled for oil and gas production and data on rock properties and potential for brine production indicate that these geothermal aquifers are the “low-hanging fruit” in Deep Direct Use (DDU) geothermal energy. The geothermal resource temperatures are sufficient for combined heat and power (CHP) applications, with the geofluid generating power from an Organic Rankine Cycle (ORC) binary plant prior to the direct-use applications.

In a multi-tiered primary reservoir design, deeper aquifers in the Ordovician system at depths of 3000m or greater with high flow characteristics and temperatures greater than 150°C will be used for the production wells. Injection wells will return spent fluid to a different, shallower aquifer to eliminate cooling effects in the production reservoir and thereby extending its useful life.

Even at this preliminary stage we found it useful to attempt an initial characterization of project readiness using the National Renewable Energy Library (NREL) GeoRePORT Assessment Protocol (GAP) as a guide. GAP assesses project readiness using three categories – Geological, Technical, and Socio-Economic. In its full application each Readiness category is further sub-

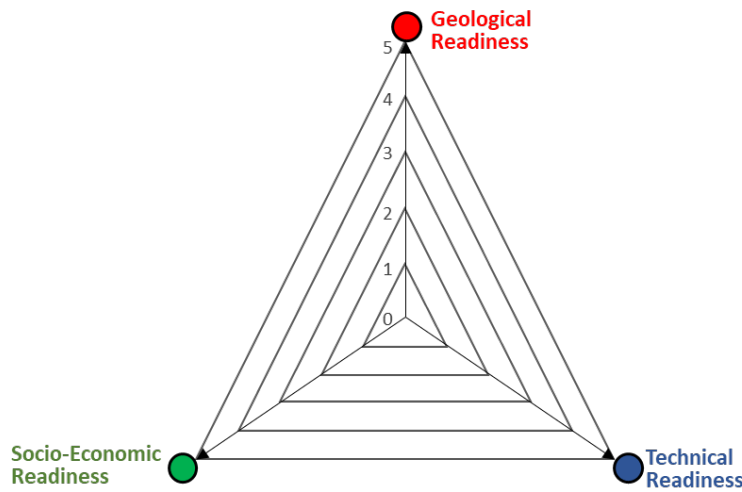


Figure 3: GeoRePORT Assessment Scale

divided into four Grade Attributes. Attributes are assessed on a 0 (low) to 5 (high) scale, and then aggregated for display as shown in Figure 2.

At this early stage we consider just one component of the protocol, Characterization, to provide an overall indication of the current state of readiness; the Activity Index and the Execution Index were not considered.

An informal approach is used, with assessments based on a combination of UND research,

information in the literature shown in bold type, and anecdotal information from industry contacts. The assessments are in Tables 1, 2 and 3 below, with the rationale following.

Table 1: Geological Characterization

<b>Geological</b>	<b>Temperature</b>	<b>Volume</b>	<b>Permeability</b>	<b>Fluid Chemistry</b>
A	>300°C or steam	> <b>10 km<sup>3</sup></b>	Very High	Ideal
B	230 - < 300°C	> 5- 10 km <sup>3</sup>	<b>High</b>	Favorable
C	<b>150 - &lt; 230°C</b>	> 2.5 - 5 km <sup>3</sup>	<b>Medium</b>	Challenging
D	<b>90 - &lt; 150°C</b>	> 0.5 - 2.5 km <sup>3</sup>	Low	<b>Difficult</b>
E	< 90°C	≤ 0.5 km <sup>3</sup>	Very Low	Acidic/Caustic

Rationale:

- Temperature: C/D. Using the TSRTAT tool (Gosnold et al, 2012) to model the temperature gradient (T-Z) profile of numerous wells in the NDGS catalogue we have determined that that wells drilled to aquifers in formations in the Ordovician system will encounter temperatures of at least 150°C and likely higher. This would give a ‘C’ rating in the Temperature category; however, to be conservative at this stage we have opted for the ‘D’ rating although it will be at the high end of this category. Data from exploratory wells, or reliable data from nearby oil and gas wells that have achieved thermal equilibrium, will be used to confirm this rating during preliminary design.
- Volume: A. UND has made significant advances in identifying and characterizing the geothermal resource base in North Dakota and the midcontinent (Crowell et al 2011, Crowell 2015, Gosnold et al 2012, Gosnold et al 2016). There is a high degree of confidence in the accuracy of this rating.
- Permeability: B/C. Permeability is known to be high to very high to high in many locations, but it is also known to vary with location.
- Fluid Chemistry: D. Chemistry is known to be difficult; recent discussion with geothermal project in southwest Saskatchewan confirms paying particular attention to this parameter is extremely important.

<b>Technical</b>	<u>Drilling</u>	<u>Logistics</u>	<u>Reservoir Management</u>	<u>Power Conversion</u>
A	< 2km	<b>Ideal</b>	<b>Ideal</b>	> 18%
B	2-3km	<b>Favorable</b>	<b>Favorable</b>	16-18%
C	<b>3-4km</b>	Challenging	Moderate	14-16%
D	4-5km	Difficult	Difficult	<b>11-14%</b>
E	> 5km	Impossible	Very Difficult	< 11%

Rationale:

- Drilling: C. As noted above, temperatures above 130°C require drilling to depths of 3 to 4km.
- Logistics: A/B. The logistics expertise for many aspects of this project is excellent and readily accessible; however, geothermal projects are not identical to oil and gas projects and some challenges are expected.
- Reservoir Management: A/B. Technologies to evaluate the geothermal resource include: (1) Aquifer formation determination using stratigraphy column of North Dakota, temperature gradient distribution, and public accessible information.; (2) Water production volume statistics, history investigations, and reservoir life for water production prediction from current production and abandon wells located in the Lodgepole and Tyler formations using reservoir numerical simulation modelling and the information from North Dakota Industrial Commission; (3) Reservoir characterization via pressure transient analysis, (4) Identifying the subsurface mineral and reservoir fluid properties by means of reservoir characterization from core samples in the target formations; (5) Water quality analysis to investigate the chemical compositions and salinity content in the formation water based on laboratory measurement; (6) Water disposal and reuse suggestions based on numerical simulation analysis; (7) Water rights

and new drilling request investigation through legal collaboration with the relevant division and industry; and (8) Economic analysis if newly drilled wells are needed, including pipeline cost and related material expense.

- Power Conversion: D. Recent studies indicate conversion efficiencies in the 10 – 15% range are expected (Lee et al 2019, and Trota et al 2020). Actual results depend on various design choices including the thermal cycle and the working fluid.

<b>Socio-Economic:</b>	<u>Land Access</u>	<u>Permitting</u>	<u>Transmission</u>	<u>Market Conditions</u>
A	Ideal	No permitting barriers present	Ideal	Favorable
B	<b>Favorable</b>	<b>Manageable permitting barriers</b>	<b>Favorable</b>	Manageable
C	Moderate	Permitting barriers present	Moderate	<b>Acceptable</b>
D	Difficult	Difficult permitting barriers	Difficult	Difficult
E	Very Difficult	Extreme permitting barriers	Very Difficult	Very Difficult

Rationale:

- Land Access: B. Drilling is common in ND and the process including land access is well known. Challenges are expected but they are unlikely to be problematic.
- Permitting: B. The same rationale as Land Access applies to Permitting.
- Transmission B. We have not investigated this area in any detail, but for the power range and short transmission distances being considered (1 – 10MW) we anticipate favorable negotiations with the utilities involved.
- Market Conditions: C. Market conditions will be highly influenced by two factors: a) success or failure of the first few projects, and b) inclusion (or not) in the ND energy transition strategy. Inclusion in the energy transition strategy will be influenced by initial project results and evidence that enough geothermal energy production can be installed to merit inclusion in the strategy. That scale will require hundreds of DDU units be installed and a proportionate number of production and injection wells. Considering that there are already more than 38,000 wells in the NDGS well index that level of drilling activity should not be seen as a barrier.

Public opinion will also be a factor. Survey results (n=1500) from the Pacific Northwest (British Columbia, Canada, and Washington and Oregon, USA) reported in a recent study indicate a preference for wind, solar, wave/tidal and geothermal as fuel sources for electric power generation over fossil fuels, nuclear and hydropower fuel sources (Hazboun and Boudet, 2020). The survey methodology is comprehensive; replicating this survey in ND would give an accurate indication of state preferences.

(3) Advanced Energy Storage. This sub-system uses proven technology in an innovative way to create a ‘geothermal battery’ (Green, 2020). A storage reservoir using a shallower aquifer, such



as Inyan Kara, will receive water heated to 250°C from a heat exchanger powered by solar or wind energy, which is then retrieved later. While the technology components are well-known, there are few such systems in operation today, therefore the overall sub-system is not well understood. It is included in the reference design for its potential to improve the overall system but is not included in the economic analysis in the next section.

(4) Grid Connect/Disconnect. This switching arrangement will allow bi-directional electric power flow according to operational requirements. Power not required for local purposes can be transferred to the grid, and the grid can provide backup power.

### 3. CREST Simple Economic Assessment

To get an early indication of economic viability we have used the Cost of Renewable Energy Spreadsheet Tool (CREST) Geothermal, version 1.4 in the ‘Simple’ Cost level of Detail mode.

CREST is a financial and economic analysis tool that takes project costs, planned duration and funding plans as inputs and generates financial and cost of energy information. The intended use of this information is to determine appropriate energy incentives for the project.

Our use of CREST here is as a starting point that will eventually results in a completed model ready for detailed examination by investors and policy makers once the project is ready for funding. By using CREST in this way, from the start of the pre-feasibility study, we have a means of providing feedback on the financial and economic impacts of technical and project options during the initial planning stages when risks are at their greatest.

CREST provides three analysis options: Complex, Intermediate and Simple. In Simple mode, capital costs excluding exploration costs are estimated based on a single input, \$ per kW, for Installed Cost; Total Exploration Costs, also a single value in \$ per kW, are estimated separately. Operating and maintenance costs are similarly constrained to be percentages or constants covering the planned useful life of the system. At this stage the purpose is not to predict a rate of return or cost of energy with any degree of accuracy, but to run a number of scenarios and examine if the range of results indicates “stop now”, or “proceed with caution”. If the indication is “proceed with caution”, CREST would be used in Intermediate and then Complex mode as more information is gathered in the run up to the submission of a detailed design for funding approval.

Using CREST in this way serves two purposes:

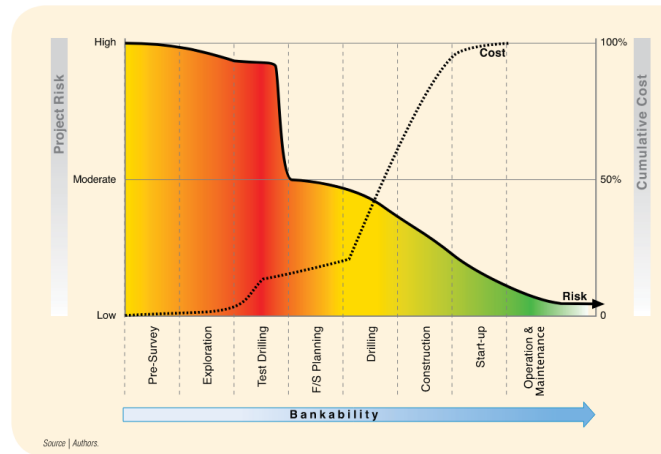


Figure 4: Geothermal project cost and risk profile during the project life cycle (ESMAP)

- as noted earlier, as continuous feedback when evaluating technical and project options, with the overall intent of reducing risk or identifying risk mitigation strategies; and
- as a communication tool for policy makers and investors, with the intent of initiating a collaborative discussion framework from the outset for creating a robust geothermal energy industry that is part of the state clean energy transition plan.

We used the following assumptions for the model:

- Generator: Binary ORC with nameplate capacity of 10MW<sub>e</sub>
- Geofluid flows of 50L/s to 100 L/s flow  $\geq 150^{\circ}\text{C}$  or greater
- No grid interconnection costs – these will be determined and added at a future time.
- Costs for geological, engineering and other reports and studies, as well as regulatory costs for permits, licenses, environmental impact assessments, etc. are included in Installed Cost
- No confirmation phase estimate is included at this time. As noted in the geothermal assessment above, a substantial amount of information is already available, which will be supplemented by exploration data. We will revisit this item during preliminary and detailed design.
- Costs for preparing design, tender and procurement documents are included in Installed Cost.
- At this point we have assumed no grants or subsidies and 100% equity or debt financing for all phases. For a given cost structure, the model determines if the Debt Service Cost Ratio (DSCR) is within acceptable limits. If it is not, and the debt/equity financing ratio is fixed, the DSCR red flag is an indication that grant or incentive funding is required for the project to be financially viable. There were no DSCR red flags for either scenario.
- We set the value of energy at using the current ND commercial rate of \$0.0845/kWh. The escalation value of 1.15% is based on the average annual rate of increase from the 2015 value.
- As this is an optional component, the cost of the geothermal battery is not included.

Table 2 shows the range of input parameters we examined, grouped as two scenarios (lower cost range) and B (upper cost range).

Table 2: CREST Input Parameters (Simple mode)

Parameter	Units	Scenarios	
		A	B
Generator Nameplate Capacity (MW)	MW	10	10
Net Capacity Factor, Year 1	%	0.6	0.6
Annual Plant Production Degradation	%	0.5	0.5
Ratio of Plant Capacity to Thermal Potential	ratio	0.7	0.7
Annual Degradation of Thermal Resource	%	1	2
Project Useful Life	years	30	25
Installed Cost per kW (excluding exploration costs)	\$/kW	5,335	7,962
Total Exploration Costs	\$/kW	175	210

Replacement Well Cost	\$	6,000,000	7,260,000
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Net Capacity Factor accounts for parasitic losses for the wells and the plant itself to achieve net generation greater than 5MW during the operating life of the plant. We set Plant Useful Life in Scenario A we set the useful life to 30 years, and to 25 years in Scenario B to observe the financial impact. Based on the values from Table 3 (below) we calculated the most important input value for the model, Input Cost per kW, to be \$5,335/kWh for Scenario A and \$7,962/kWh for Scenario B.

Table 3 shows the costs used to calculate the input value Installed Cost per kWh for each scenario; this parameter does not include exploration costs. The generator nameplate rating in Table 2 is used to determine the installed cost per kW.

Table 3: Installed (non-exploration) Cost inputs

		Scenarios	
<u>Installed (non-exploration) Cost Calculation</u>	<u>Units</u>	<u>A</u>	<u>B</u>
Total Production Wells Needed	#	3	4
Total Injection Wells Needed	#	2	2
Cost of production wells	\$	36,000,000	58,080,000
Cost of injection wells	\$	12,000,000	14,520,000
Non-Drilling Wellfield Costs (included)	\$	1,350,000	2,178,000
Power Plant Cost (non-well)	\$	4,000,000	4,840,000
Installed Cost, excluding exploration costs	\$	53,350,005	79,618,006
<u>Input to Cost of Production Wells</u>			
Cost per production well	\$	12,000,000	14,520,000
Cost per injection well	\$	6,000,000	7,260,000
Non-Drilling Wellfield Costs per Well	\$	150,000	181,500

Table 4 shows the key summarized results for each scenario. Recall that Scenario B is modeled for a 25-year period, hence there is no IRR given for 30 years.

Table 4: Summarized key results from the CREST model (Simple mode)

		Scenarios	
<u>Summarized Key Results</u>	<u>Units</u>	<u>A</u>	<u>B</u>
Net Nominal Levelized Cost of Energy	¢/kWh	37.55	38.25
Payback Period	years	6.2	6.2
Internal Rate of Return (IRR), 25 years	percent	15.0	15.0
Internal Rate of Return (IRR), 30 years	percent	15.0	-

The model outputs show the Net Nominal Levelized Cost of Energy values to be consistent with values reported by the EIA (U.S. Energy Information Administration 2020), providing a high-level indication that the results are reasonable. In both scenarios, the relatively long plant useful

life values (30 years and 25 years respectively) account for the similar results for payback period and internal rate of return.

#### 4. Conclusion

As noted earlier, the purpose in performing this analysis based on a DDU CHP reference design is to assess if we should “stop now” or “proceed with caution”. Based on a design that can be realized using commercially available technology in a very well-studied geological formation with initial cost estimates that indicate reasonable LCOE and payback period values, the conclusion is that the work to implement DDU CHP-based geothermal energy strategy should “proceed with caution”.

The next phase of work should be to identify an early adopter with a candidate project, and then start the preliminary design. The preliminary design work should continue to update the reference design to maintain the focus on building hundreds of units and not just the early adopter project. Also, updating the CREST economic model in Intermediate mode would help move the degree of costing accuracy from rough-order-of magnitude (ROM) to something more reasonable (e.g. +/- 25 to 30%).

Creating an oversight committee for the early adopter project that includes potential investors as well as state energy policy makers such as EERC/SERC would help build stakeholder momentum for strategic geothermal energy solutions.

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#### REFERENCES

- Crowell, A. M., "Identifying potential geothermal resources from co-produced fluids using existing data from drilling logs: Williston, North Dakota." *Theses and Dissertations* 65. (2011)  
Available: <https://commons.und.edu/theses/65>
- Crowell, A. M., Klenner, R., and Gosnold, W. D. “GIS Analysis for the Volume and Available Energy of Selected Reservoirs: Williston Basin, North Dakota.” *GRC Transactions*, 35 (2011) 1581-1585.
- Crowell, A. M. “Geostatistical Analysis of Bottom-Hole Temperatures in the Denver and Williston Basins: North America.” *Geothermal Resources Council Transactions*, 36, (2015) 1035-1038.
- Dawo, F., Wieland, C., and Spliethoff, H. “Kalina power plant part load modeling: Comparison of different approaches to model part load behavior and validation on real operating data.” *Energy* 174 625-637. Elsevier (2019)
- Gosnold, W.D., McDonald, M.R., Klenner, R., and Merriman, D. “Thermostратigraphy of the Williston Basin.” *Geothermal Resources Council Transactions* Vol 36 663-670 (2012)
- Gosnold, W., McLaughlin, S., and Colby, C. “Three-Dimensional Temperature Structure of the Williston Basin.” *Geothermal Resources Council Transactions* Vol 40 639-642 (2016)

- Green, S., McLennan, J., Panja, P., Allis, R., Newhart, R., Moore, J., and Kitz, K. "Large-Scale Subsurface Seasonal Solar Heat Storage for Future Value." University of Utah Workshop 2020 May 19. Workshop report to be published by the National Science Foundation.
- Hazboun, S. O., and Schaffer Boudet, H. "Public Preferences in a Shifting Energy Future: Comparing Public Views of Eight Energy Sources in North America's Pacific Northwest." *Energies* 13, 1940 (2020)
- Lee, I., Tester, J. W., You, F. "Systems analysis, design, and optimization of geothermal energy systems for power production and polygeneration: State-of-the-art and future challenges." *Renewable and Sustainable Energy Reviews* 109 551-557 (2019)
- Schifflechner, C., Dawo, F., Eyere, S., Wieland, C., and Spliethoff, H. "Combined Heat and Power Generation by Enhanced Geothermal Systems: Comparison of Direct and Indirect Concepts for Water and Supercritical CO<sub>2</sub> as Heat Carriers." *Proceedings of the 5th International Seminar on ORC Power Systems Athens* (2019)
- Tester, J. W., Anderson, B. J., Batchelor, A. S., Blackwell, D. B., DiPippo, R., Drake, E. L., Garnish, J., Livesay, B., Moore, M. C., Nichols, K., Petty, S., Toksöz, M. N., and Veatch, Jr., R. W. "The Future of Geothermal Energy." Idaho National Laboratory External Report INL/EXT-06-11746, Idaho Falls, ID, 396p. (2006) Available: <http://geothermal.inl.gov> or [http://www.eere.energy.gov/geothermal/future\\_geothermal.html](http://www.eere.energy.gov/geothermal/future_geothermal.html)
- Trota, A., Ferreira, F., Gomes, L., Cabral, J., and Kallberg, P. "Power Production Estimates from Geothermal Resources by Means of Small-Size Compact Climeon Heat Power Converters: Case Studies from Portugal (Sete Cidades, Azores and Longroiva Spa, Mainland)." *Energies*:2839 (2019)
- U.S. Energy Information Administration. "Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2020." (2020) Available: [https://www.eia.gov/outlooks/aeo/pdf/electricity\\_generation.pdf](https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf)
- Van Erdeweghe, S., Van Bael, J., Laenen, B., and D'haeseleer, W. "Optimal Configuration for Low-T Geothermal CHP Plants." *Geothermal Resources Council Transactions Vol 41* 2110-2125 (2017)
- Young, K., Wall, A., Levine, A., Badgett, A., and Dobson, P. "GeoRePORT Protocol Volume I: Background Document." *National Renewable Energy Laboratory NREL/TP-4A00-72980*. (2019). Available: <https://www.nrel.gov/docs/fy19osti/72980.pdf>