Introduction

Academic interest in the potential for integrated renewable energy systems is not uncommon (e.g., wind-solar, wind-solar-geothermal, solar-geothermal). Nonetheless, to the best of our knowledge an underexplored option is an integrated wind-geothermal system. While few such systems exist in practice, integrated systems have the added benefit of being able to co-generate electricity. Cogeneration may be the key to overcoming economic thresholds often considered a barrier to renewable energy systems. Moreover, the benefits of cogeneration exceed simply greater energy supply by targeting and addressing weaknesses in each system (Suleman et al., 2014). A potential reason for the gap in the current literature may relate to the regional crossover typically required for both geothermal and wind energy systems to operate individually.

While there are a variety of different geothermal systems (e.g., binary cycle, closed-loop, open-loop) at their base they all require a higher geothermal gradient to reduce drilling costs, usually in combination with an active hot water source (Sharmin et al., 2023). In addition to this, inefficiencies in geothermal systems often require them to exist within close proximity of either (1) populated centres or (2) large, effective transmission lines. However, a combination of the need to potentially create and store energy through hydrogen electrolysis and the addition of larger, more effective transmission lines globally may make the placement of geothermal power plants in more remote settings a possibility (DOE, 2012; Johnson et al., 2024). Indeed, the idea of utilizing wind to create and store hydrogen as a way to maximize energy creation is already being actively studied within Europe and abroad (Johnson et al., 2024). Furthermore, there have been a few publications that highlight the potential for enhanced geothermal systems (EGS) that could utilize low porosity-permeability (i.e., Φ-K) rock through activating fractures and flowing colder water to the warmer zone (Sharmin et al., 2023). Another possibility that is increasingly of interest is the potential to utilize colder zones as a form of thermal heat storage that could be accessed at a later date (Sharmin et al., 2023).

Similar to geothermal, there is a significant amount of nuance to variations within wind systems, with key differences focusing around turbine design. The two conventional designs are horizontal-axis and vertical axis (EIA, 2024). Ultimately, the key inputs that determine the efficiency of the turbine is wind speed, Reynold’s flow numbers, density, humidity, and air temperature (Karic, 2022). While, currently onshore wind accounts for 93% of installations there has been a rapid increase in the expansion rate of offshore wind in recent years (IEA, 2024). With this there has also been a push towards a better understanding of the stabilization options offshore. Broadly the platforms can be broken out into bottom-fixed and floating (IEA; Jiang, 2021). Bottom fixed options include monopile, gravity based, and jacket. Floating turbines are more difficult to characterize, but can be classified within a ternary diagram wherein the stabilization endmembers are ballast, buoyancy, or mooring (Jiang, 2021).

One potential site of future interest with this combination of factors could be the Norwegian Continental Shelf (NCS). In this study we explore the potential for an integrated wind-geothermal system within current license zones for wind generation (NVE, 2024).

Background theory and methodology

The two energy systems (i.e., wind and geothermal generation) rely on completely unrelated sources to create energy (Table 1). However, the benefit of integration may lie in the similar mode of energy generation for the system (Table 1). Specifically, both utilize the movement of air to spin a generator, that then collects and feeds the energy to connected transmission lines (Sharmin et al., 2023; EIA, 2024). The difference and consistency of the sources provides for a combination of potential for cogeneration and addressing system inefficiencies.

Wind has limits around minimum and maximum speed that often result in a significant portion of a single day not being utilizable (EIA, 2024; Solbrekke and Sorteberg, 2022). Since, wind currents are tied to the solar warming of the Earth’s surface, two scenarios occur frequently. (1) Wind is within the potential speed range for energy production during the day, but a drop-off in temperature results in insufficient wind speeds at night. (2) Alternatively, wind speeds are within the potential speed range for energy production during the night, but a rise in temperature during the day corresponds to higher wind speeds pushing it beyond the maximum (Solbrekke and Sorteberg, 2022). Nonetheless, average wind speed maps are valuable in understanding potential for a given area (Figure 1).

Table 1 *Summary of two diverse energy systems (i.e., wind and geothermal) including their minimum input requirements, potential daily max energy generation, and the energy generation system utilized.*

Energy System	**Minimum Input Requirements**	**Maximum Energy Generation**	**Energy Generation System**
Wind Generation	Wind speeds (m/s) Minimum: 3-4 Optimal:14-17 Maximum: 25	12 MW/hour (per turbine) 288 MW/day (per turbine)	Variations in air current created by solar warming of the Earth's surface turns a ***propellor*** attached to a ***generator***
Geothermal Generation	Categories (°C) Energy storage: 99-149 Heat range: 99-149 Binary cycle power: 95+ Power: 150+ EGS minimum: 220+	8 MW/hour (per well) 196 MW/day (per well)	Differential in heat supplied from the subsurface to the surface results in flashing steam which turns a ***propellor*** attached to a ***generator***

Geothermal energy has clear cutoffs for different potential forms and uses expressed in formation temperatures (Table 1). The average geothermal gradient is 24-41°C/km (DOE, 2024), so utilizing the centroid power generation is typically initially feasible at c. 4.65km depth. However, as gradient is sensitive to basal heat flow, lithology, and circulating groundwater numerous localized hot spots exist globally (DOE, 2024; Sharmin et al., 2023). Heat flux (mW/m^2), which describes the amount of energy passing through a given surface, is typically utilized to map and visualize regional hot spots. Locally, bottom hole temperatures (BHT) in combination with geophysical mapping can be utilized to accurately estimate anomalies (Figure 1). When deemed appropriate, BHT for a given license was calculated utilizing the methodology presented by Johnson et al., (2022).

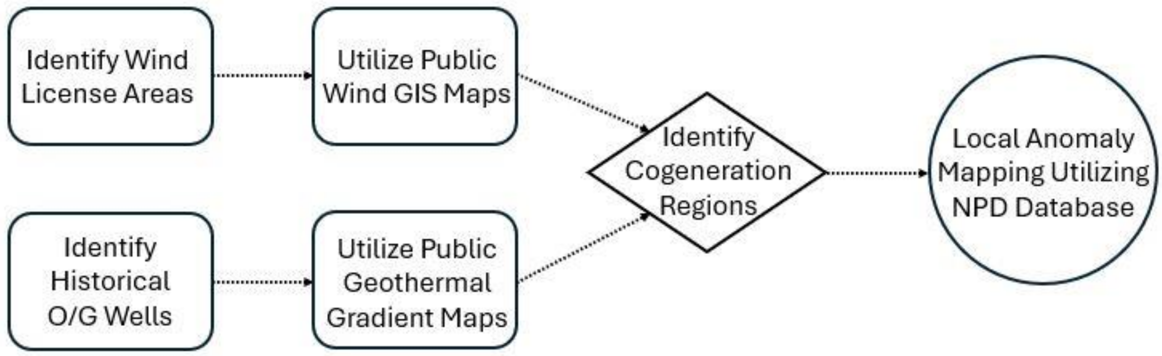

Figure 1 *Simplified workflow for identifying regions of cogeneration and local anomalies that could be ideal for initial testing within said regions.*

Here we utilize a combination of a literature review, publicly available data (NPD, 2024), and an analytical approach in order to identify potential regions of the Norwegian North Sea that could be ideal for testing an integrated wind-geothermal cogeneration system in the future. Figure 1 outlines our workflow, integrating data critical to identifying functioning wind and geothermal systems.

Proposed Wind-Geothermal Cogeneration System

Integrated renewable energy systems can benefit from cross-utilization of the same engineering systems at certain junctures within the system (Suleman et al., 2014). While it is currently unclear how these two systems might be integrated from an engineering perspective there is clear crossover in basic principles for certain components (Table 1). For many of the wind license sites wells already exist in the area up to 4500+ meters placing them within range to utilize geothermal energy currently. Cogeneration utilizing wind and geothermal would likely double energy production that could be delivered to the grid (Table 1), while also dampening uncertainty around delivery. Furthermore, this system has the potential to be further integrated into developing plans for the NCS that could include the electrolysis of H2 utilizing seawater (Xie et al., 2022). Subsequent storage within several potential options (Johnson et al., 2024) and then delivery to market would result in greater energy efficiency.

Results

While there are a limited number of places that have a high enough heat flux to support geothermal energy in Norway onshore, heat flux offshore along the passive margin can be quite high (Figure 3, left). Of the 20 active wind licenses, 11 of them at a regional level have a sufficient heat flux to deserve further investigation (Table 2). Unsurprisingly, all of the wind licenses have a reasonable average wind speed. However, some license zones could be considered better than others based on long term averages for wind speed (Table 2). The licenses can be broken out into 4 zones with long term average wind speeds in the range of ~ 8, 9, 10, and 11 m/s.

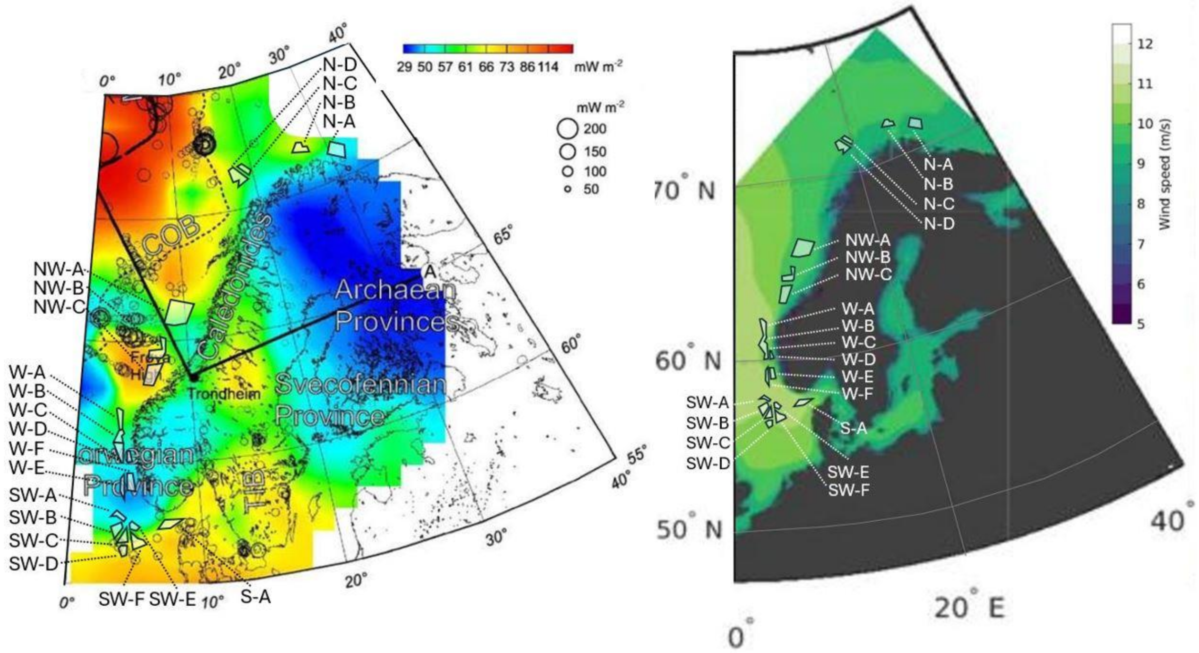

Figure 3 *Map of thermal heat flux (left) for the NCS with wind licenses overlaid in shaded white (modified from Slagstad et al., 2009) and average wind speed from 1996-2019 with wind licenses overlaid in shaded white (modified from Solbrekke and Sorteberg et al., 2022).*

Discussion

BHT was calculated for sites that were deemed to deserver further investigation based on a cut-off from the average heat flux (i.e., 60 mW/m^2) utilizing the methodology presented in Johnson et al., (2022). All BHT's are projected to an average temperature for the area given a depth of 5km.

Table 2 *A comprehensive top-level review of all license zones for wind and geothermal power generation potential, including average wind speed zone (green=faster, blue=slower), average heat flux (red=hotter, blue=colder), and when applicable average BHT based on nearby wells at a projected depth of 5km.*

License (direction, letter)	S, A	SW, A	SW, B	SW, C	SW, D	SW, E	SW, F	W, A	W, B	W, C	W, D	W, E	W, F	NW, A	NW, B	NW, C	N, A	N, B	N, C	N, D
Wind (m/s)	11	11	11	11	10	11	11	11	10	10	9	9	11	9	9	9	9	9	8	8
Heat flux (mW/m^2)	70	33	56	60	74	39	69	60	54	49	48	44	29	63	71	84	52	69	61	67
BHT (ºC)	190	-	-	152	162	-	151	169	-	-	-	-	-	171	157	157	-	176	133	138
Ranking (#)	1	3	2	1	1	3	1	1	2	2	2	3	4	1	1	1	2	1	2	2

A ranking between 1-4 was given for each of the license sites depending on their viability for cogeneration. The levels are as follows:

1. An ideal site for cogeneration of power utilizing both wind and geothermal energy sources. Nonetheless, further analysis would be required to confirm geothermal potential.
2. This ideal site for generation of wind power merits further investigation to determine potential for cogeneration. However, current data suggests that it would be better suited to energy storage, binary cycle power production, and/or heat production.
3. While an ideal site for generation of wind power, it is unfortunately not ideal for cogeneration of power and may not be suited for energy storage
4. An ideal site for generation of wind power, however data suggests that it is unlikely to be suited for energy storage. Furthermore, it is extremely unlikely to be suited for cogeneration of energy.

Conclusions

This dominantly qualitative review highlights the potential for cogeneration of electricity along the NCS utilizing wind and geothermal energy. Offshore license sites well suited to field testing of wind-geothermal cogeneration have been identified and ranked based on high-level criteria. Combined with hydrogen storage this integrated renewable energy system could be a natural fit for the Norwegian energy portfolio.

Acknowledgements

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