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Geothermal – not just for Earth

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INTRODUCTION

As humanity expands into the solar system, resilient power will be needed. For spacecraft to date this has meant solar panels or Radioisotope Thermoelectric Generators (RTGs) – a fission source. Each of these power sources have drawbacks; solar is subject to the inverse square law of decreasing solar flux with distance, while fission sources emit radiation that must be protected against with shielding mass and distance. One possibility with potential for powering installations on planetary bodies, particularly the outer solar system, is geothermal generation. All that is needed to produce geothermal energy is an exploitable temperature differential between a source and a sink. This technology has been producing electricity on Earth for more than 100 years from temperature differences of about 125°C or greater. This generation is typically done via a fluid phase change driving a turbine/generator.

Many moons and dwarf planets are water/ice worlds with an outer crust of ices overlying a planet-wide ocean. On these bodies, such as the moons of Jupiter and Saturn, there is probably an exploitable 150-250°C difference between the temperature of the ocean and the ambient surface temperature. Various geothermal engineering approaches could generate usable power from this setting.

The rim of polar region craters on the Moon offer a different near-term potential geothermal-ish development option using ThermoElectric Generators (TEG) and the ~150°C difference between the sunlit and permanently shadowed sides. TEG have low efficiencies, but this might be offset by the lack of moving parts (greater reliability) and ability to deploy may TEGs cheaply and quickly. This could be a resilient and reliable adjunct to solar cells or other power sources.

While significant engineering issues need to be solved in producing this style of energy, the potential, particularly on icy bodies is on the order of Megawatts of power generation per well.

1 GEOTHERMAL SYSTEMS AND APPLICATION IN SPACE

Geothermal power is traditionally defined as using the heat from deep in the Earth to generate electricity (or using the heat directly). Humanity has been generating electricity from geothermal sources for over a century (Parri, & Lazzeri 2016). Geothermal power is not limited to the Earth however. Any celestial body with an appropriate energy source and geologic configuration is suitable for geothermal power development. Probes throughout the solar system have clearly shown that many bodies have geothermal potential, particularly moons of the gas giants and some dwarf planets. Most of these bodies, except Io (a volcanic moon of Jupiter), are icy and many have clear or circumstantial evidence of subsurface oceans. The implied 150°C or great difference between the ambient surface and subsurface ocean temperatures is adequate for generating power if the engineering can be perfected.

The ability to generate power locally, without a logistics tail, and without the mass and financial cost of sending nuclear reactors or extensive solar arrays opens a window of opportunity. As humanity pushes deeper into the Solar System, a network of powered facilities will be a necessary part of the economy and infrastructure. These may be as simple as communication relays or more complex like mining/refueling stations or power beaming plants. The abundance of icy bodies with subsurface oceans, at least as far out as Pluto and Charon, might provide all or part of such a network.

Potential methods of accessing geothermal energy are varied, but fundamentally, they rely on using a temperature difference to produce work, and therefore generate electricity. On icy moons and dwarf planets, where there is a subsurface ocean, a roughly 150°C temperature difference will exist (with second order variations due to structure and chemistry). On Earth this delta is sufficient to generate power on the order of megawatts per well that connect a hot reservoir in the subsurface with a cold sink (usually ambient air

temperature). The non-trivial differences and difficulties of doing something similar in the outer solar system condense to several immediate challenge areas:

1. Shifting the entire system 150-200°C to the colder side
    a. Fluid dynamics and chemistry will likely require different fluids in the system more suitable for these temperature regimes
    b. Material issues in this temperature regime (e.g. metals becoming brittle)
2. Penetrating (drilling may not be the right term) a few to tens of kilometers of ice crust
    a. Melt-probes are a possibility as is directed energy drilling, both of which have been tried on Earth
3. Building the surface (or subsurface) plant which converts thermal energy into electricity
    a. Can they be built on the spot via additive manufacturing & robotics?

There are many more lesser or unanticipated issues to be dealt with, but these are clearly first-order problems.

2 KNOWLEDGE OF THE MOONS AND DWARF PLANETS

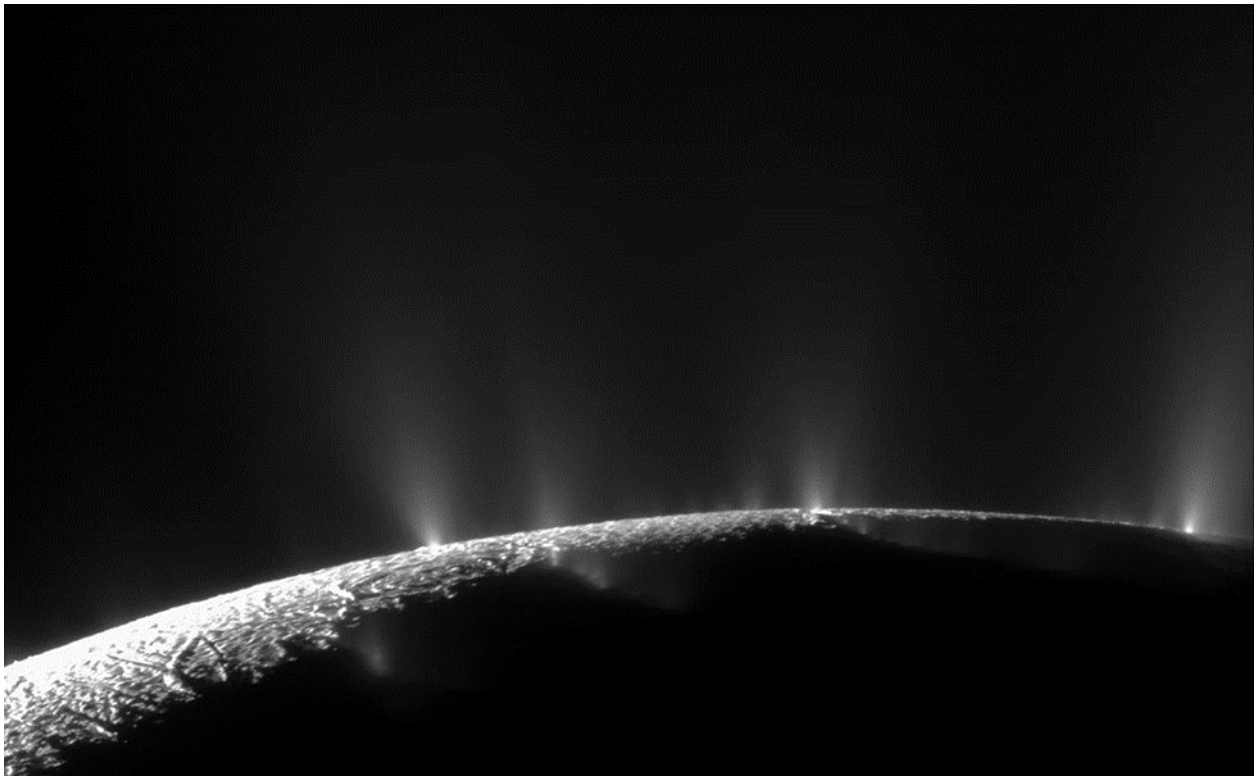


Figure 1. Active geysers on Saturn's moon Enceladus. Thermal output from this region is estimated to be in the Gigawatt range (NASA).

Knowledge of the moons and dwarf planets in the outer Solar System, though still very incomplete, points to some key aspects of most of these bodies. Though exact numbers and degree of confidence vary greatly, approximately half the explored bodies have confirmed or suspected subsurface oceans (Soderlund et al. (2024). The structure of the ice crust, ocean, and sub-ocean rock mantle are unique to each world. Europa, the current target of multiple probes is relatively simple with a comparatively thin (1 to tens of km) ice crust overlaying a thick ocean (~100km) which in turn overlies a rocky mantle and metallic core (totaling ~1500 km). The average surface temperature is around -170°C. Although pressure and salinity as well as other mineral content will affect freezing temperature, perhaps substantially (Nimo 2025), we will assume a temperature at the top of the ocean of 0°C. This difference between surface and ocean temperature is exploitable to produce usable power. The other outer bodies with oceans are varied, but Table 1. shows estimates for the key parameters for some of the bodies. Note that although crusts can be many kilometers thick, on at least some moons, the thickness could be interpreted as going to zero in places due to the presence of active geysers (Figure 1). Also, as you move further out in the Solar System the surface temperature generally decreases, providing a

larger temperature difference for power generation, though often with the presence of a very thick crust and associated engineering challenges.

Table 1. Properties of selected outer Solar System bodies (after Wisian 2022) with additions from Nimmo (2025), McKinnon & Kirk (2014).

Body (State)	Surface Temperature (°C)	Ice Crust thickness (km)
Europa (Moon of Jupiter)	-171	3-80
Ganymede (Moon of Jupiter)	-163	75-100
Callisto (Moon of Jupiter)	-139	75-100
Titan (Moon of Saturn)	-179	50-150
Enceladus (Moon of Saturn)	-198	6-25
Triton (Moon of Neptune)	-234	250
Pluto (Dwarf Planet)	-229	180-260

Conceptually, a geothermal system would consist of a wellbore that connects the surface to the ocean (Figure 2.) A fluid would flow both directions in the coaxial well. Depending on the fluids involved, a heat exchanger could be part of the system to transfer heat from the ocean water to a more useful fluid that then drives the power generation.

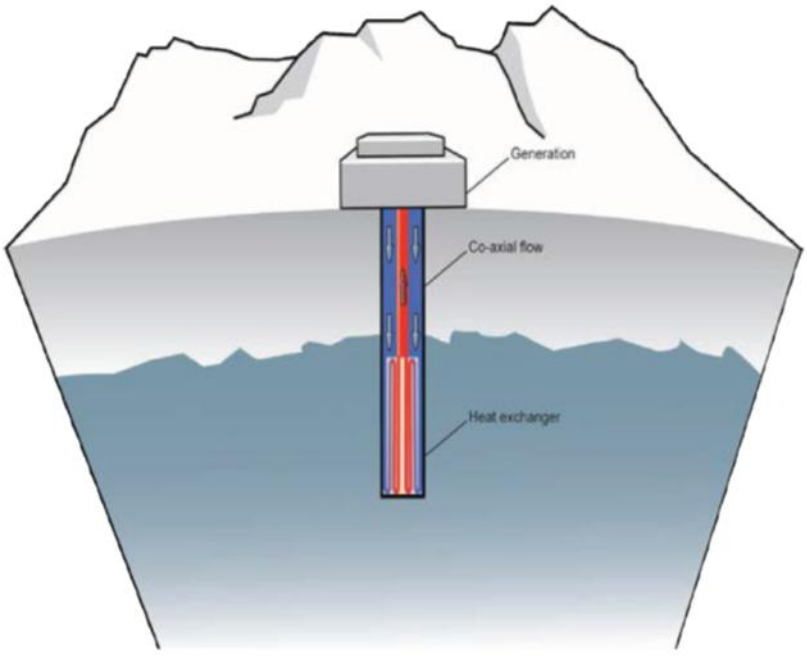


Figure 2. A geothermal well system on an icy body with a subsurface ocean. The temperature difference between the ocean and the surface is used to drive a turbine or Thermo-Electric Generator (TEG) and generate electricity. Many engineering options are available: shown here is a heat exchanger extending into the ocean to transfer heat to the surface. After Wisian (2022).

For the purposes of this simple analysis, many complicating compositional factors for the ice(s) and water are ignored. First ices other than water are present on many bodies, increasing as you move outward and ambient

temperature drops, primarily nitrogen, methane, ammonia and carbon dioxide ices are present. Also, water is never pure H_2O and will have a variety of impurities based on interaction with rocks and the various ices or an atmosphere if present. Further, water ice under pressure can exist in several polymorphs at different temperature and pressure conditions thus it is possible that the subsurface oceans could be between layers of ice polymorphs. This could in turn insulate the ocean from chemical and thermal interaction with the rock mantle. Ice I ("normal" ice) is likely to make up the crust of the worlds considered here, at least to any reasonable depth of ocean top.

3 A DEEP SPACE POWER NETWORK

Moons and dwarf planets that maintain or retain a source of internal heat appear to be common throughout the outer Solar System. The estimated thermal output for even a small moon like Enceladus is in the Gigawatt range (Spencer et al. 2006), (Spencer et al. 2013), (Abramov & Spencer 2009). These bodies could be the basis of a power network providing for communication, refueling, facility life support or any other need. This could, if appropriate bodies are discovered, extend even to the Ort Cloud approximately a light-year from the Sun. A particular area of interest would be the 550 AU (~3 light days) minimum gravitational lens focal distance of the Sun. The 550 AU point is of strong interest for high-resolution imaging of exoplanets and enabling interstellar communication (Landis 2017), (Maccone 2011). This in-turn could provide a significant "outpost chain" leading to the nearest stars. This network would be a dynamic configuration, dependent on the orbits of the bodies. The varying geometry could be a drawback for some missions at times, but regardless would be a relatively stable backbone for a Solar System–wide network with a near-indefinite lifetime, reducing the need for off-body (floating in space) power systems such as fusion or fission reactors that are expensive in terms of cost and weight, need fuel resupply and significant maintenance.

4 THE MOON

The Moon is a target for rapid, near-term habitation and economic development by countries and companies. Due to the presence of water in the permanently shadowed polar craters, these regions are likely to be the first locations developed. Although there is abundant solar power generation and storage likely available, it would be wise to diversify power sources when help is days to weeks away and life expectancy in the absence of power may be shorter than the help timeline. A variation on geothermal power could provide energy resilience and redundancy.

The interior of polar region craters on the moon are permanently shadowed and thus have temperatures relatively near absolute zero. The sunlit side of a polar crater with a low natural slope angle might be 50-200K (-223—73°C) (Williams et al. 2017). The hot side temperature could be enhanced by building a more vertical regolith structure thus increasing the sun incidence angle to nearly 90° and yielding a local temperature at or above 200K. The net result is a large temperature difference between the sunlit and shadowed side of a polar crater. This temperature delta can be over a very short distance due to the lunar regolith's very low thermal conductivity (Yu & Fa 2016) . This temperature difference can be exploited to generate electricity. For this situation, where water and other fluids are likely not available to use in a conventional sense to drive a turbine, a different method is needed – Thermo-Electric Generators (TEG).

A TEG is a solid-state device – essentially a stack of thermocouples. This can generate electricity from a temperature difference with no moving parts – a major advantage in a remote and hostile location. TEGs have been in use in space for decades to generate the power for deep space probes by exploiting the temperature of a radioactive mass (Tohidi et al. 2022). Thus, in principle a TEG bridging the sunlit and shadowed sides of a polar crater lip could provide an extremely reliable power source on the moon.

5 CONCLUSION

Geothermal power, drawing on the temperature difference between a sub-surface ocean (found on many outer Solar System bodies) and ambient surface temperature, or in the case of the Moon, exploiting temperatures deltas across the rim of permanently shadowed polar craters, has potential to provide a cost effective, resilient and long-term power supply alternative to solar, fusion and fission sources for Solar System infrastructure.

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