DIANA Challenge Proposal 2023

PROPOSAL TITLE: Renewable Electricity for Sensing in Polar Regions

PART 1: ABSTRACT

Persistence of undersea monitoring is limited in polar regions, where ice sheets separate the surface and subsurface domains. Harsh environmental conditions complicate providing energy to and collecting data from both stationary and mobile sensing platforms. Scalable Arctic/Antarctic Thermoelectric Generator (SATEG) modules offer unlimited renewable energy by harnessing thermal energy stored within the ocean without refueling or maintenance requirements. Low cost, modular, scalable, lightweight and easily deployed SATEG modules can be integrated into free-floating or ice tethered buoys that serve as observation stations, communications gateways and recharging points for mobile sensing platforms. Combined with batteries and solar, SATEG offers the ultra-long lifetime of those thermoelectric generators (TEG) demonstrated by decades of powering deep-space probes without relying on a radioisotope or fossil fuel heat source.

PART 2: RELEVANCE TO THE CHALLENGE TOPIC

Unmanned observations in the polar regions provide vast amounts of meteorological and oceanographic data for environmental research, weather forecasting and critical security needs. Growing unmanned presence in polar waters for surveillance purposes requires on-site power for sensing and data transmission. Today, ice buoys and platforms deployed for this purpose rely on power from bulky batteries that are limited by weight and volume constraints in addition to reduced lifespans in frigid winters. Solar and wind power generation is available, but at high latitudes these technologies are limited by hours of sunlight and strong winds that require large, expensive structures to survive. Development of innovative capabilities that use the temperature gradient between air and ocean to generate electricity in-situ offers a readily available renewable energy source and improves the continuity of observations in polar regions.

Thermal gradients between the air and ocean surface, expressed as a temperature difference, can be directly converted into electrical energy using SATEG modules. Polar air temperature varies widely from -50 to 32°C, while ocean surface temperature varies less from -1.8 to 3°C. Seasonal fluctuations of radiant solar energy and thermal energy of the ocean complement each other, which makes it possible to create a continuous sustainable energy supply system based on local renewable energy sources. Power generated by SATEG can be used by meteorological and oceanographic stations, naval surveillance systems, military and civilian navigation systems, telecommunications systems and docking stations for charging unmanned underwater vehicles (UAVs). By increasing the effective range and time on station for sources of persistent autonomous observations, SATEG modules stand to significantly improve the domain of observations available for understanding the undersea environment on the harbor scale. They also maintain the continuity of such observations by providing sufficient power to operate efficient satellite communications technology such as Starlink hardware throughout the polar night.

Figure 1. Prototype SATEG Modules

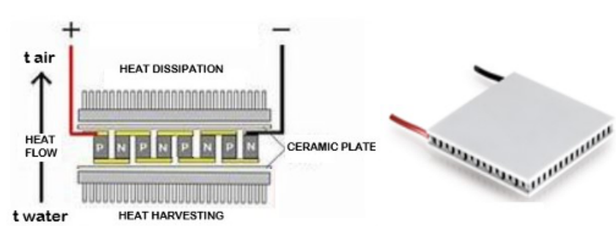

Figure 2. Thermoelectric Module

PART 3: TECHNICAL SOLUTION

The SATEG power system is a robust and survivable device concept for harvesting polar thermal energy in-situ, easily integrated with buoy-based sensor and communication platforms. The core of the power system is the SATEG module, consisting of water- and air-side finned heat exchangers, linked by thermosiphons to a generator body containing thermoelectric modules. The main structural material is aluminium and there are no mechanical moving parts or consumable materials. One or more SATEG modules, shown in Figure 1, connected to a secondary battery through a power conditioning unit comprises a basic SATEG system. Through modular scalability, the SATEG can harvest sufficient power to support different mission profiles from low power level sensors and data communications to higher energy operations for recharging autonomous underwater vehicles (AUV).

The proposed energy conversion system is an application of the thermoelectric method of direct conversion of thermal energy into electricity. It is based on the Seebeck effect, which produces a thermal EMF during heat flow in a circuit consisting of dissimilar materials. TEGs are characterized by extremely high reliability, which makes them ideal for critical terrestrial, sea, and space missions. For example, TEGs used in the Voyager deep-space probes have demonstrated such reliable performance that both probes are still operational after over 40 years, having been propelled beyond the heliosphere of the solar system.

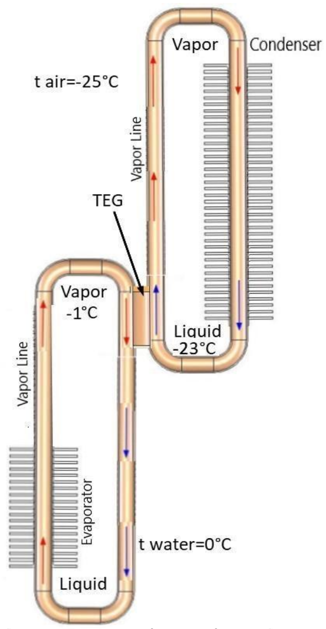

Figure 3. SATEG Thermodynamics

The basic building block of a TEG is a thermoelectric module, which contains p- and n-type semiconductor elements connected in series, as shown in Figure 2. These individual elements and their electrical interconnects are mounted between two ceramic plates. The plates hold the overall structure together mechanically and electrically insulate the individual elements from one another and external surfaces. The temperature difference between the junctions of elements creates a thermal-EMF (E), proportional to the temperature difference on the elements ΔT=(Th-Tc) and the number of thermoelectric elements, n (i.e. E=neΔT). When the circuit is connected to a load, power is generated. Harvesting and dissipating thermal energy on opposite surfaces of thermoelectric modules is the main design challenge, since the temperature difference is small and the energy source and heat sink are diffused in the surrounding environment. A SATEG module harvests the heat of ocean water through the large surface area of its water-side finned heat exchanger, inside which liquid (e.g. green ammonia) boils at a temperature of approximately 0°C as shown in Figure 3. Thus, the heat is concentrated in the liquid vapor, which rises through a connecting pipe to the surface of the thermoelectric modules, where it condenses, and under the action of gravitational forces flows back into the finned heat exchanger, initiating a natural circulation cycle. The process of condensation increases the heat flux density by several hundred times. Passing through the thermoelectric modules, the heat flow creates a working temperature difference, which facilitates the emergence of a thermal EMF and useful power. The other (upper) surface of the thermoelectric modules is subjected to evaporative cooling as liquid in the air side loop boils. The vapor rises to the surface of the air heat exchanger, where it condenses, and the heat is dissipated through its surface to air in the surrounding environment which is in turn replaced by colder, denser air, allowing the process to continue. The key to optimising this system for maximum heat flux and thus maximum power output is to create conditions under which the total thermal resistance of the heat exchange systems is equal to the thermal resistance of the thermoelectric energy converter. This is achieved by optimizing the ratio of the areas of the heat transfer surfaces of the heat exchangers and the physical parameters of the TEG.

Two prototype SATEG modules have been built, one tested in a lab and the other in a relevant environment, following an extended theoretical analysis and creation of a mathematical model. For the modelling exercise, several specific buoy mission profiles in the Arctic were provided by Woods Hole Oceanographic Institution (WHOI), including location, load cycle, and target persistence level. The energy system created incorporates a combination of SATEG modules for thermal scavenging and batteries for storage. The analysis showed the SATEG approach is more effective than battery power alone. It also showed that there is a significant benefit in addressing the demand side (not only the supply side) aspects of optimising thermal harvesting scenarios for Arctic communications buoys. This could include a staggered use of a single docking buoy by multiple AUVs during the peak energy generating period (cold period) and seasonal adjustments to the AUV duty cycle that better match SATEG generating capabilities for non-time sensitive survey missions. However, since security-linked underwater applications seldom have the luxury of adjusting deployment schedules, this proposal seeks to outfit SATEG modules with their natural complement, photovoltaics, to maintain a mission driven observational duty cycle and communications capability for buoys and AUVs year round.

Verification of the analysis was carried out by means of experimental studies of a laboratory prototype of the SATEG. A single module, when deployed through the 200 mm bore hole in an ice floe produces 75-150 kWh of electricity per year, depending on location. A comparison of experimental (markers) and calculated (curves) data is shown in Figures 3 - 4. The experimental results are in excellent agreement with the results of the mathematical model.

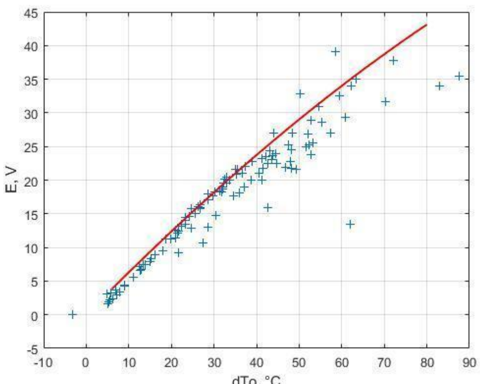

Figure 4. Dependence of thermal-EMF on the temperature difference E=f(dTo).

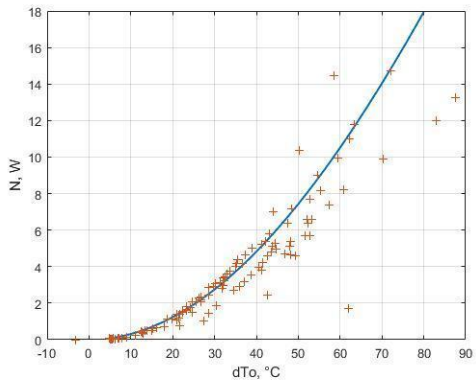

Figure 5. Dependence of power on the temperature difference N=f(dTo).

The feasibility study modelled and analysed SATEG performance at two different locations, one in the southern latitudes of the Arctic (Prudhoe Bay, Deadhorse, AK, 70.4°N, 148.53°W, with a mean annual temperature of -6.7°C) and the other further north (Birgit Koch Tinder, Greenland, 83.38°N, 33.22°W, with a mean annual temperature of -17.8°C). The analysis showed that sufficient energy is generated during the Arctic winter to power an Arctic buoy through an entire year with the help of a small secondary battery. Arctic systems requiring 7, 30, and 280W nominal power were analysed representing a communication buoy, a Tethyse LRAUV recharging buoy, and a REMUS 600 recharging buoy. In all cases, the SATEG was an improvement over a pure battery solution. For example, an Arctic observation buoy that consumes a nominal 7W requires 300 kWh of battery storage to support a 5-year mission and only requires 25 kWh of storage when coupled with a single SATEG module. These findings show that Starlink satellite uplink hardware that consumes a nominal 20W to remain connected to the low earth orbit (LEO) satellite network and 50-75W while accessing the internet for data uploads and downloads can be supported with the SATEG modular technology.

PART 4: DEVELOPMENT ROADMAP WITH RISKS & MITIGATIONS

The current development status of the SATEG is TRL 5, as evidenced in Figure 1. Two prototype SATEG modules have been assembled and tested for validation of the concept. One unit was tested in the lab using ice water and liquid nitrogen to simulate the entire temperature range of polar operating conditions. The second unit was tested in a natural outdoor pond where nighttime temperature cold spells were sufficient to generate low levels of electricity.

The milestones planned for the next six months are aimed at advancing the technology toward a TRL 6 demonstration. They include developing a new mathematical model that incorporates photovoltaics with the SATEG module to reduce reliance on batteries and building a prototype SATEG module with several improved design elements, mainly (i) replacing bulky machined evaporator plates with micro-channel extrusions to improve efficiency, (ii) upgrading individual thermoelectric elements with a pre-assembled vacuum sealed TEG to reduce internal losses, and (iii) optimize the heat carrier for lowest possible vapor pressure at the highest target operating temperature to reduce internal mechanical stress. A risk mitigation control strategy will also be devised for preventing icing of the water-side finned heat exchanger, which has been identified as a possible operational threat. Beyond the initial six months, the one year development target is to fully achieve TRL 7 by developing a power management system for controlling the three primary components of the system (SATEG module, photovoltaic array and battery), buildout of the prototype and demonstration in a relevant operating environment. The key risk in the latter development phase is to properly identify energy use cycles for a relevant polar sensing, observational and communications platform and to reflect those clearly defined requirements in the system design and power management protocols which will be mitigated by leveraging access to DIANA partners.

PART 5: COMMERCIAL ANALYSIS

Customer discovery discussions with stakeholders including WHOI, Office of Naval Research (US), UCAR/NCAR, AMRC at UWISC, and international Automatic Weather Station programs confirms that there is significant unfilled demand from a low cost, scalable and resilient energy harvesting product capable of providing low levels of reliable and persistent power in polar regions. The market consists of two distinct segments: military and civilian, with differentiation in terms of cost sensitivity, reliability and persistence requirements. Early technology adopters are mostly military and civilian research organizations involved with observation, including increased spatial coverage for an array of sensing missions (ONR AMOS INP). Similarly, the National Science Foundation funded program Navigating the New Arctic supports large, co-located collections of instrumentation with centralized telemetry, higher sampling rates and other investigative methods that are currently limited by energy constraints. The range of equipment deployed in polar regions is increasing in both numbers and sophistication (i.e. require more energy). Future deployments of observation platforms will include AUVs (e.g. Tethys LRAUV, REMUS) that require additional energy to support buoy-based docking stations for recharging and data acquisition. Today, energy constrained platforms such as the Dynamic Ocean Topography and Autonomous Ocean Flux buoys are forced to resort to auxiliary energy storage units and propane-based fuel cells that have charge or fuel capacity limitations. In addition to sensing of traditional weather and climate related factors, energy is needed for supporting ice-thickness modelling, under-ice surveys at multiple scales, communications relays and sensing platforms for anti-submarine warfare. Other markets for the SATEG include oil and gas exploration, as well as the creation of new shipping lanes in the Arctic where the ice cap is receding. The company has a historical relationship with WHOI which it plans to leverage for the purpose of eventually integrating SATEG modules into WHOI's polar buoys.

PART 6: INTELLECTUAL PROPERTY, PATENTS, AND PUBLICATIONS

- A patent has been awarded to the principal inventor of the SATEG: Lobunets, Y. *Thermoelectric Generator for Ocean Thermal Conversion*, Patent UA143177U, 10 July 2020.
- Unpublished IP from over five years of R&D at SATEG Corp and previously at parent company before spinout
- A white paper titled "Renewable Low-Power Electrical Energy Generation in Polar Regions" will be available for review on the Company's website at www.sategcorp.com

PART 7: USE OF GRANT FUNDS

Grant funds will be used to rapidly accelerate and progress development of SATEG modules from TRL 5 toward TRL 6.

Expense category	Estimated 6-month expenditure (Total = €100,000)	Comments, if any
Salaries	€50,000	Modelling, design and assembly of a deployable SATEG prototype module
Major equipment, computers, material	€30,000	Materials for prototype SATEG module (e.g. commercial thermoelectrics, finned heat exchangers, hardware, etc.)
Software, compute-resource access, data sets	€2,500	Software licenses
Travel to proposal-related activities	€7,500	Travel and transportation of prototype for simulated in-situ testing
Other (legal consultation, IP filing, testing & evaluation, etc) – please list in Comments	€10,000	Testing and evaluation, IP filing