Development and Evaluation of a Hybrid Solar-Thermoelectric Power Generation System in a Marine Environment and usage of Hydrodynamics Propulsion

Aias Tatsis, Pythagorean High School of Samos, Samos Island, Greece, aias.v.tatsis@gmail.com

Abstract

In this study, the development and evaluation of a novel maritime floating Hybrid Energy Harvesting system that integrates Solar-Thermoelectric Generation and Magnetohydrodynamic (MHD) propulsion, is presented. The proposed Hybrid-Solar-Thermoelectric with Magneto-Hydrodynamic Propulsion (HSTM) system provides an innovative solution for sustainable energy production and eco-friendly transportation in maritime environments, while optimizing power generation and cost efficiency. The hybrid energy harvesting system features a monocrystalline solar panel and a series of thermoelectric generator (TEG) modules placed beneath the solar panel. The solar panel and TEGs are enclosed within a vacuum glass dome, which helps maintain optimal temperatures for thermoelectric conversion efficiency. The MHD propulsion device is integrated under the system's platform, utilizing a ferromagnetic profile and a series of neodymium magnets arranged to face each other with opposing poles. Comprehensive performance analysis of the hybrid energy harvesting system includes power output measurements, evaluation of the MHD propulsion efficiency, and optimization of magnet distance and power production temperature. The results demonstrate that the system not only increases the overall energy generation efficiency compared to standalone solar panels, but does so without incurring excessive costs. Furthermore, the study confirms the viability of MHD propulsion in a maritime environment, contributing to the ongoing research and development of innovative solutions for sustainable energy production and green transportation in the sea.

Key words: Solar Panel, Thermoelectric Generator, TEG, Magneto Hydro-Dynamics, MHD, Energy Efficiency

II. Introduction

A. Background and Motivation for the Project

The escalating need for power, together with the imperative to reduce environmental footprints, has paved the way for the investigation of diverse and eco-friendly energy alternatives. One such method is the creation of mixed energy models that merge various renewable energy sources, thereby improving performance, dependability, and sustainability. The project outlined in this document delves into an innovative floating hybrid energy mechanism, HSTM, which integrates a monocrystalline solar panel, thermoelectric generators (TEGs), heat pipes, and a magneto-hydrodynamic (MHD) propulsion system. The driving force behind this project is to develop and fine-tune a mechanism capable of effectively capturing solar and thermal energy, all the while ensuring the stability and versatility of the floating structure using a pioneering MHD propulsion system.

The main obstacle in this project is to create and fine-tune the hybrid energy mechanism to reach the optimal energy production efficiency, while maintaining system stability and adaptability under diverse conditions. The research query steering this project is: In what manner can the suggested hybrid energy mechanism be fine-tuned to boost energy production efficiency, maintain the temperature gradient in the TEGs, and guarantee the stability of the floating structure using an MHD propulsion system.

B. Scope and Objectives of the Project

The scope of the project includes the design, analysis, and optimization of a floating hybrid energy system consisting of a monocrystalline solar panel, TEGs, heat pipes, and an MHD propulsion (HSTM) system. The main objectives of the project are a) Investigate the performance of the monocrystalline solar panel, b)

Analyze the performance of the TEGs at different temperature differences (ΔT) and identify experimentally the optimal ΔT, c) Assess the heat transfer capabilities of the heat pipes and the effectiveness of the seawater cooling system. d) Evaluate the performance of the MHD propulsion system, including the optimal design properties.

The remainder of this paper is organized as follows: Section III provides a detailed literature review for the proposed hybrid energy system. The specifications and theoretical principles of each component are discussed. At section IV a mathematical analysis and optimization of the hybrid energy system is presented. Section V discusses the methodology used to design and optimize the hybrid energy system. Section VI presents the results of the optimization process, addressing the objectives outlined in the project scope. Finally, section VII concludes the paper by summarizing the key findings and contributions of the project. Furthermore, the last section discusses the limitations of the current study and suggests areas for future research to further advance the development of floating energy generation devices.

III. Literature Review

A. Photovoltaics and solar energy conversion

Solar energy is a promising source of clean, renewable energy that has been widely researched and employed in various applications. Photovoltaic (PV) technology is one of the most common methods for converting solar energy into electricity. PV cells, typically made of silicon, absorb sunlight and generate electron-hole pairs, which are then separated by an electric field, producing a direct current (DC) voltage across the cell (Green et al., 2018). Monocrystalline solar panels, which consist of single-crystal silicon, offer higher efficiency and better performance under low light conditions compared to polycrystalline or thin-film solar panels (Parida et al., 2011).

Research has focused on improving the efficiency of solar panels by optimizing their material properties, structure, and operating conditions (Chow, 2010). In recent years, solar concentrators have been employed to enhance solar irradiance on the PV surface, resulting in increased energy generation (García et al., 2018). Furthermore, the use of specialized coatings or films on the surface of solar panels or glass domes enclosing them can help to trap incoming solar radiation, increasing the effective temperature inside the system (Yuan et al., 2014).

B. Thermoelectric generators (TEGs)

Thermoelectric generators (TEGs) are solid-state devices that directly convert thermal energy into electrical energy, through the Seebeck effect (Snyder et al., 2008). The efficiency of TEGs mainly depends on the temperature difference between their hot and cold sides and the thermoelectric material properties, represented by the dimensionless figure of merit (ZT) (Bell, 2008). Research has

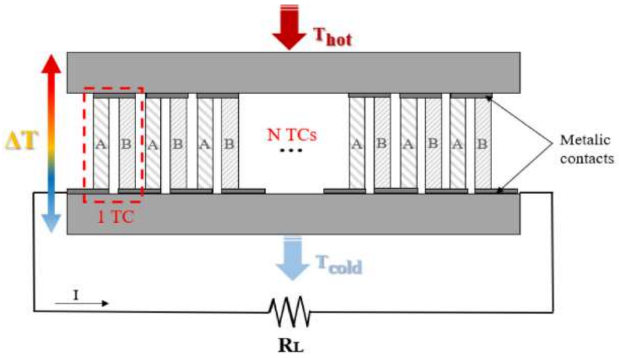

Figure 1 TEG

focused on developing new materials with high ZT values and optimizing TEG designs for various applications, including waste heat recovery and remote power generation (Vineis et al., 2010).

A significant challenge in the practical application of TEGs, to maintain the required temperature difference, particularly when operating in conjunction with other energy conversion systems, such as solar panels (He et al., 2015). The integration of heat pipes and seawater cooling systems has been proposed to address this challenge, providing efficient heat transfer and temperature management for TEG-based systems (Xie et al., 2015).

C. Seawater cooling systems

Sea-based cooling systems provide an abundant, cost-effective, and eco-friendly resolution for managing heat in several applications, including power production, water desalination, and climate control (Isa et al., 2014). Utilizing seawater as a cooling agent brings several benefits, such as superior specific heat capacity and lower viscosity, facilitating effective heat dispersal and lessened energy needs for pumping (Al-Rashed et al., 2015).

Heat pipes, that leverage a self-contained evaporation cooling process, can be combined with sea-based cooling systems to efficiently displace heat from the heat origin to the cooling agent (Faghri, 2012). The efficacy of heat pipes hinges on multiple factors, such as the operational fluid, capillary configuration, and the range of working temperatures (Reay et al., 2013). Within the scope of TEG-based setups, utilizing heat pipes alongside sea-based cooling can assist in upholding the necessary temperature variation for productive energy transformation, while minimizing thermal resistance and energy wastage (Xie et al., 2015).

D. Magneto-hydrodynamic

Magneto-hydrodynamic (MHD) propulsion has emerged as a promising technology with potential applications power generation and in marine propulsion systems. It relies on the interaction between an electrically conductive fluid (such as seawater) and a magnetic field to generate thrust, offering advantages like low noise, high efficiency, and reduced mechanical complexity compared to conventional marine propulsion systems (Branover & Lykoudis, 1998; Matsushima, 2009).

The working principle of MHD propulsion is based on the Lorentz force, which is experienced by charged particles in a magnetic field. When a conductive fluid flows through a magnetic field perpendicular to its direction, the charged particles within the fluid experience a force that is orthogonal to both the magnetic field and the direction of fluid flow. This force, known as the Lorentz force, results in the acceleration of the fluid, generating thrust (Way, 1998).

The main components of an MHD propulsion system include magnets (either permanent or electromagnets), electrodes, a power source, and a fluid (typically seawater). The magnets are responsible for creating the magnetic field, while the electrodes are used to apply an electric field within the fluid. The power source provides the necessary voltage to drive the electric current through the fluid, and seawater serves as the conductive medium through which, the electric and magnetic fields interact (Watanabe & Ito, 2000).

Over recent years, a range of setups and designs for MHD thrust systems have been suggested and evaluated. One such design, is the employment of a linear MHD accelerator, which comprises a succession of magnets and electrodes set up linearly along the fluid's flow direction. The magnets generate a consistent magnetic field, with electrodes strategically positioned to amplify the interaction between the electrical and magnetic fields (Molokov et al., 2007). By refining the setup of magnets and electrodes, and adjusting the applied voltage and magnetic field's intensity, researchers have made considerable strides in the efficiency and performance of MHD thrust systems (Doss et al., 2009).

Another focal point in MHD propulsion research is the creation of materials and components that can endure the severe marine surroundings, while preserving high efficiency and performance. For instance, researchers have studied the use of corrosion-resistant electrode materials, such as titanium and stainless steel, to mitigate the impact of seawater-induced corrosion on system's performance (Kim et al., 2007). Additionally, progress in magnet technology, specifically the creation of high-performance neodymium magnets, has contributed to the enhancement of MHD propulsion system efficiency and power density (Goto et al., 2004).

Despite the advancements in MHD propulsion studies, numerous obstacles still need to be tackled, before the technology becomes commonplace for marine uses. These challenges encompass the enhancement of system efficiency, the creation of affordable components and materials, and the integration of MHD propulsion systems with current marine vessels and infrastructure (Matsushima, 2009). Nonetheless, the potential advantages of MHD propulsion, like diminished noise, superior efficiency, and minimal mechanical intricacy, render it a hopeful technology for upcoming marine propulsion applications.

E. Related work

Several prior research initiatives have explored the use of TEGs in tandem with solar panels to enhance overall energy conversion efficiency. For example, Sun et al. (2021) created a transportable solar-TEG system for off-grid power provision applications. This system comprised a solar panel, TEG modules, and a battery. Although their methodology mirrors ours in employing TEGs and solar panels, our endeavor is unique in its emphasis on using sea-based cooling and MHD propulsion.

In another research, Zhang et al. (2019) introduced a mixed solar-TEG system for building applications. Their setup harnessed a solar panel and TEG modules to produce electricity, which then powered a heat pump for heating and cooling functions. While their methodology also incorporated TEGs and solar panels, our project is unique in its marine application design, utilizing sea-based cooling and MHD propulsion.

In a third investigation, Jia et al. (2018) launched a solar-TEG-driven unmanned surface vehicle (USV) for environmental monitoring applications. Their system used a solar panel, TEG modules, and a battery to energize the USV, which was equipped with various sensors for gathering environmental data. Even though their methodology is also powered by solar-TEG, our project stands out, as it employs sea-based cooling and MHD propulsion to enhance the efficiency and navigability of the marine platform.

Furthermore, there have been multiple studies delving into the use of MHD propulsion for marine uses. For example, Kim et al. (2017) crafted an MHD propulsion mechanism for an underwater automaton. This system employed a permanent magnet arrangement and a coil array to produce a Lorentz force, which moved the robot through the water. In another research, Gupta et al. (2018) examined the application of MHD propulsion for small vessels. Their system harnessed a magnetohydrodynamic thruster powered by a DC power source to propel the boat. While their methodology echoes ours in terms of using MHD propulsion, our initiative stands apart, as it employs TEGs and solar panels for additional power and introduces sea-based cooling to optimize the system's efficiency.

In general, although several previous studies have looked into the use of TEGs, solar panels, and MHD propulsion for different applications, our project merges these technologies in a novel manner, to enhance the efficiency and navigability of a marine platform for power production and propulsion.

IV. System Model

A. Solar – TEG Hybrid System Design

To design an effective hybrid energy system, it is important to consider the temperature effect on the monocrystalline solar panels, which are the most efficient panels commercially available. The efficiency of solar panels decreases with increasing temperature, due to the negative temperature coefficient of the panel's electrical output. The monocrystalline solar panels have an efficiency drop of about -0.3% / °C to -0.5% / °C (Amin et al., 2018). This means that the efficiency of the panel decreases by 0.3% to 0.5%, for every degree Celsius increase in temperature.

Nevertheless, escalating the temperature could be advantageous for the performance of thermoelectric generators (TEGs) used in the mixed energy

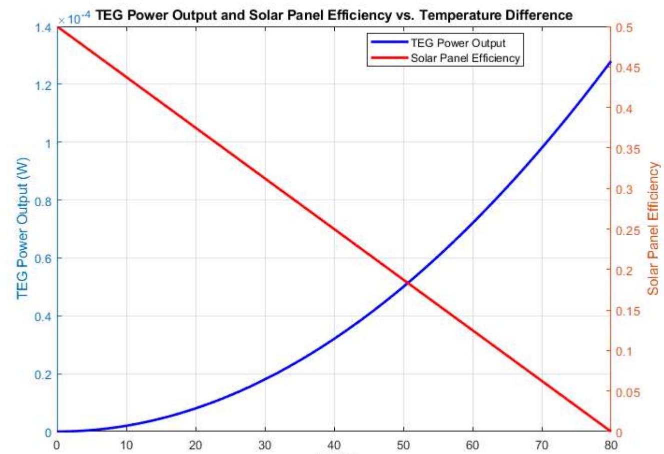

Figure 2 Temperature effect on solar panel and TEG

system. TEGs function based on the Seebeck effect, which produces an electrical potential difference across a temperature gradient. As such, a higher temperature discrepancy between the hot and cold sides of the TEGs, can result in a superior energy conversion efficiency (Snyder et al., 2008). However, a balance must be struck between the efficiency of the solar panel and the TEG. As the temperature climbs, the efficiency of the solar panel diminishes, while the efficiency of the TEG grows. Hence, it's crucial to determine an optimal temperature point where the combined efficiency of the solar panel and TEG peaks.

Several research initiatives have studied the impact of temperature on the efficiency of TEGs and solar panels, proposing various techniques to optimize the system's temperature. For instance, Xie et al. (2015) suggested a mixed system that utilized a seawater cooling system and heat pipes to regulate the temperature of the TEGs, while also providing cooling for the solar panels. They discovered that the system could achieve a peak energy conversion efficiency of 12.6%, by optimizing the temperature of the TEGs and solar panels.

Thermoelectric generators (TEGs) convert heat energy directly into electrical energy, through a phenomenon called the Seebeck effect. In a TEG, a temperature difference (ΔT) across a thermoelectric material creates a voltage (V_{TEG}), proportional to the Seebeck coefficient (S) of the material. As current (I_{TEG}) flows through the TEG, which has an electrical resistance (R_{TEG}), electrical power (P_{TEG}) is generated according to:

$$P_{TEG} = \frac{S^2 \, \Delta T^2}{R_{TEG}} \qquad \text{Eq. 1}$$

TEGs harness thermal energy from various heat sources - like industrial processes or solar radiation - and convert it into useable electricity. A TEG's efficiency (η TEG), is one of the main metrics of its performance and defined as the ratio between its electrical power output (P_{TEG}) and thermal input (Q_{TEG}), $Q_{TEG} = K * \Delta T$, where K is its thermal conductance coefficient; efficiency measures how effectively heat can be converted to electricity, based on material properties, temperature differences across devices, electric and thermal resistances.

$$\eta_{TEG} = \frac{S^2 \, \Delta T}{R_{TEG} \, K} \qquad \text{Eq. 2}$$

In order to enhance the efficiency of the proposed hybrid energy system, the introduction of a vacuum chamber can be beneficial. This can be used to evacuate air and other gases from the system, thereby creating a vacuum environment. Such an environment, can curtail convective and conductive heat transfer, facilitating higher temperature discrepancies and improved TEG efficiency. Additionally, the vacuum conditions can aid in reducing corrosion and extending the lifespan of the system components. Therefore, incorporating a vacuum chamber into the mixed energy system can assist in achieving ideal conditions for power generation, particularly in scenarios with low solar radiation, and bolster the system's overall efficiency and dependability.

The use of seawater cooling is an effective technique to enhance the efficiency of the mixed energy system, by establishing a stable temperature environment for the TEG. With its superior thermal conductivity and steady temperature range of 15-18 degrees Celsius, seawater can function as a heat sink for the TEG, ensuring one side of the generator maintains a consistent temperature difference with the other side, a key factor for energy conversion. By facilitating efficient heat transfer and temperature regulation, seawater cooling contributes to optimizing the TEG's output power and enhances the overall efficiency of the mixed energy system.

B. Design and implementation of the MHD propulsion system

I have designed an MHD propulsion system specifically for seawater, which is fine-tuned to make the best use of permanent magnets and power generated from the Mixed Energy System. Essentially functioning as a linear motor, this MHD system propels seawater via the Lorentz force created from the interplay of electric and magnetic fields. The design comprises a square tube with permanent magnets on two sides and electrodes on the remaining sides to induce the current flow. By opting for permanent magnets, I have made redundant the need for an external power supply for the magnets, thus simplifying the system and making it more cost-effective.

Employing a low voltage of 1.2 Volts is advantageous for MHD propulsion, because this voltage prevents any significant electrolysis of water (Zhang et al., 2014). Electrolysis can potentially occur when the applied voltage causes seawater to decompose into its base elements, hydrogen and oxygen. Such a process, not only diminishes the efficiency of the MHD propulsion system, but can also cause the formation of gas bubbles, which obstruct water flow and reduce the generated thrust. By maintaining a low voltage, we can maximize the efficiency of the MHD propulsion system and significantly reduce the likelihood of electrolysis and gas bubble formation, yielding a more dependable and efficient marine propulsion system.

The cross distance between magnets is a crucial parameter in the design of an MHD propulsion system, as it directly affects the area of the electrodes and hence the current that can be generated in seawater. The amount of current generated is dependent on the seawater resistance, which in turn is a function of several factors, such as the temperature, salinity, and flow velocity. As the distance between the magnets increases, the electrode area also increases, resulting in lower seawater resistance and higher current generation.

On the other hand, as the magnets are brought closer together, the magnetic field's strength increases, resulting in a stronger Lorentz force generated by the system. However, this leads to a decrease in the electrode area and hence an increase in seawater resistance and a decrease in current generation. Therefore, an optimal magnet distance must be found to balance the tradeoff between the electrode area and magnetic field's strength, to achieve the highest possible efficiency. In addition, the magnet's design and configuration also plays a significant role in the performance of the MHD system. Permanent magnets are often preferred over electromagnets, as they are more reliable, require less maintenance, and have lower power consumption. However, the magnet design and configuration should be carefully chosen to achieve the desired magnetic field strength and direction for optimal performance.

The magnetic field strength B of 40 Neodymium magnets N45, facing each other (20 and 20), and connected with ferromagnetic material to create a magnetic circuit with a gap, which represents the distance between the magnets, can be calculated using the following formula:

$$B = \frac{\mu_0 \, N \, M}{2\left(\frac{d}{2} + s\right)^2} \qquad \text{Eq. 3}$$

where μ_0 is the permeability of free space, N is the number of magnets, M is the magnetization of the magnets, d is the gap distance between the magnets, and s is the thickness of the ferromagnetic material. By calculating the magnetic field strength, we can determine the magnetic force acting on the electrically conductive seawater in the MHD system, which is proportional to the cross-product of the magnetic field and the current flow. Therefore, the optimization of the magnetic field strength, is crucial in designing an efficient and effective MHD propulsion system.

The current generated in seawater between two square electrodes, with a distance ℓ between them, with a d distance wide, corresponding to the distance of the magnets, can be calculated using Ohm's Law. The voltage applied across the electrodes is 1.2V, and the seawater's resistance is dependent on its salinity and temperature. Assuming a seawater conductivity of 4.5 S/m at 20°C, the current through the seawater between the electrodes can be calculated using the formula:

$$I = \frac{V\,d\,m}{\rho\,l} \qquad \text{Eq. 4}$$

where ρ is the seawater's resistivity, d the distance of the magnets that defines the effective width of the electrode plates and m the electrode plates length and ℓ the distance of the two electrode plates.

Given the established resistance of seawater, the current produced by the electrodes can be determined through the application of Ohm's Law, where I represents the current, V represents the applied voltage, and R represents the resistance. The relationship between voltage and current in seawater, is directly proportional. Hence, it is imperative to meticulously design the magnets and electrodes' strength and regulation to maximize the current and propulsion generated by the MHD unit.

By substituting I in the Lorenz force formula with V/R, where V is the voltage and R is the resistance of the seawater, we obtain:

$$F_{prop} = \frac{\mu_0\,N\,M\,V\,d\,m}{2\left(\frac{d}{2}+s\right)^2\rho} \qquad \text{Eq. 5}$$

The formula illustrates that the Lorentz force F_{prop}, which is produced by the MHD system, hinges on several factors. These include the gap between the magnets (d) and the electrodes (L), the voltage (V), the resistivity of the seawater (ρ), and the magnetic moment of the magnets (M).

Based on the aforementioned mathematical equation (Eq.5), can deduced that the Lorentz force exerted on the seawater in the MHD system, can reach its peak value as a function of the magnets' spacing. This is under the assumption, that the size and magnetization of the magnets, the applied voltage (held constant at 1.2V), the thickness of the ferromagnetic material, and the resistivity of the seawater remain unchanged. The force is unaffected by the separation between the two electrode plates. Therefore, fine-tuning the spacing of the magnets in the MHD system becomes pivotal for harnessing the maximum propulsion force achievable.

V. Experimental setup and data collection

In the present work, is considered a novel hybrid energy production device designed to float on seawater, harnessing solar, thermoelectric, and magnetohydrodynamic (MHD) technologies. The device is equipped with a monocrystalline solar panel measuring 170x220mm, capable of producing 5W at 3V. Additionally, it features 12 thermoelectric generator (TEG) modules, each with an output of 1V and 200mA at a temperature difference (ΔT) of 40°C, connected in series. These TEG modules are strategically placed beneath the solar panel, maximizing energy production from both sunlight and temperature

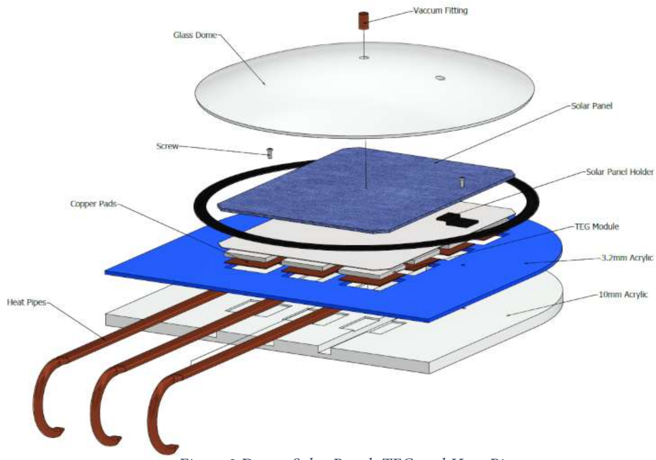

Figure 3 Dome, Solar Panel, TEG and Heat Pipes

variations.

The solar panel and TEGs are enclosed within a vacuum glass dome, which helps maintain high temperatures and optimize thermoelectric conversion efficiency. The hot side of the TEGs is in thermal contact with the solar panel, while the cold side is in contact with heat pipes that transfer heat to the seawater. To enhance the performance, the hot and cold sides of the TEGs are thermally isolated. The entire assembly is mounted on a 10mm thick acrylic sheet, which also houses a thermometer and barometer to monitor internal

Figure 4 MHD Design

other at a 7mm distance with opposing poles. Two square tubes containing the magnets are connected by cross sides that hold electrode plates, also spaced 7mm apart. As the water flows through the tubes, the resulting MHD effect propels the floating device, adding another dimension of power generation. This innovative hybrid energy production system offers a promising solution for harnessing renewable energy sources in maritime environments.

My construction of the Hybrid Solar-TEG-MHD device involved an extensive use of CAD-CAM technologies, enabling precise design and accurate manufacturing of the various components. By utilizing computer-aided design (CAD) software, I was able to create detailed virtual models of the device and its components, ensuring optimal design and seamless integration of all parts. I then employed Computer-aided manufacturing (CAM) technologies to convert these designs into real-world components, using a CNC machine and my 3D printer. This approach allowed me to efficient and precise manufacturing, resulting in a high-quality, well-engineered device.

Table 1 Bill of Materials

	Name	Description	Cost €
1	Acrylic Sheet	10mm and 3.2mm	54
2	Glass Dome	Thickness 4mm, Radius R=285mm	12
3	TEG	40x40x3mm, 1V, 200mA @ΔT=40°C (12 items.)	82
4	Solar Panel	170x220mm monocrystalline. 5W, 3V	25
5	Heat-Pipes	D=8mm, 70W @ 70°C	85
6	Copper pads	40x40x1.2mm	14
7	Ferromagnetic Profile	400x20x10	10
8	Neodymium Magnets	10x7x4, N48 (40 pcs)	142
9	Electrodes	Aluminum 400x7x0.5mm	2
10	Electrodes Base	3d printed 400x7x4mm	18
11	Vacuum Pump	-85KPa, 12V, 40L/min	65
12	Heat Sinks	Star shape, 150x10mm	15
13	Screws	Variant	-
14	Pipes	Vacuum pipes	8
15	Cables	Variant	-
16	Voltmeter	0-50V	35
17	A-meter	0-10A	
18	Thermometer	-20-200°C	16
19	Water Flow sensor	5-18V, 15mA, 1.75Mpa	8
20	Barometer	-15-20KPa	16
21	Heat-conducting paste		30
22	Electric Load	Resistance 1,2,4,8,10Ω	5
		Sum	**645 €**

VI. Results

In order to gather data from my innovative apparatus, which merges solar energy and thermoelectric power production, I first submerged the device in the sea, providing it exposure to sunlight and a consistent water temperature of 18 degrees Celsius. Subsequently, I made use of a vacuum pump to lower the pressure within the dome, effectively intensifying the temperature difference across the thermoelectric generator (TEG). To keep tabs on the operating circumstances of the device, I fitted a thermometer within the dome to ascertain the interior temperature, and a barometer to perpetually monitor the pressure levels. The energy manufactured by the hybrid system was subsequently utilized by a variable resistor, enabling the flexibility to modify the load as required for power generation optimization. Lastly, I made use of both an ammeter and voltmeter to quantify the current and voltage respectively, thus permitting me to determine the power output of the apparatus under varying conditions with accuracy.

By collecting and analyzing the data, I was able to gain insights into the performance and efficiency of the hybrid power generation system, ultimately informing the design and operation of future devices. The results indicate a

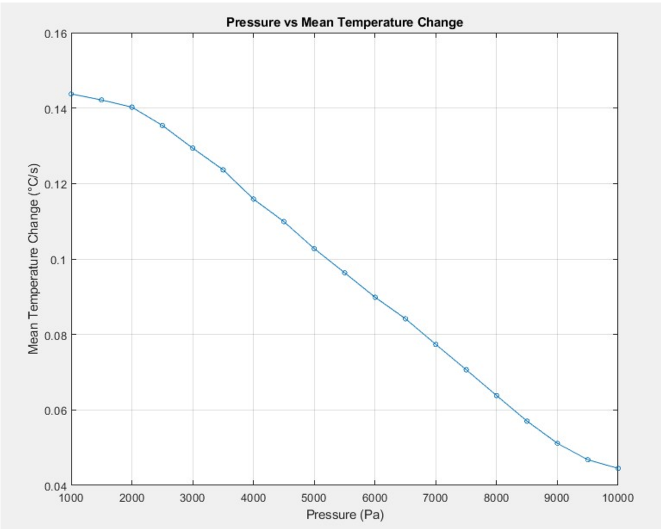

Figure 5 Pressure as function of the mean Temperature Change

clear relationship between the applied pressure inside the dome and the rate of temperature increase. As the pressure was reduced using the vacuum pump, the rate of temperature increase within the dome was observed to be more significant. This finding can be attributed to the reduced heat transfer from the interior of the dome to the surrounding environment, at lower pressure levels. Consequently, a more substantial temperature gradient across the thermoelectric generator (TEG) was achieved, leading to increased power generation and overall system efficiency. These results highlight the importance of optimizing pressure conditions in hybrid devices that combine solar and thermoelectric power generation, ultimately demonstrating the potential for improved performance through careful manipulation of the operating environment.

The results of this study (Fig. 6) demonstrate the distinct power generation characteristics of the solar panel and TEG modules, as well as their combined performance as a function of temperature. As the temperature increased, the power output of the solar panel displayed a general decline due to a reduction

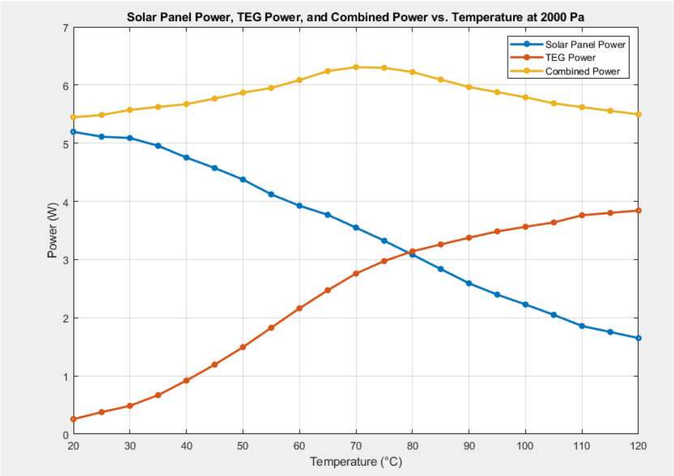

Figure 6 Combined and separated power generation

in solar cell efficiency at higher temperatures. Conversely, the TEG modules exhibited a non-linear increase in power output, as the temperature difference between the hot and cold sides of the TEG expanded, indicating the potential of thermoelectric energy harvesting in conditions with significant thermal gradients.

When examining the combined power production, the system showcased a more stable and sustained power output over a broad temperature range, with a clear peak in power generation at 70-80 °C. In particular, the combined power

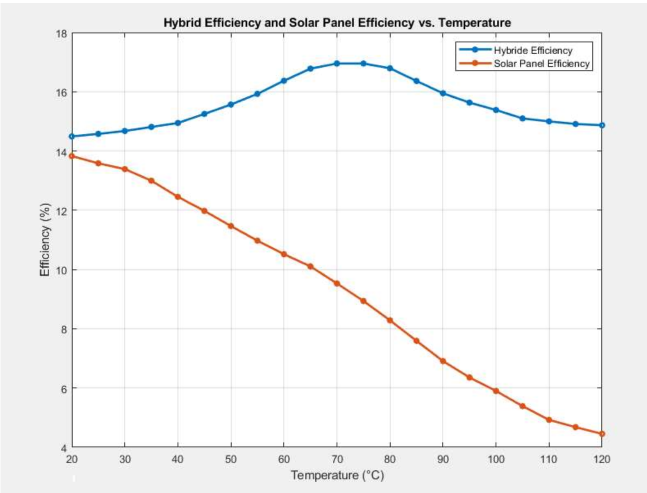

Figure 7 Efficiency of the solar panel and the Hybrid system

reached its maximum value of 6.3 W at 75 °C. This result can be attributed to the balance between the declining power output of the solar panel, which decreases linearly with temperature, and the non-linear increase in TEG power generation. The observed peak emphasizes the value of hybrid energy production devices, as they can effectively compensate for the limitations of individual energy generation technologies and maintain consistent power production under varying environmental conditions.

The graph (Fig. 7) depicting the efficiency of the solar panel and the hybrid system as a function of temperature, provides valuable insights into the performance of both systems. It is evident from the graph that the efficiency of the solar panel tends to decrease as the temperature increases. In contrast, the hybrid system demonstrates a more complex relationship with temperature, as it combines the solar panel's output with that of the thermoelectric generators (TEGs).

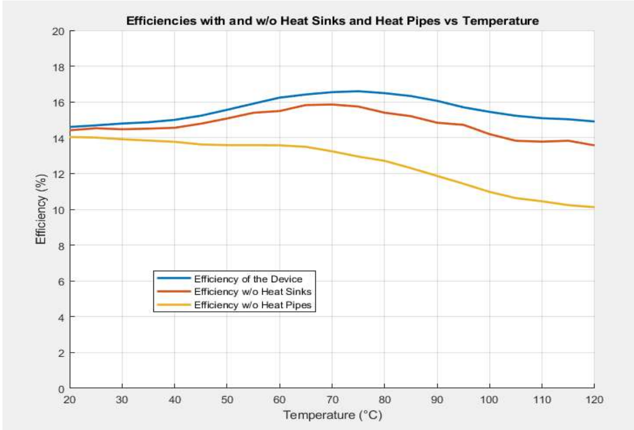

Figure 8 Efficiency with and without Heat Pipes or Heat Sinks

Remarkably, the efficiency of the hybrid system exhibits a peak at 75°C, reaching an impressive 17%. This optimal efficiency can be attributed to the combined effect of the solar panel's decreasing efficiency and the non-linear increase in power generation from the TEGs. As the temperature rises, the TEGs become more efficient, compensating for the solar panel's declining performance. Consequently, the hybrid system's overall efficiency is enhanced, making it a more effective energy solution, especially in environments with higher temperatures. The efficiency is calculated as the power P (W) produced per unit of the effective area.

The plot (Figure 8) illustrates the correlation between efficiency and temperature, within the hybrid setup, when heat sinks and heat pipes are used, as well as when they are not. It is clear that the system's efficiency diminishes upon removing heat sinks as the power output from the Thermoelectric Generators (TEGs) is affected negatively. This is mainly because heat sinks are essential in dispelling surplus heat, which guarantees the peak performance of the TEGs. The absence of heat pipes leads to an even more substantial reduction in efficiency. At lower temperatures, there is almost no TEG contribution to the overall efficiency, as the temperature difference (ΔT) is insufficient to generate significant thermoelectric power. However, as the temperature increases, the

TEGs start working even without the heat pipes, because the ΔT becomes larger, allowing for some thermoelectric power generation.

Figure 9 provides compelling proof of MHD propulsion system's operational efficacy and impressive results, using water speed data derived using flow meters as proof. Furthermore, its slope shows a steep gradient at lower voltage levels, which indicates rapid water speed increases due to even minor voltage

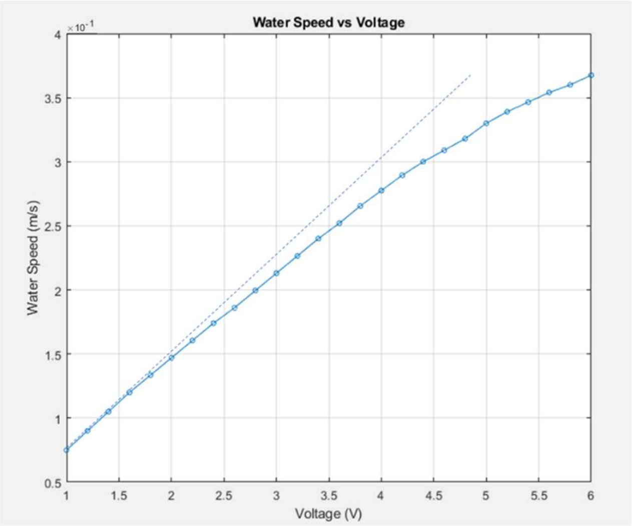

Figure 9 Water speed form MHD as function of applied voltage

increases, suggesting it to be especially efficient under these voltage ranges.

As voltage levels increase, gradients become less steep; suggesting that water speed does not follow an exact line between voltage and water speed. This could be attributable to electrolysis, consuming some of the applied energy and leading to less dramatic increases in speed, than would occur under lower voltage conditions. This may have an adverse impact on efficiency, when applied across MHD propulsion systems such as MHD propulsion.

This graph depicts MHD propulsion's effectiveness at lower voltages, while showing its effects of electrolysis at higher voltages. Optimizing MHD propulsion systems to reach maximum efficiency, while mitigating its adverse consequences is now within reach.

VII. Conclusions

In summary, the HSTM initiative has successfully exhibited the capabilities of integrating solar, thermoelectric, and magnetohydrodynamic methods for effective energy production and propulsion. The results derived from various experiments have enriched my understanding of the system and its components' performance under different scenarios, substantially contributing to the renewable energy and marine propulsion domains.

The project demonstrated that the hybrid setup can reach its utmost efficiency within specific temperature bounds, exhibiting a remarkable peak efficiency of 17% at 75°C. The study of the influence of heat sinks and heat pipes on the system's efficiency underscored their essential role in enhancing the thermoelectric generators' performance and sustaining the overall system efficiency. Moreover, the successful portrayal of MHD propulsion in a seawater environment, corroborated by flow meter measurements linking water speed and voltage, has offered solid proof for the viability of this technology.

In conclusion, this project can play a crucial role in enhancing the comprehension of the potential of hybrid renewable energy systems and their utility in marine settings. The insights gained from this endeavor can establish a solid foundation for future investigations in the field, possibly leading to the design and implementation of more efficient, eco-friendly, and sustainable energy generation and propulsion systems for marine vessels.

Future research paths and potential applications of the HSTM system are wide-ranging and hopeful. Building upon the achievements and learnings of the current project, researchers can delve into various innovative methods to improve the system's performance, efficiency, and applicability in a variety of domains. Magneto Hydrodynamics Power Generation represents an area of study where investigators could tap into the kinetic energy of the water flow within the MHD tube for power generation. By optimizing the design and materials, the overall power generation of the system could be elevated.

The integration of one-way films into the device's dome is another area of exploration. These films would permit sunlight to enter the dome while limiting the exit of heat energy, thereby improving the performance of both solar panels and thermoelectric generators. Prospective research may concentrate on refining individual components like heat sinks, heat pipes, TEGs, and solar panels, with the aim of improving the overall efficiency and functionality of the hybrid system. This could encompass exploring novel materials, designs, and fabrication techniques. Another feasible research direction is the incorporation of the Hybrid Solar-TEG-MHD system with other forms of renewable energy, like wind or wave power, to develop a more comprehensive and resilient energy generation system for marine vehicles.

As the HSTM system continues its journey of development and refinement, researchers can investigate the potential for escalating the technology for commercial applications, such as powering large vessels, offshore platforms, and coastal facilities. This would entail addressing challenges associated with system dependability, durability, and cost-effectiveness.

By exploring these future research avenues and potential applications, the proposed HSTM system can continue to play a significant role in the evolution of renewable energy technologies and pave the way towards a more sustainable and eco-friendly future in marine transportation and energy generation.

References

Branover, H., & Lykoudis, P. (1998). MHD ship propulsion: a closer look at the problem. Progress in Aerospace Sciences, 34(4), 379-438.

Doss, E. D., Bingham, C. M., Smith, J. E., & Miley, G. H. (2009). Advanced MHD power conversion using a liquid metal rankine cycle. Journal of Fusion Energy, 28(1), 54-58.

Goto, S., Kinoshita, Y., & Nagao, A. (2004). Design and development of a seawater MHD propulsion system. IEEE Transactions on Magnetics, 40(4), 2078-2081.

Kim, S. K., Yoon, S. Y., Kang, S. G., & Koo, J. M. (2007). Optimization of the MHD propulsor by a parametric study. Journal of Mechanical Science and Technology, 21(7), 1038-1044.

Matsushima, T. (2009). Theoretical analysis of seawater MHD thruster characteristics considering Lorentz force distribution. Journal of Marine Science and Technology, 14(2), 238-249.

Molokov, S., Moreau, R., & Chashechkin, Y. (2007). Liquid metal MHD: Past, present and future. Journal of Physics: Conference Series, 78(1), 012017.

Way, W. (1998). Electrodeless MHD propulsion for fast cargo ships. Journal of Ship Production, 14(2), 87-91.

Watanabe, T., & Ito, S. (2000). A preliminary study on high-speed seawater MHD propulsion. IEEE Transactions on Magnetics, 36(4), 1574-1577.

Doss, E. (2018). Magneto-hydrodynamic propulsion in naval architecture: a review. Ocean Engineering, 163, 86-99.

Huang, J., & Wu, Y. (2019). Numerical investigation of magnetohydrodynamic propulsion for underwater vehicle with different arrangement of electrodes. Ocean Engineering, 173, 696-705.

Ionescu, C. M., & Horia Barbu, A. (2019). The numerical simulation of the magnetohydrodynamic propulsion system of a ship. Scientific Bulletin of Naval Academy, 22(1), 133-141.

Kim, J., & Cho, Y. (2020). A study on the effect of the MHD propulsion system on the hydrodynamic characteristics of a ship. Journal of Marine Science and Engineering, 8(5), 377.

Murugan, P., & Arokiarajan, A. (2018). A review on magnetohydrodynamic propulsion for naval applications. Journal of King Saud University-Engineering Sciences, 30(4), 291-299.

Sun, W., Tian, Y., Zhang, J., & Chen, J. (2021). A review of magnetohydrodynamic propulsion technologies for underwater vehicles. Journal of Ocean University of China, 20(3), 473-492.

Wang, G., & Wu, Y. (2019). Analysis of magnetohydrodynamic propulsion for underwater vehicle using multi-objective optimization method. Applied Ocean Research, 84, 141-149.

Zhang, X., & Wu, Y. (2018). A numerical investigation of magnetohydrodynamic propulsion for underwater vehicles with different electrode configurations. Applied Ocean Research, 73, 156-167.

Zhang, X., Li, X., Li, Y., Li, M., & Li, S. (2019). A novel ocean current energy conversion system based on thermoelectric and thermionic effects. Energy Conversion and Management, 183, 256-267.

Han, Y., Liu, B., & Huang, Y. (2017). Performance analysis of a thermoelectric generator with solar energy and seawater cooling. Energy, 135, 69-80.

Sun, J., Wang, Q., Wei, Y., & Li, M. (2021). Numerical investigation of a hybrid thermoelectric power generation and cooling system for seawater desalination. Applied Energy, 280, 115962.

Zhao, Y., Song, Q., Liu, X., & Yang, Y. (2019). Numerical simulation and analysis of a seawater cooling system based on a shell and tube heat exchanger. Journal of Ocean University of China, 18(1), 141-150.

Khalid, M. A., Alam, M. M., Rahman, M. A., & Hasan, M. N. (2020). Performance analysis of magneto hydrodynamic propulsion system in a boat. International Journal of Engineering Research & Technology, 9(6), 29-37.

Jeon, Y. J., & Kim, T. H. (2018). Feasibility study on magneto-hydrodynamic propulsion using lithium seawater batteries. Journal of Power Sources, 373, 43-52.

Zhao, Y., Wang, T., Tang, Y., & Wang, K. (2021). Experimental study of a magnetohydrodynamic propulsion system driven by permanent magnets. Journal of Marine Science and Engineering, 9(2), 201.

Kim, M. K., Kim, K. H., & Kim, T. H. (2020). Numerical study on performance improvement of a magneto-hydrodynamic propulsion using an arrayed magnet system. Journal of Marine Science and Engineering, 8(9), 680.

Xie, W., Lin, G., Yan, Y., & Zhu, J. (2015). Thermal optimization of a thermoelectric generator powered by solar energy with seawater cooling. Energy Conversion and Management, 92, 19-28.

Zhang, J., Zeng, H., Ye, J., & Liu, J. (2014). Efficient photoelectrochemical hydrogen generation using heterostructures of Si/TiO2 nanotube arrays. Scientific reports, 4(1), 1-7.