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Review

MHD Generation for Sustainable Development, from Thermal to Wave Energy Conversion: Review

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Abstract: Magnetohydrodynamic (MHD) generators are direct energy conversion devices that transform the motion of an electrically conducting fluid into electricity through interaction with a magnetic field. Developed as an alternative to conventional turbine-generator systems, MHD generators evolved through the 20th century from large units, which are intended to transform thermal energy into electricity using plasma as a working fluid, to smaller units that can harness heat from a variety of sources. In the last few decades, an effort has been made to develop energy conversion systems that incorporate MHD generators to harvest renewable sources such as solar and ocean energy, strengthening the sustainability of this technology. This review briefly synthesizes the main steps in the evolution of MHD technology for electricity generation, starting by outlining its physical principles and the proposals to convert thermal energy into electricity, either using a high-temperature plasma as a working fluid or a liquid metal in a one- or two-phase flow at lower temperatures. The use of wave energy in the form of acoustic waves, which were obtained from the conversion of thermal energy through thermoacoustic devices coupled to liquid metal and plasma MHD generators, as well as alternatives for the transformation of environmental energy resources employing MHD transducers, is also assessed. Finally, proposals for the conversion of ocean energy, mainly in the form of waves and tides, into electric energy, through MHD generators using either seawater or liquid metal as working fluids, are presented along with some of the challenges of MHD conversion technology.

Keywords: MHD power generation; renewable energies; wave energy; liquid metal; direct energy conversion

Citation: Domínguez-Lozoya, J.C.; Domínguez-Lozoya, D.R.; Cuevas, S.; Ávalos-Zúñiga, R.A. MHD Generation for Sustainable Development, from Thermal to Wave Energy Conversion: Review. *Sustainability* **2024**, *16*, 10041. https://doi.org/10.3390/su162210041

Academic Editor: Pablo García Triviño

Received: 13 October 2024
Revised: 4 November 2024
Accepted: 11 November 2024
Published: 18 November 2024

1. Introduction

The search for technological solutions that make it possible to take advantage of the enormous potential of renewable energy sources in the short term is a priority that must be addressed to face current energy and environmental challenges. In this context, the efficient transformation of thermal or mechanical energy from solar and oceanic energy sources into electricity has gained interest in recent years. To achieve this goal and aim toward sustainable development, it is necessary to develop new technologies as well as adapt and improve existing ones.

In this review, attention is focused on Magnetohydrodynamic (MHD) energy conversion systems for electricity generation. The main component of these systems is the MHD generator, which is a device that transforms the kinetic energy of an electrically conducting fluid into electricity through interaction with a magnetic field. The first MHD generator, patented a hundred years ago [1], marked the beginning of a technology that was widely developed throughout the 20th century and is currently driving innovative applications.

Most developments related to MHD technology for electricity generation have been based on the conversion of thermal energy, which is mainly obtained from sources such as fossil fuels [2], nuclear [3], solar [4], and waste heat [5], involving a wide range of operating temperatures. Plasma MHD generation, which requires high operating temperatures, was the first to be developed for large-scale applications [6]. The use of liquid metals as working fluids made it possible to reduce temperature and material requirements while diversifying the heat sources used. Two-phase flow MHD generators were proposed for space [7] and terrestrial [8] applications and, afterward, for the use of solar sources [9]. Later, thermoacoustic MHD generators provided a new technological development to convert heat into electricity without the need for two-phase flows [10].

In the last few decades, MHD generation has been increasingly focused on finding alternatives that make use of energy scavenging [11] as well as renewable energy sources, particularly energy harvesting devices capable of converting ocean wave energy into electricity. In fact, the proposal to use MHD generators to harness ocean wave energy appeared in the last few decades of the 20th century, first using sea water [12,13] and later liquid metals [14,15]; due to the enormous potential of ocean sources, it has gained interest in recent decades, as has happened with different ocean energy technologies.

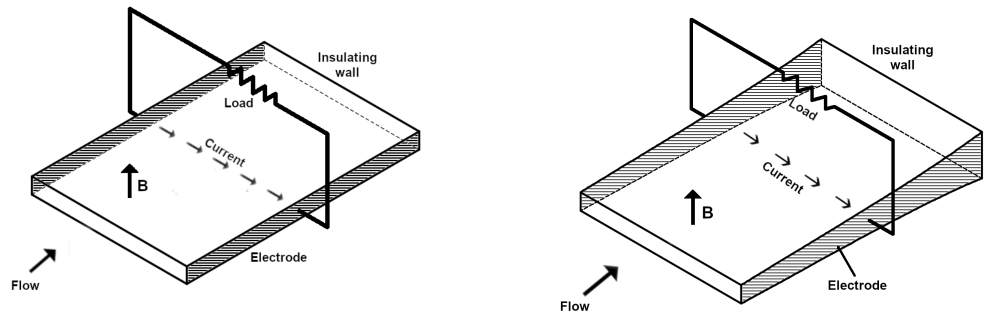
The present contribution is intended to present, in a rather synthesized way, the main steps in the evolution of MHD generation technology and its transit toward sustainable proposals. We start by presenting an overview of the physical principles of MHD generation and the projects to convert thermal energy into electricity, first using a plasma as a working fluid, and secondly, using liquid metal in one- or two-phase flows, which allows the operation at much lower temperatures while offering the possibility of using low-temperature sources such as solar or waste heat. A description is presented for thermoacoustic devices coupled to MHD generators, as well as for other alternatives for energy harvesting, with vortex MHD generators. Then, we address the proposals for the conversion of ocean energy, mainly in the form of waves and tides, into electric energy, through MHD generators using either seawater or liquid metal as working fluids. Finally, some of the challenges of MHD conversion technology are addressed.

2. Principles of MHD Generation

In its simplest form, conventional electrical power generation uses mechanical energy to move a solid conducting material through a stationary magnetic field. The relative motion of the electrical conductor and the magnetic field induces an electromotive force in the conductor that results in an electrical current that can be extracted from the generator. The main difference between conventional generators and MHD generators is that the moving electrical conductor is a fluid, which implies that the power production in the latter is a volumetric effect instead of a surface effect as occurs, for instance, in solid core linear generators. Due to this fact, in principle, MHD generators can be smaller and more compact. Moreover, the use of a fluid as an electrical conducting medium reduces the complexity of the direct power generation system, allowing for simpler designs. Over the years, several concepts have been proposed involving a variety of geometries, sizes, primary power sources, operation temperatures, and working fluids, depending on the required power output and particular applications.

In general, we can distinguish between conductive and inductive MHD generators. In conductive MHD generators, energy is extracted from the MHD transducer through electrical contact between the working fluid and electrodes connected to an external load. Additionally, in inductive MHD generators, magnetic induction is used to transfer energy from the conducting fluid to the armature without the need for electrodes.

One of the most common conductive designs is the continuous electrode Faraday MHD generator [16] in which an electrically conducting fluid is propelled through a duct of constant or increasing rectangular cross-section exposed to a static magnetic field transverse to a pair of insulating walls, while the walls parallel to the field constitute the electrodes which are connected to an external load resistance. The relative motion of the fluid and the magnetic field gives rise to an induced electric current orthogonal to both the fluid motion and the applied magnetic field, which can be drawn through the electrodes to the external load (see Figure 1). The induced electric current circulating in the fluid interacts with the applied field, producing a Lorentz force that opposes the fluid motion. Therefore, a high enough pressure gradient has to be provided to overcome this force. When the fluid flow is unidirectional, a DC current is induced, converting the kinetic energy of the fluid directly into electrical energy in the absence of mechanical moving parts [17]. While constant cross-section generators have been mainly used for incompressible working fluids, such as liquid metals, for compressible media such as plasma and two-phase fluids, ducts with increasing cross-section have been proposed (see Figure 1).



(**a**) (**b**)

Figure 1. Faraday MHD electric generator with constant cross-section for incompressible working fluid (**a**) and with variable cross-section for compressible working fluid (**b**).

There are several designs of inductive MHD generators. In one of the first proposals [18], the conducting fluid moves in a rectangular channel surrounded by a stator that produces a traveling magnetic field in the same direction as the fluid flow. In this way, a current is induced in the fluid, and when the flow velocity is higher than the synchronous velocity of the traveling magnetic field, part of the kinetic energy of the working fluid is converted into electrical power. The use of an alternating magnetic field instead of a traveling field has also been explored using an annular duct [19]. Apart from not requiring electrodes, these generators can use plasma or liquid metal as working fluids and have the advantage of not needing DC-AC inverters. Furthermore, the terminal voltage can be increased using the stator windings as a step-up transformer. Recently, interesting options for inductive MHD generators have emerged, where the plasma is produced by non-equilibrium periodical ionization while the charge carriers are separated, producing time-varying electrical currents that are magnetically coupled to an external coil [20–22]. Since these devices require high frequencies for the conversion process [23], they may not be suitable for some applications such as ocean wave harvesting.

3. Plasma MHD Generation

When it began, MHD generation focused mainly on the conversion of thermal energy into electricity at a large scale. In the last century, approximately between the 1940s and 1990s, a broad effort was undertaken in different countries (mainly the former Soviet Union and the USA) to develop MHD generation to a commercial scale using an ionized gas or plasma as working fluid, obtained from combustion products of a fuel with a hot oxide and adding seeding material to increase electrical conductivity [6,24]. In these systems, which were considered a suitable alternative to gas turbines, the plasma performs the functions of both a thermodynamic and electrodynamic fluid, since when passing through the MHD generator, it acts as a thermodynamic fluid by converting thermal energy into mechanical energy as it expands against the induced Lorentz force, and as an electrodynamic fluid by directly transforming mechanical energy into electrical energy, by interacting with the magnetic field. In this way, the MHD generator combines the functions of two conventional units, namely a turbine and a generator, into a single unit with a very simple design.

In the early plasma MHD generation systems, an open-cycle configuration was adopted where the gas heated by combustion flows through the MHD generator and is afterward rejected into the atmosphere [2]. In the 1980s, the closed-cycle MHD generator was proposed, which allowed the operation with low-temperature plasma through non-equilibrium ionization [25]. An example of this concept is the Fuji-1 MHD disk generator [26] that used seeded argon as the working fluid, obtaining an enthalpy extraction ratio over 20% and a maximal output electrical power over 500 kW .

The power density in an MHD generator is proportional to the product $\sigma B^2 \overline{u}^2$ [24], where σ is the electrical conductivity of the fluid, B is the applied magnetic field strength, and $\overline{u}$ the average fluid velocity in the generator. Although high speeds can be achieved through the plasma expelled from gas turbines [2], obtaining reasonable power output depends largely on having a very strong magnetic field and an adequate conductivity of the working fluid. Therefore, plasma MHD generation requires high operating temperatures since suitable conductivity can be attained by thermal ionization at temperatures in the range of 2700–3000 K. In principle, the possibility of working at temperatures much higher than the operating temperatures of any conventional turbine offers the advantage of achieving high thermal efficiencies. However, high temperatures were, and continue to be, the main obstacle to the development of plasma MHD generation due to the demands placed on the generator materials. A comprehensive perspective and historical review of plasma MHD systems and power plant development is available in [2,6]. Although the development of plasma MHD generation is currently less intense, it remains an active field of research. In fact, recently, the use of an MHD generator coupled with a turbine has been considered with the aim of increasing the total efficiency of fossil power plants by adopting a bi-plant design [27]. As mentioned above, inductive MHD generators offer new alternatives for working with plasma at much reduced temperature [21].

4. Liquid Metal MHD Generation with One- and Two-Phase Flows

In order to overcome the limitations of using plasma as a working fluid, particularly the difficulty of working at high temperatures, liquid metals were proposed as an alternative. The use of a liquid metal with a low melting point has great advantages over an ionized gas, especially because it has a much higher electrical conductivity at lower temperatures. In fact, the velocities that can be reached by the liquid metal, about one or two orders of magnitude smaller than those of the plasma, are compensated by its much higher electrical conductivity, at least four orders of magnitude greater than that of ionized gas, so that the power density of liquid metal MHD (LMMHD) generators is comparable to plasma MHD generators or even higher. To incorporate a liquid metal in a thermodynamic cycle, the proposal of including in some part of the cycle a gas phase through a two-phase flow, that is, a mixture of hot liquid metal with gas or vapor in direct contact, was introduced. As the gas expands, it transforms heat energy into mechanical work, propelling the liquid conductor. This mechanical work, in turn, is transformed into electrical energy by the liquid metal through its interaction with the applied magnetic field. Cycles were explored, where only liquid metal flows through the MHD generator (single-phase generators) [28] or those where the mixture of hot liquid metal with gas or steam passes through the generator (two-phase generators) [4].

In the sixties, liquid metal MHD generation was directed toward space applications using a two-phase flow generator to convert heat from a nuclear reactor into electricity, taking advantage of the absence of rotating parts [7,28,29]. In fact, the performance characteristics of a LMMHD generator using a single-phase NaK and two-phase NaK-N_2 fluids were experimentally evaluated [30]. Open thermodynamic cycles for terrestrial applications were also explored that used the product of the combustion of carbon and air as a gas phase, which was mixed with a chemically compatible liquid metal (copper or its alloys) [31].

The mixture passed through the generator and was separated at the outlet, expelling the gas into the atmosphere and recirculating the liquid metal. However, these cycles operate with temperatures ranging between 1300 and 2000 K, which, although lower than those of plasma MHD cycles, are still high, with the additional drawback of involving fossil fuels.

Although possibilities for improving the performance of nuclear reactors through LMMHD energy conversion technology were also assessed [3,32], in the eighties and early nineties, the efforts were focused on reducing operating temperatures so that solar or other low-temperature sources (e.g., waste heat) could be incorporated [4,5]. This resulted in new proposals for the conversion of thermal energy from solar sources into electricity using LMMHD generators, taking advantage of the flexibility in coupling different heat sources through the use of two working fluids [33,34]. The development of these systems, led by the Argonne National Laboratory, USA, and the Ben-Gurion University of the Negev, Beer-Sheva, Israel, focused on small and medium-sized dispersed conversion units using low-temperature heat sources independent of fossil fuels [35]. An interesting development was the ETGAR Program, which involved a simple direct conversion system with natural circulation (see Figure 2), employing a lead–bismuth alloy, operating in a temperature range of 338–423 K, and delivering an electrical power output of 8 KW and an overall efficiency of 8.8% [36,37].

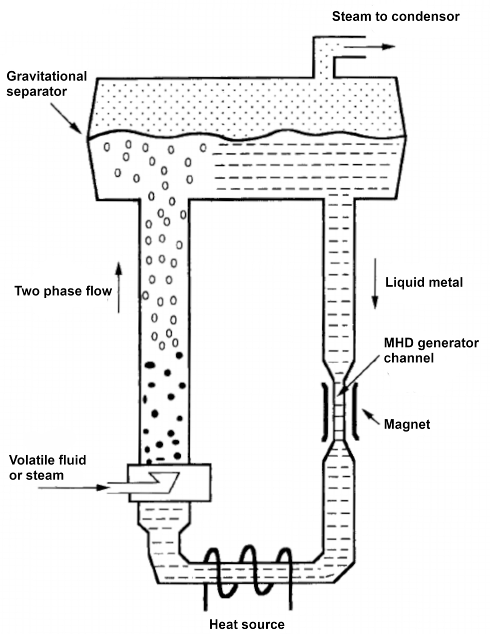


Figure 2. MHD system for direct conversion of heat to electricity with natural circulation using a lead–bismuth alloy, operating in a temperature range of 338–423 K. Developed in the ETGAR Program [36,37].

5. Thermoacoustic MHD Generators

In the late 1980s, an intensive research program on thermoacoustic machines was conducted at Los Alamos National Laboratory, USA, led by G. W. Swift [38]. These machines are based on the thermoacoustic effect, which converts heat into acoustic energy, that is to say, into oscillating motion. The thermoacoustic effect is associated with the generation of motion in a compressible fluid through the creation of pressure waves (acoustic waves) by a thermal gradient. A thermoacoustic device enables the conversion of thermal energy into acoustic waves (serving as a prime mover) or, conversely, the transformation of acoustic waves into thermal energy (acting as a heat pump). A variety of techniques exist for the conversion of thermal energy into electrical energy through the use of thermoacoustic devices. Comprehensive reviews of this topic have been published, see for example [39,40]. Los Alamos program investigated a variety of devices, with a particular focus on their potential for cooling and energy applications [41,42]. In view of the necessity for an efficient and high-power acoustic-to-electric transducer, Swift put forward the concept of a liquid sodium standing-wave thermoacoustic MHD generator [10,43,44]. This device is an alternative concept for converting thermal energy into electricity without the need for a two-phase flow of liquid metal. The device comprises a cylindrical stainless steel resonator filled with liquid sodium (see Figure 3). The interior of the resonator contains, at each extremity, an array of stacked molybdenum plates with hot and cold heat exchangers situated at either end of the array. The generation of a thermal gradient along these plates is sufficient to cause the sodium within the resonator to oscillate spontaneously, thereby establishing a high-amplitude sound wave with an operating frequency of approximately 1 kHz. The spontaneous oscillation can be converted into electrical energy by using a MHD transducer. In this configuration, a magnetic field is applied in the central region within the resonator, perpendicular to the direction of the acoustic velocity. Electrodes in contact with sodium allow the flow of an alternating electric current, which can be extracted for further processing. The main drawback of this type of device is that high working pressures are required within the resonator to generate acoustic waves (linear oscillatory motion) in the working liquid. However, there are no moving mechanical parts and no global circulation of the liquid metal, thus offering clear advantages.

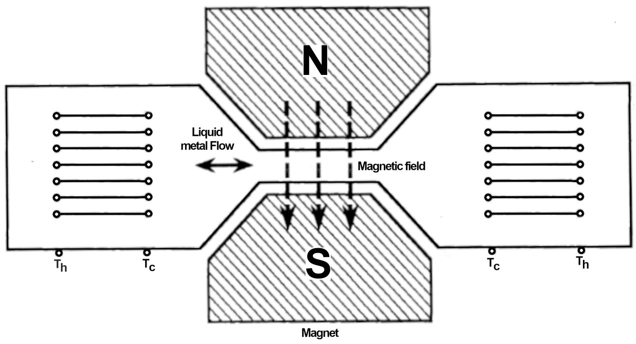


Figure 3. Schematic illustration of a liquid metal MHD thermoacoustic generator with two prime movers [10].

Based on this pioneering proposal, various studies have been carried out in order to transform thermoacoustic energy into electrical energy through the implementation of alternating MHD generators either conductive or inductive.

5.1. Conductive Thermoacoustic MHD Generators

A proof of concept of an alternating MHD generator that uses two different fluids separated by gravity was presented in [45]. Air was used as a working fluid within the resonator, coupled with a liquid electrolyte in the MHD transducer. The generation of thermoacoustic waves in the resonator results in an oscillatory linear movement in the air, which is then transferred to the electrolyte. The oscillatory motion of the electrically conducting fluid in the presence of a magnetic field generates an induced current that can be extracted by electrodes in direct contact with the electrolyte and fed into an external electrical load. The main disadvantage of this device is that the electrical conductivity of the electrolyte is very low. This means that very high velocities in the electrolyte or very intense magnetic fields are required to obtain a useful power output. The conceptualization of the experimental device with two different fluids interacting through an interface led to the design of more complex experimental devices.

Ibáñez et al. [46] developed an analytical model to analyze the optimal performance of an alternate LMMHD generator, using the conventional isotropic electrical efficiency and an overall second law efficiency, based on the global entropy generation rate. In turn, with the aim to identify the conditions for generating thermoacoustic waves in a resonator filled with an electrically conducting liquid under an applied magnetic field, Ovando et al. [47] performed a theoretical study to determine the influence of the magnetic field on the stability of thermoacoustic oscillations. Vogin and Alemany [48] conducted a theoretical analysis of a conductive alternate LMMHD generator using a two-dimensional model taking into account the effects of the magnetic Reynolds number in the oscillatory liquid metal flow. They considered the conductivity of the electrodes and included the coupling with a thermoacoustic transducer that generates the oscillatory motion.

More recent work has also explored conductive MHD generators coupled to thermoacoustic devices. For instance, in a recent study [49], a standing wave thermoacoustic electricity generation system with a liquid sodium MHD transducer based on the Swift proposal was explored through numerical modeling with the aim of illustrating the potential of this conversion system in small-scale electricity generation. It was found that as long as the risks of corrosion and exposure to air and water are avoided, the system can be highly reliable and have a long service life with a power density as high as 150 kW/m^3, which surpasses some commercially available technologies. Furthermore, a thermal efficiency of around 8% of the Carnot limit can be achieved, with a temperature difference of 563 K. In turn, Zhu et al. [50] performed a transient numerical analysis of a high-frequency conductive LMMHD generator using COMSOL software with the aim of assessing the effects of inlet velocity, load resistance, and operating frequency on the generator's performance. Additionally, a prototype of a LMMHD generator was designed, built, and tested by using a linear compressor. It was found that for an operating frequency of 15 Hz and an inlet velocity of 4.3 m/s, the generator prototype reached an output voltage and current of 113 mV and 1720 A, respectively, with an output power of 68 W at a corresponding acoustic-to-electric efficiency of 24%. Nevertheless, a discrepancy between the numerical predictions and the experimental results was found. The authors stressed the potential advantages of operating only with liquid sodium in comparison to operating with other thermoacoustic MHD concepts in which a gas is used for thermoacoustic conversion while liquid metal is only employed for MHD generation.

5.2. Inductive Thermoacoustic MHD Generators

Further studies have investigated inductive LMMHD generators coupled with a thermoacoustic prime mover, taking advantage of the fact that the latter delivers mechanical energy directly in an alternating manner, which is compatible with the use of MHD generators based on magnetic flux variations [51–54]. According to this concept, the thermoacoustic engine generates an oscillatory motion in a liquid metal confined in a duct that houses an MHD transducer consisting of a permanent magnet and a coil of an electrical conducting material. The oscillatory motion of the liquid metal under the imposed permanent magnetic field generates an alternate electric current at the same frequency as the velocity oscillations, which, in turn, creates an induced magnetic field and a time-varying magnetic flux that induces an electric current in the coil connected with the load. The induced electric current depends, evidently, on the electrical conductivity of the coil material and the number of turns, as well as on the characteristics of the external load.

In a recent article, Alemany et al. [55] proposed an innovative inductive LMMHD disk generator for the transformation of alternating mechanical energy into electricity. This device consists of a central tube connected to a toroidal cavity partially filled with liquid metal while the remaining volume is filled with gas. The system is designed to be coupled to a thermoacoustic engine, which produces a pressure wave in the tube that is transmitted to the free surface of the liquid. Therefore, the liquid is forced to oscillate radially inside the disk channel under a transverse magnetic field produced by a permanent magnet that increases its strength along the radius. The liquid metal oscillating under the magnetic field induces a toroidal electric current in the fluid, which acts as the primary winding of a transformer. A copper coil is wrapped co-axially with the central tube performing as the secondary winding of a transformer which, in turn, is electrically connected to the load. With the aim of maximizing the induction in the volume of the channel, the structure of the device is made of a ferromagnetic material. Hence, inductive coupling allows the generation of electrical power without a direct connection between the internal and external parts of the device. The system can be powered by thermal energy from solar, residual, and geothermal sources, among others, and is expected to reach 50% of the Carnot efficiency.

5.3. Thermoacoustic MHD Generators for Space Applications

Recently, there has been particular interest in using thermoacoustic machines coupled with LMMHD generators to supply power for future space exploration missions. The "Space TRIPS" project, funded by some European countries, has developed a thermoacoustic engine designed to convert thermal energy from a hot source originating from radioisotopic elements into mechanical energy, delivered as velocity and pressure oscillations inside a tube filled with argon gas [56,57]. The mechanical energy is converted into electricity by an inductive sodium MHD generator, which delivers an output power of about 6 W. In this device, the oscillations produced by the thermoacoustic engine are transmitted to the liquid metal, which oscillates under an imposed magnetic field, inducing an alternating current. This current in the sodium produces an AC magnetic field, which, in turn, induces an electromotive force in the output coil. The physical process occurring in the inductive MHD generator has been modeled through an equivalent circuit approach [58]. In another related study, an analytical model of the MHD generator was developed with the aim of evaluating the electromagnetic and fluid dynamic behavior of the device, allowing to determine the characteristic values of efficiency and output power of the generator [59]. Within the context of space applications, Zhu et al. [60] proposed a three-stage looped thermoacoustically-driven conductive LMMHD generator, looking to improve the power density and capacity of these devices. Using a numerical model, the authors found that for a temperature difference between 300 K and 900 K, a thermal-to-electric efficiency of 27% with a total electric power of 4750 W can be obtained at a load factor of 0.92.

5.4. Plasma MHD Thermoacoustic Generators

Theoretical and experimental efforts have also been made to couple a thermoacoustic prime mover to an inductive MHD generator using plasma as the working fluid. For instance, Alemany et al. [53] proposed a device whose operation does not require an external magnetic field since the energy conversion is performed by induction. The idea is to produce charge carriers in a gas through an electrical discharge, obtain a plasma, and use a high-voltage electrostatic field to separate charge carriers of opposite sign, reaching an equilibrium state. The plasma is then set into oscillation by a thermoacoustic device so that the charge carriers generate an alternating electric current that, in turn, induces an electromotive force in a toroidal coil wound around the duct and connected to the load, completing the energy conversion process. Using the design criteria to obtain a first approximation of the parameters of the generator, the authors used a numerical model to confirm the assumptions of the design phase and to obtain preliminary results about the feasibility and performance of the system. In turn, considering a similar concept as in [53], Carcangiu et al. [54] developed a multi-objective optimization algorithm for the design of a thermoacoustic plasma MHD generator considering conflicting objectives. In this way, the simultaneous maximization of the generated power was addressed, and the minimization of the voltage necessary to maintain the cloud of charges separated. In addition, the minimization of the mass and size of the device was introduced as an objective function, with the aim to optimize the generator for aerospace applications. The closed-cycle MHD conversion of an oscillatory plasma driven by a thermoacoustic engine coupled to a conductive MHD generator has also been analyzed using a one-dimensional model [61]. Some characteristic parameters regarding the oscillation frequency, electromagnetic induction, and load factor that allow an efficient energy conversion were determined. For an optimized case, an efficiency of 24% with a corresponding output power of 1644 W was found.

6. MHD Energy Harvesting

Energy harvesting is a rapidly developing field that offers substantial benefits in terms of technical innovation, economic gains, and environmental sustainability for autonomous systems. At its core, energy harvesting refers to the conversion of environmental energy resources, which are often considered to be latent or wasted, into a usable form, primarily electrical energy [11]. This electrical energy serves as a power source for small electronic applications that typically operate at low power densities. The range of energy sources suitable for harvesting includes mechanical, thermal, chemical, solar, and radio frequency domains, each with varying degrees of feasibility and effectiveness [62]. Mechanical energy sources in nature, which are characterized by low frequencies and high amplitudes, are commonly found in phenomena such as ocean waves [63], wind flow [64], and human motion [65]. Conversely, thermal energy can be harnessed through thermoelectricity [66,67], which employs temperature differentials between objects or within environments to generate electricity via thermoelectric generators, effectively transforming environmental heat into usable power. The emergence of triboelectric nanogenerators has also facilitated the conversion of mechanical energy from vibrations and motion into electrical energy [68–70]. This innovative technology offers a scalable solution for powering small electronic devices in remote or autonomous environments. In combination, all diverse energy harvesting technologies expand the potential for sustainable energy solutions across various sectors, enhancing the efficiency and reach of autonomous systems and small-scale applications.

The design of energy harvesters necessitates robustness to withstand cyclic, irregular, and extreme forces. For instance, in the context of human body motion, it is essential to consider aperiodic movements and high stresses. These complications have the potential to damage certain harvesting systems, such as piezoelectric devices. Furthermore, it is crucial for these systems to operate over a significantly broader range of oscillation. Fluid-based systems are emerging as a viable solution due to their ability to withstand mechanical stresses even under challenging conditions. Within the realm of energy harvesting, one avenue explores the use of fluids to drive conventional technologies, such as rotors. While efficient, such systems often involve moving components and can pose scalability issues when applied to tasks with dimensions of a few centimeters or less. This complexity can lead to the creation of intricate and delicate systems. An alternative avenue of exploration delves into unconventional energy conversion mechanisms centered on electrically conductive fluids, which directly convert mechanical energy into electricity [71].

A noteworthy approach in utilizing conducting liquids for energy harvesting involves gallium-based liquid metals (GBLM). The liquid nature of GBLM, coupled with its electrical properties, enables efficient kinetic energy conversion into electrical energy through Magnetohydrodynamic (MHD) effects. Pioneering applications of GBLM's MHD generators for energy harvesting initially focused on human motion, as evidenced by studies conducted by Jia et al. [72] and Dai et al. [73]. These studies introduced innovative approaches to tap into and harness human kinematical energy. In the initial work by Jia et al. [72], a prototype was developed to capture energy from wrist swing motions, demonstrating remarkable efficiency and robustness in electricity generation. Furthermore, the authors proposed that by interconnecting multiple GBLM's MHD generators and strategically optimizing their placement, it becomes feasible to generate a substantial quantity of electricity from human body movements, all at a notably low cost. Subsequently, in the study conducted by Dai et al. [73], a system was devised to harness biomechanical energy during walking. This system employs the foot's motion to activate two liquid metal pumps discreetly integrated within the shoe. Consequently, the liquid metal flows through MHD generators, effectively producing electricity. The setup attained a maximum power output of 80 mW with an efficiency rating of approximately 1.3, making it a favorable option for supplying power to wearable or implantable micro/nano devices.

Recent studies by Panchadar et al. [71] and West et al. [74] have introduced an interesting concept for LMMHD harvesters. This generator is designed to harness energy from a wide range of ambient mechanical energy sources by inducing a vortex flow characterized by circular motion of conductive liquid metals like mercury or galinstan within a cylindrical cavity surrounded by a powerful magnetic field. Previous theoretical work in this field, such as that presented by Michiyoshi and Numano [75,76], focused primarily on the performance of vortex-type MHD power generators utilizing partially ionized gases as conductive fluids and investigated the influence of the Hall effect. A significant advantage of the vortex MHD generator lies in its circular design, effectively mitigating the typical electrical power losses encountered in conventional MHD generators and resulting in an overall performance enhancement. The vortex MHD generator developed by Panchadar et al. [71] operates as a direct current (DC) device, and the authors claim to achieve a power density of 34 W/cm^3 in its current configuration. Furthermore, the authors suggest the potential to significantly increase these power densities up to 102 W/cm^3, through geometric optimization. In addition, West et al. [74] introduced an AC-based vortex MHD generator concept. In this approach, the swirling motion of the liquid metal serves as a driving force to activate an internal electrical switch, with the overall goal of converting the low-voltage output into higher-voltage alternating current (AC) using a transformer. However, it should be noted that the actual power generation of the device is lower than expected, with a power output of approximately one watt.

A theoretical study of a similar liquid metal vortex MHD generator, explored by Ávalos-Zúñiga and Rivero [77], highlights a significant discrepancy between the DC and AC configurations and their expected performance. This discrepancy is primarily due to high internal resistance, which is much greater than what theoretical calculations predicted. Furthermore, the unreliable operation of the internal switch exacerbates the issue, leading to a decrease in the overall efficiency of the device. Despite these challenges, the authors emphasize the potential applications of this generator concept. The study by Ávalos-Zúñiga et al. [78] employed analytical and numerical models for the investigation of a liquid metal vortex MHD generator, making use of previous works [71,77] as a point of reference. The models were validated to a certain extent through a laboratory prototype that had a geometry similar to that of previous studies. The results of the numerical analysis indicated that an external electrode size of approximately 90° arc length is optimal for power extraction under specific inlet velocity and magnetic field conditions, resulting in an 8% increase in electric power output. While this work identifies an optimal configuration, the authors emphasize that further research is needed to fully determine the best possible configuration.

In a recent work, Gupta et al. [79] investigated a three-phase AC vortex LMMHD generator that has the potential to produce power on the scale of watts. In contrast to conventional LMMHD generators, which generate low voltages at low fluid velocities, this configuration employs a three-phase alternating current and a vortex flow to augment power production. The results demonstrate that the generator is capable of producing up to 7 W of power without the use of an impeller, transformer, or switch. The proposed LMMHD generator has the potential to be employed for the harvesting of energy from a range of environmental sources. The authors hypothesize that this technology can be readily scaled for applications requiring power in the range of milliwatts to watts.

7. Ocean Energy Conversion Through MHD Generators

Among different forms of marine energy, wave energy has a great potential with the main characteristic of having a high energy density [80]. Various devices of different types have been proposed, each one defined by a particular design and power takeoff system (PTO), which transforms the energy captured by Wave Energy Converters (WECs) into useful energy (electricity) [81,82].

A possible way to classify the WECs is by the PTO system. Roughly, they can be classified into two categories, indirect conversion and direct conversion [83,84]. Indirect power conversion systems transform the energy captured by the WECs in two or more steps, for example, a system of a hydraulic motor coupled to a rotary electric generator that transforms the energy captured by the attenuator into electricity. In fact, due to the maturity of the technology, most current prototypes are based on this kind of indirect conversion system. However, the mechanical parts used to couple the low-frequency motion of the ocean waves with the high-frequency motion of the rotary generator have a direct impact on the overall efficiency of these systems. On the other hand, direct power conversion systems transform the energy captured by the WECs into useful energy in a single step, which minimizes the use of mechanical parts and, therefore, increases the overall efficiency of the system. Actually, the vast majority of direct conversion systems are based on solid core linear generator technology and their variants, which have certain limitations and challenges such as the high attractive force between translator and stator that complicates the mechanical and bearing designs and requires constant maintenance.

LMMHD generators present a suitable alternative to direct power conversion to transform the energy captured by WECs in a single step. This proposal presents interesting possibilities, although there are also important challenges to overcome. In fact, the use of ocean energy in the form of mechanical energy, whether through ocean currents, tides, or waves, provides an alternative for the generation of electricity from MHD devices, which are well suited for mechanical energy sources characterized by high forces, low characteristic frequencies, and small displacements [71]. Actually, the mechanical impedance of ocean waves can be matched very well by MHD generators, which can hardly be achieved with other wave energy systems [85].

The interest in the conversion of wave energy into electrical power through MHD technology is related partially to electromobility. In fact, electromobility in all modes of transport requires the availability of electrical energy resupply sites. In the case of maritime transport, there is an increasing need for electricity on the coast and offshore. This encourages experimental research aimed at developing prototypes that can adapt to the different wave conditions present in the world, in addition to having a variety of options in their production capacities and more efficient designs.

There are several proposals for the use of ocean energy through MHD generators, and the first distinction that can be made among them is related to the electrically conducting fluid used to carry out the conversion process. Although the idea of using seawater as a working fluid has been explored, having the advantage of availability, the low conductivity of the fluid imposes strong limitations on the power output and the requirement of very high velocities and strong magnetic fields. On the other hand, liquid metal MHD generators offer higher power output through coupling with different types of WECs.

7.1. Seawater MHD Generators

Hendel [12] patented in 1979 a Faraday-type MHD generator for the conversion of the kinetic energy of saline water into electricity, in which the MHD duct has a constricted throat section to increase the flow velocity. In addition, wave-powered devices designed to augment the kinetic energy of seawater flowing through the MHD duct were incorporated. The randomly alternating current produced by the MHD generator, resulting from changes in the direction of water flow, is converted into a relatively constant DC current through electrical control circuits and condensers in series with the electric load circuits. The proposal includes parallel rows of MHD ducts connected in series attached to a structure anchored to the bottom of the ocean in order to increase the power output.

In 1992, Rynne [13] patented an ocean wave energy conversion system to harness wave energy using an MHD generator with seawater as the working fluid. The system comprises a reciprocating buoy, driven by the difference in wave height coupled to an MHD generator located below the sea surface level. Due to the reciprocal vertical motion of the float, sea water flows up and down through the MHD generator, inducing an AC current that can be drawn through electrodes to an external load. At the ends of the MHD duct, constricted regions are included to increase the sea water velocity.

Experimental and computational studies of a helical-type seawater MHD generators using a solenoid superconducting magnet was presented by Takeda and collaborators [86–88]. The device is intended not only to directly transform the kinetic energy of an ocean or tidal current into electricity but also to generate hydrogen gas as a by-product. To increase the power output and compensate for the low electrical conductivity of the working fluid, a superconducting magnet supplying a magnetic field of 7 T was used. The helical-type generator consists of double-cylindrical coaxial electrodes, a helical insulation wall, and a solenoid superconducting magnet that provides a magnetic field parallel to the coaxial direction. Thus, when seawater rotates around an anode in the presence of the magnetic field, an electromotive force (fem) is generated and an electric current is induced. Experimental results showed that the fem increases proportionally to average flow velocity and magnetic field and that the generator power output increases quadratically to these variables. When the fem exceeds the electrolysis voltage, in addition to the electric power produced, hydrogen gas is obtained as a by-product generated by the circulating electrical current. The helical-channel seawater MHD generator was also investigated numerically using full 3D simulations, and a very complex behavior was found in the flow, which may lead to energy losses [89].

In a recent study, an experimental device comprising an electrochemical flow cell was built with the aim of simulating a linear-type seawater MHD generator and investigating the effect of magnetic field on seawater electrolysis during the MHD power generation process and the effect of Lorentz force on ions in a NaCl solution [90]. It was found that the strength of the magnetic field, which was raised up to 7 T, affected the current value of seawater electrolysis and that the hydrogen evolution reaction efficiency improved under the MHD power generation conditions.

Within the energy harvesting context for the marine environment, a seawater MHD generator has been proposed to meet the energy needs of sensors or bio-loggers for monitoring marine life, as well as acquiring climate and biological information [91]. The idea is to fasten a small, milliwatt-size MHD generator to a marine animal so that the fluid flow around the animal is channeled through the generator, producing electricity to power sensors or other devices and increasing their lifespan.

7.2. Liquid Metal MHD Wave Generators

The idea of harnessing the energy contained in the waves through a power takeoff (PTO) system based on MHD technology has been explored more intensively in recent decades. Although several prototypes at different scales have been developed, the technology is still under development.

In one of the first studies aimed to harness ocean wave energy through MHD generators, Altshuler and Koslover [14] investigated theoretically an LMMHD generator coupled to a WEC. The wave energy converter consists of a housing (moored to the ocean floor) attached to a drag disk connected through a spring to the MHD generator, which, in turn, is attached to a float. As the float and the generator oscillate, driven by ocean waves, a liquid metal performs an oscillatory motion under the magnetic field inside the generator, inducing an AC current and generating electric power. The objective of the authors was to analyze a method to maximize the power output from the MHD wave energy converter by controlling the applied load impedance.

Later, Koslover and Law [15] patented a Faraday type MHD generator in which a NaK-78 liquid metal is forced to flow due to very strong, but slow moving forces, such as those created by ocean waves, obtaining usable electric power. A pair of bellow reservoirs at the extremes of the MHD channel are used for conveying the external force to the conducting fluid. The magnets in the generator have a tapered side surface adjacent to the fluid channel to reduce the power losses caused by end effects. The generator is designed to work in a modular way, but it is possible to make couplings of several units depending on the conditions of the force generated by the flow of liquid metal.

Another development was carried out by the Scientific Applications & Research Associates (SARA), who designed, built, and tested a 100 kW prototype LMMHD generator for wave energy conversion [92]. Although very scarce information is available, results reported that the efficiency from mechanical input to output electricity is about 50%.

7.2.1. Development of LMMHD Wave Generators in China

In the last few decades, important studies have been carried out in China, aiming to develop and consolidate the liquid metal MHD generator technology for the transformation of wave energy into electricity. These efforts stem from studies of the energy potential of marine waves in China, which determined a maximum capacity per meter of wave of around 10 kW [93]. Therefore, promoting the development of optimized technology for small-capacity, high-efficiency power generation is important to tap the potential of China's coasts. One of the first works that promoted research in this area in China was the theoretical analysis of the mechanical and electrical behavior of a model with real operating conditions of an LMMHD generator coupled to a WEC, which was presented in 2008 by a group of researchers from the Institute of Electrical Engineering (IEE) of the Chinese Academy of Sciences (CAS) [94]. The authors found that with a wave amplitude of 1 m, a wave period of 6 s, a load factor of 0.85, and the use of U-47 as working fluid (liquid metal composed of bismuth, lead, tin, indium, and cadmium), the efficiency achieved by the system is 67% when the friction losses are neglected. They concluded that the system is highly efficient and very compact, while the matching between the LMMHD generator and the mechanical impedance of ocean waves is excellent.

After this work, several theoretical studies of different models of MHD generators coupled to WECs have been presented. These studies analyze different phenomena such as the dynamic interaction between the wave and the LMMHD-WEC system [95], the electrical performance of the generator for different operation conditions [96–99], the power electronics connected to the LMMHD generator to modify the electrical output of the system [100,101] and the numerical simulation of the liquid metal flow inside the LMMHD generator [102]. In these new design proposals for harnessing wave energy using LMMHD generators integrated into WECs, the coupling between both systems follows the same principle for most of the proposals. Figure 4 shows the simplest model for the coupling of the WEC and the LMMHD generator, where the oscillating buoy is connected by means of a thrust rod to a double-acting piston, which drives a working fluid and indirectly makes the liquid metal flow bidirectionally through a neoprene diaphragm [96].

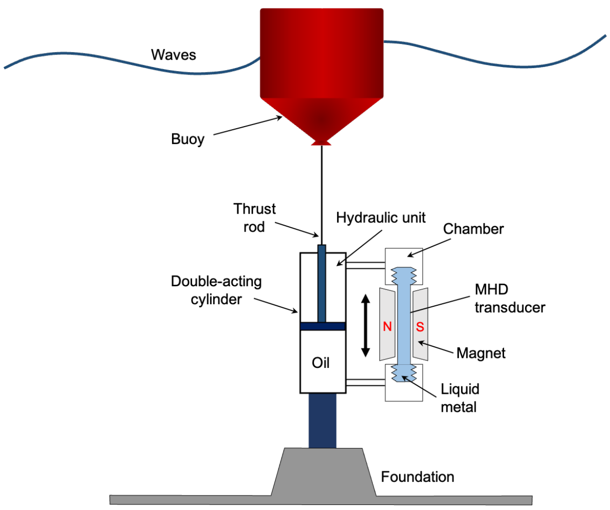


Figure 4. Sketch of a WEC coupled to an LMMHD generator using a double-acting piston system with a working fluid and a neoprene bellow that drives the liquid metal [96]. A similar system can operate with multiple coupled devices [99].

In fact, researchers from the IEE-CAS have patented different prototypes of WEC coupled to LMMHD generators, one of the first being a system based on a swinging type WEC [103]. The system consists of a sealed container that floats on the ocean surface. A communicating vessel is mounted inside the container, which consists of two reservoirs and a rectangular cross-section oscillating duct that connects the reservoirs; the MHD transducer is located in the central part of the duct. The communicating vessel system is filled with liquid metal while an inert gas fills the reservoirs. When the container sways with the movement of the sea waves, the position of one reservoir is near the crest of the wave while the other is near the valley, generating a height difference that causes the liquid metal to flow through the rectangular channel from one reservoir to the other. The relative motion between the liquid metal and the magnetic field generates induced currents which are extracted through copper electrodes to an external electrical load. In 2011, a floating WEC system based on LMMHD generators was patented [104]. In this case, the entire energy conversion system is above water on a floating platform anchored to the seabed. The energy from the wave motion is captured by a WEC and transformed into a linear oscillatory motion, which is then transmitted through a moving shaft to the LMMHD generator. The system is designed to connect multiple LMMHD generators in series in order to increase the power and output voltage. In 2015, the same group patented an underwater charging platform based on LMMHD generators [105]. The system is proposed as a power recharging station for autonomous underwater units. It consists of an offshore moored floating system that converts the ocean's wave motion into electricity using LMMHD generators. An absorbing point type WEC transforms the wave energy into a vertical linear oscillatory motion, which is transmitted to the LMMHD generator located below the ocean surface. This invention would greatly reduce the downtime of autonomous underwater devices due to surfacing for charging.

In addition to patents and theoretical studies, the Chinese research group has also carried out diverse experimental studies at a laboratory scale. The first experiment in China to demonstrate power production from ocean waves using an LMMHD generator was conducted in 2010 [106]. The experimental laboratory prototype, capable of simulating the bidirectional flow generated by the interaction of a buoy with ocean surface waves, consists of a hydraulic piston actuated by a hydraulic power unit, where the piston imposes an oscillatory motion to the working fluid (mercury) that is confined in the LMMHD generator. The mercury flows in a reciprocating way through the MHD generator, which is composed of an effective rectangular cross-section 132 mm wide and 10 mm thick, where a pair of permanent magnets provides a magnetic field intensity of 0.5 T in the middle plane between the magnets, while a pair of copper electrodes are located at the lateral walls. It was demonstrated that with a load factor K (ratio of applied electrical resistance with the internal electrical resistance of the generator) between 0.5 and 0.6 and working fluid velocities in the range of 2.5 to 5.0 m/s, it is possible to produce 160 W of power. In 2014, the same group conducted an experimental study seeking to improve the efficiency of an LMMHD generator [107], testing different temperature conditions of the working fluid known as U-47 alloy, which has a fusion temperature of 47 °C. The authors found that the temperature of the liquid metal plays an important role in the electrical contact resistance between the electrodes and the liquid metal since this resistance increases quadratically as the temperature increases. They also found that the electrical conductivity of the liquid metal alloy decreases linearly as the temperature increases, thus requiring a temperature control mechanism in the LMMHD generator. In 2015, a 1.1 kW laboratory experimental prototype of an LMMHD generator using U-47 alloy with an effective generator cross-section 50 mm wide and 6 mm thick was tested [108]. A pair of permanent magnets with tapered corners were used to provide a magnetic field of 0.9 T in the midplane between the magnets, while a pair of copper electrodes were located on the side walls of the duct. Using liquid metal velocities close to 5 m/s and different values of electrical load resistance in the range of 45–200 μΩ, an electrical power output of 1.1 kW was achieved, with a maximum electrical current and voltage output values of 3200 A and 0.33 V, respectively. The experimental results obtained were reproduced by a numerical model.

7.2.2. Laboratoy Prototype

Recently, Domínguez-Lozoya et al. [109] carried out an experimental study of the fluid dynamics and electrical performance of an alternate LMMHD generator. The developed laboratory prototype allowed for the introduction of an Ultrasonic Doppler Velocimetry (UDV) transducer inside the LMMHD generator to measure the liquid metal oscillating axial velocity using the eutectic alloy Galinstan as the working fluid. Figure 5 shows a photograph of the experimental device, which consists of a reciprocating mechanism based on a slider-crank system that is driven by a direct current motor and controlled by a voltage regulator. The reciprocating mechanism, which mimics the motion of ocean waves, is coupled to a piston that is in direct contact with the liquid metal confined in an oscillation duct, which has a constant rectangular cross-section. The duct is composed of two principal sections, namely the MHD transducer and the measuring zone. The latter is an open section where the UDV transducer is immersed in the liquid metal to measure the axial oscillating velocity. In the MHD transducer, a magnetic field with an average strength of 0.18 T is applied transversally to the oscillating flow through a pair of neodymium magnets located in two parallel insulating walls, while two parallel copper electrodes are arranged in the lateral walls. In operation the driving mechanism produces a linear oscillatory motion through the piston, which in turn, transfers the oscillating motion to the liquid metal. The relative motion between the liquid metal and the imposed magnetic field induces an electric current that can be extracted through the copper electrodes to an external load. The experimental data allowed for the determination of the axial velocity of the working fluid inside and outside the generation zone. These experiments also provided information about the fluid velocity, voltage and current for different load factors. The entrance flow region where the oscillating flow interacts with the fringing magnetic field was theoretically explored by Dominguez-Lozoya et al. [110]. It was found that non-linear effects in the boundary layer originate the appearance of steady streaming vortices superimposed in the oscillatory flow whose extension and strength grow as the magnetic field gradient increases. Nevertheless, it was found that the disturbance created by the steady streaming vortices is not expected to affect the performance of the MHD generator.

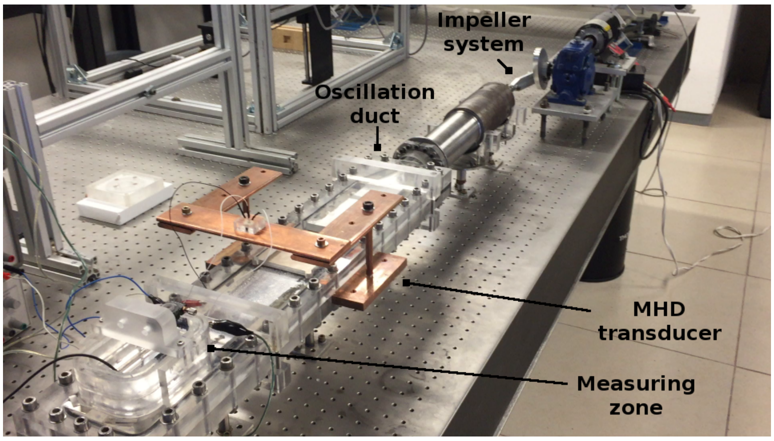


Figure 5. Laboratory scale of a conductive alternate liquid metal MHD generator [109].

8. Some Technical Challenges

MHD electric generation is a promising technology with great versatility to take advantage of different energy sources, particularly renewable sources. There are, however, different challenges to overcome for this technology to establish itself as a viable option for the production of useful energy. In fact, energy losses are a major drawback for LMMHD generators, and this is, in part, the reason for the discrepancy between the theoretical and experimental efficiency of the prototypes studied so far.

End effects are one of the main phenomena that affect the performance of LMMHD generators and lead to internal energy losses. They are related to the finite dimensions of the permanent magnets and electrodes since near the edges of the MHD transducer, there are abrupt changes in the intensity of the magnetic field and in the electric conductivity of the lateral walls of the channel, which represent a magnetic and electrical conductivity gradient in the axial direction of the MHD generator. These gradients are responsible for the formation of current loops that affect the performance of the generator. Therefore, the reduction in end effects is vital for the development of an efficient LMMHD power generator. In this context, different approaches have been proposed with the aim of mitigating end effects in LMMHD generators, for instance, increasing the aspect ratio of the MHD transducer, inserting insulating vanes in the end zone, and tapering the edges of the permanent magnets. The effect of varying the aspect ratio (electrode length/distance between electrodes) in the performance of the LMMHD generator has been investigated using theoretical models [111,112], finding that the performance of the generator improves with increasing the aspect ratio. The impact of placing insulating barriers in the electrode borders zone and between the electrodes has also been analyzed. Using a two-dimensional numerical simulation, Yamada et al. [113] found that inserting insulating plates at the end zone of the LMMHD transducer suppresses eddy currents and increases the efficiency of the LMMHD generator from 74.0% to 80.8%. Another possibility to reduce end effects is to modify the magnetic field at the edges of the magnet (flattening the edges) so that the magnetic field gradient is as small as possible. In fact, employing a three-dimensional numerical simulation, Lin et al. [114] and Zhao et al. [115] found that reducing the magnetic field gradient at the end of the LMMHD generator is a key factor in reducing end effects. Recently, a method to optimize the distribution of the external magnetic field in order to suppress end effects in an LMMHD generator was proposed by [116]. The study was conducted by implementing a three-dimensional numerical simulation of the unidirectional turbulent liquid metal MHD flow in a rectangular cross-section channel. The authors concluded that when the electrostatic field exceeds the motional electromotive force (emf), end currents are generated, which can be mitigated through a special magnetic field distribution.

Another challenge to overcome is that the electrical output of conductive LMMHD generators is characterized by delivering low voltages (of the order of mV) and high electric currents (of the order of kA), which differs significantly from the electrical characteristics of transmission networks (high voltage–low current). As a solution, it has been proposed to connect in series the terminals of multiple LMMHD generators (Modular LMMHD generators). A system consisting of sixteen LMMHD generators connected in series was patented by Koslover et al. [15] to harness ocean wave energy. With a simplified model, they found that with a buoy diameter of 5 feet and a mechanical input power of 225 kW, the system generates 125 kW of electrical power, with an output voltage in the range of 10 V and an output current of around 12 kA. They argue that with this voltage value, it is possible in a certain way to use high-efficiency power electronic system to modify the voltage to the necessary levels required in different applications. An alternative proposal for overcoming low voltage generation is a three-phase alternating current liquid metal vortex MHD generator proposed by Gupta et al. [79], which appears to be capable of generating power at a scale of watts and voltages on a scale of volts from a diverse range of environmental energy sources.

The contact resistance of liquid metal with electrodes is also a factor that may affect the performance of conductive LMMHD generators, although procedures can be implemented to reduce it and improve electrical contact [117]. Problems arising from the existence of electrodes are avoided in MHD induction generators, where the transfer of energy from the conducting fluid to the armature is carried out by magnetic induction with no electrodes. However, for energy transfer to occur efficiently, sufficiently high frequencies are necessary [10], which can be an obstacle for wave energy applications from ocean sources. Nevertheless, as discussed in Section 5, LMMHD induction generators can be a suitable option to couple with thermoacoustic devices [22,51,53,56].

Marine applications obviously require the proper choice of materials that can withstand harsh environmental conditions. Fortunately, this is an aspect that has long been considered for the development of different ocean engineering applications, and the technical knowledge is available [118,119].

9. Final Comments

Since their appearance one hundred years ago, MHD generators have undergone a significant evolution, moving from large-scale devices, which are designed to convert thermal energy into electricity using high-temperature plasma, to smaller, more versatile, systems capable of harnessing renewable energy sources. The use of liquid metals in one- or two-phase flows allows the MHD energy conversion process to be performed at temperature ranges suitable for low-temperature sources such as solar and waste heat, which enhances their adaptability and efficiency and broadens the scope of potential applications. The effort initiated in the late 1980s to develop MHD generators, coupled to thermoacoustic engines, has recently been renewed with either conductive or inductive generators and aims at ambitious goals such as supplying energy for space missions. Also, the transformation of environmental energy into electrical energy (energy scavenging) provides an interesting opportunity for developing MHD generation in an area of increasing importance.

In recent years, the emerging role of MHD generators in converting ocean energy, such as waves and tides, into electrical energy has been more intensively explored. In fact, LMMHD generators offer an option worth exploring for harnessing marine renewable energy, and they present a promising opportunity to integrate MHD technology into the expanding ocean energy generation sector, with the potential to contribute to a more sustainable and diversified energy grid.

MHD generation faces a number of challenges, including optimizing efficiency in energy conversion, improving the scalability of the technology, and, in the case of ocean applications, addressing the technical difficulties of operating in marine environments. Overcoming these challenges requires continued research and development to determine if MHD generators could play a pivotal role in the future of renewable energy production. Overall, MHD energy conversion technology holds great promise, but further developments are needed to fully realize its potential, especially in harnessing renewable energy and environmental sources.

Author Contributions: Conceptualization, J.C.D.-L., D.R.D.-L., S.C. and R.A.Á.-Z.; methodology, J.C.D.-L., D.R.D.-L., S.C. and R.A.Á.-Z.; validation, J.C.D.-L., D.R.D.-L., S.C. and R.A.Á.-Z.; formal analysis, J.C.D.-L. and S.C.; investigation, J.C.D.-L., D.R.D.-L., S.C. and R.A.Á.-Z.; resources, S.C.; writing—original draft preparation, J.C.D.-L., D.R.D.-L., S.C. and R.A.Á.-Z.; writing—review and editing, S.C.; supervision, J.C.D.-L., D.R.D.-L., S.C. and R.A.Á.-Z.; project administration, S.C. and R.A.Á.-Z.; funding acquisition, S.C. and R.A.Á.-Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Centro Mexicano de Innovación en Energía Océano, CEMIE Océano SENER-CONACYT, grant number 249795. D.R.D.-L. thanks a posdoctoral grant from CONAHCYT.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest. The sponsors had no role in the design, execution, interpretation, or writing of the study.

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