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Review

Wireless Power Transfer for Unmanned Underwater Vehicles: Technologies, Challenges and Applications

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Abstract: Unmanned underwater vehicles (UUVs) are key technologies to conduct preventive inspection and maintenance tasks in offshore renewable energy plants. Making such vehicles autonomous would lead to benefits such as improved availability, cost reduction and carbon emission minimization. However, some technological aspects, including the powering of these devices, remain with a long way to go. In this context, underwater wireless power transfer (UWPT) solutions have potential to overcome UUV powering drawbacks. Considering the relevance of this topic for offshore renewable plants, this work aims to provide a comprehensive summary of the state of the art regarding UPWT technologies. A technology intelligence study is conducted by means of a bibliographical survey. Regarding underwater wireless power transfer, the main methods are reviewed, and it is concluded that inductive wireless power transfer (IWPT) technologies have the most potential. These inductive systems are described, and their challenges in underwater environments are presented. A review of the underwater IWPT experiments and applications is conducted, and innovative solutions are listed. Achieving efficient and reliable UWPT technologies is not trivial, but significant progress is identified. Generally, the latest solutions exhibit efficiencies between 88% and 93% in laboratory settings, with power ratings reaching up to 1–3 kW. Based on the assessment, a power transfer within the range of 1 kW appears to be feasible and may be sufficient to operate small UUVs. However, work-class UUVs require at least a tenfold power increase. Thus, although UPWT has advanced significantly, further research is required to industrially establish these technologies.

Keywords: autonomous underwater vehicles; inductive wireless power transfer; underwater docking stations; underwater wireless power transfer; unmanned underwater vehicles

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1. Introduction

According to the latest data available from the International Energy Agency (IEA), the electricity generation from marine sources increased by 400 GWh (+33%) between 2019 and 2020 [1]. However, these technologies need to be implemented much faster in order to achieve Net Zero emissions by the 2050 scenario [2]. Among them, offshore wind turbines (OWT) are the most mature technology, with many power plants commercially deployed around the world [3–5], while other technologies based on tidal, current or wave energy are promisingly being studied and tested [6–8].

All these marine technologies operate in extremely harsh conditions. In particular, they suffer from corrosion issues generated by salt water. For example, a number of critical elements such as blades, gearboxes, generators, power electronics and towers' mechanical structures are affected by corrosion in OWTs, especially their fixed or floating underwater foundations [9]. Thus, a number of maintenance actions (preventive and corrective) need to be constantly carried out for all the critical elements that make up OWTs [9]. Offshore renewable energy platforms require research in innovative solutions to improve their operation and maintenance to make them cost-effective [10].

Unmanned underwater vehicles (UUVs) such as remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) are very important tools for the visual inspection and maintenance of such offshore infrastructures. UUVs are starting to be broadly deployed in the ocean. They have potential in the operation and maintenance of marine energy plants [11,12] and also in other applications such as marine data collection [13,14], ocean observation [15–17] or aquaculture [18,19]. In general, maneuverability is a key requirement for underwater inspection tasks, and the utilization of drones with multiple propeller configurations, similar to aerial drones, is preferred [20–22]. In contrast, gliders are generally preferred for collecting data over large oceanic areas [23–25].

At the moment, mainly ROV technologies are used for underwater inspection. However, the utilization of AUV platforms is starting to be considered by the maritime industry for a number of reasons [9,26–28]:

(a) ROVs need to be operated on site. Usually, the distances between offshore wind parks and the nearest ports are significantly long. The time required for technicians to reach a given offshore park can be significant.
(b) Many times, the extreme marine weather makes it difficult for the technicians to reach offshore parks.
(c) The on site operation of ROVs is expensive, especially considering the ships and personnel involved.
(d) Operating in offshore power plants can be dangerous for technicians. According to the recent data provided in the scientific literature, work accidents are common in such marine environments. For instance, in year 2019, 865 work accidents were reported in offshore wind farms worldwide.

Due to the future widespread adoption of autonomous solutions, the time frame that technicians will need to expend in offshore parks can be significantly minimized, with all of its associated benefits. In addition to minimizing the aforementioned issues, greenhouse gas emissions can also be reduced, as the number of boat trips is minimized [28]. The first industrial example of an OWT park inspected by AUVs, which was implemented in 2022, can be found in the north coast of the United Kingdom [28].

Although this kind of technology (both remotely operated or autonomous) is very promising for marine infrastructure maintenance duties, there is still a long way to go regarding some technological aspects. For example, and in particular, electrical powering for UUVs is generally delivered via two main techniques:

1. Direct connection to a land-based or ship-based electrical energy source (grid, ship electrical system, batteries, etc.) using submarine cables (tethered systems).
2. Providing UUVs with their own batteries, which must be extracted for recharging.

Both types of powering limit the operative range and operational time of UUVs. Additionally, they require continuous supervision, leading to the aforementioned drawbacks generated when deploying technicians offshore. Thus, UUVs would benefit from the availability of underwater charging, which would increase their autonomy, both in range and in time. There is potential for underwater wireless power transfer (UWPT) to assist in achieving this goal and reduce the drawbacks and costs of UUV operation. This can create new market niches around UWPT technologies, from which marine energy infrastructures can benefit. Considering the potential relevance of charging technologies for future marine-based renewable systems, this article focuses on the state of the art in UWPT.

This manuscript is organized as follows. Section 2 introduces the standard methods for delivering power to UUVs. In Section 3, the main research areas for delivering wireless power to UUVs are described. Section 4 introduces a more detailed insight into inductive wireless power transfer (IWPT) methods, which seem to be the more promising and ready technologies for underwater charging. In Section 5, a comprehensive review of the main IWPT experiments and applications available in the literature is conducted. Section 6 summarizes the main conclusions of the study. Finally, Appendix A describes the study conducted to characterize the main technologies used for UWPT, the existing patents and the corpus of the bibliography used for the study.

2. Conventional UUV Powering Methods

Several methods for powering underwater devices are mentioned in the literature, mainly for powering ROVs and AUVs. Traditional methods such as battery swapping or direct connection using tethers are most commonly used. However, as advanced at the introduction of the manuscript, tethered systems limit the operational range of UUVs, and battery swapping is very time consuming and has very high operational costs [29]. In addition, both systems require a surface vessel, which has very high operational costs.

In recent years, other approaches have been considered, such as the use of devices powered by renewable energies and wireless power transfer in submerged dock facilities, which could reduce the previous shortcomings. These would enable the deployment of low cost AUVs, which would considerably reduce overall operation costs.

2.1. Battery Swapping

Battery swapping is one of the most common methods to supply power to UUVs. By this method, the device is resurfaced and the battery is retired for charging or directly replaced. Each operation is time-consuming and requires a vessel and manpower [30]. Additionally, during the installation and maintenance of OWTs, the vessels emit approximately 28% of the total greenhouse gas and produce significant amounts of pollutants [31].

Some efforts are being carried to try to reduce these drawbacks, such as changing the fuel used by vessels to reduce their emissions [31] or reducing mission duration with innovative battery swapping methods with modular batteries [32]. However, other options may avoid these issues.

2.2. Tether Management Systems

Tether management systems (TMS) are generally used to operate ROVs [33]. In TMS, umbilicals are used to connect the ROV to a control unit, which usually is placed on a vessel. The cable generally provides transmission of bidirectional data in real time and energy to the vehicle and allows the vehicle to be maneuvered in a controlled manner [34]. However, in deep-water applications, the operation is more complex, and tethered systems are very costly [35].

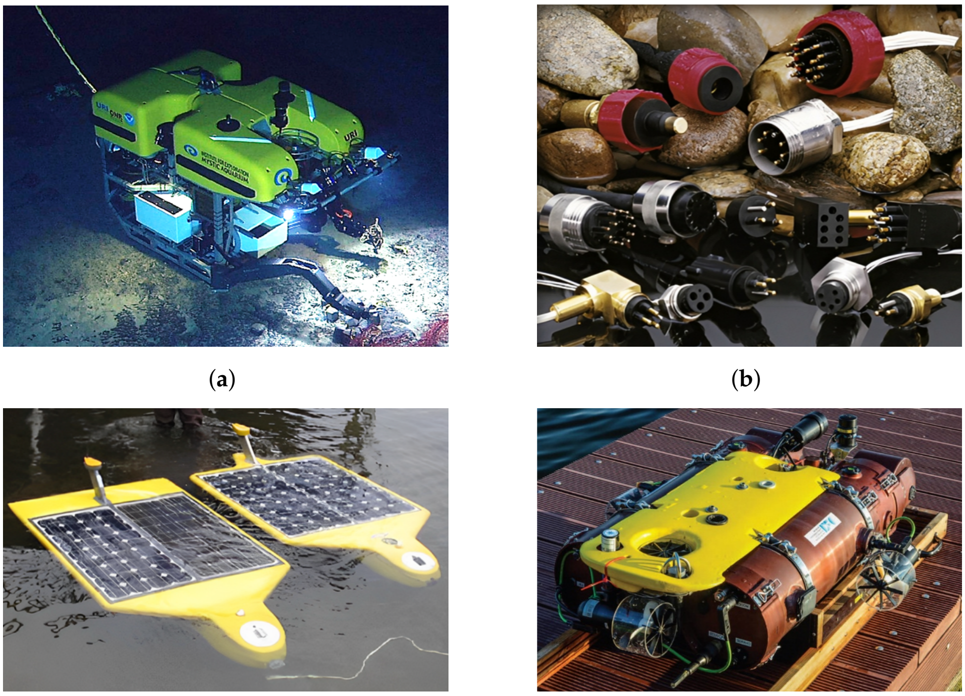
Similar to battery swapping, TMS require a vessel or a sea platform to connect the umbilical and skilled personnel to control the operation of the ROV. To increase the autonomy of these systems, self-managed umbilicals [34] have been recently proposed. Additionally, replacing the vessel with an autonomous surface vehicle connected to the tethered ROV is another interesting proposal [36]. Figure 1a shows an example of the Hercules ROV working while connected to an umbilical cable.

2.3. Renewable Energy Powered UUVs

Renewable energy sources can be harnessed to provide energy to UUVs, thereby increasing their available operational time. The main proposal, which mainly applies to underwater vehicles and buoys, is the use of solar energy. Solar panels are installed in the devices, which have to surface during daytime to harvest and store energy in their batteries [37].

An example of a solar AUV prototype developed by The Autonomous Undersea Systems Institute AUSI, Falmouth Scientific Inc. (FSI), is the SAUV-II (Figure 1c). It is designed for long-term missions that require monitoring, surveillance or station maintenance [38]. The maximum power of the device is 170 W, and the energy is stored in a lithium battery. It can submerge for up to 12 h and reaches a maximum depth of 500 m [39].

Wave energy systems integrated in AUV devices are also a feasible alternative that could allow autonomous operation in some geographic regions that present suitable wave characteristics [40]. In addition to this, other sources such as thermal and salinity gradients have been recently proposed but are still in a very early stage and generate a very limited amount of energy [41].



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

(**c**) (**d**)

Figure 1. Conventional UUV powering methods. (**a**) Hercules tethered ROV [42]. (**b**) Examples of underwater connectors [43]. (**c**) Solar-powered AUV II (SAUV-II) [44]. (**d**) DAGON hoovering AUV [45].

2.4. Wet-Mate Connectors

Underwater wet-mate connectors (example in Figure 1b) are also used to transfer power to UUVs at underwater docking stations. These connectors are a reliable and efficient method for transferring power to UUVs, and are more established than UWPT. However, these are complex to manufacture and operate, leading to higher costs and maintenance requirements [46], and are susceptible to corrosion [47].

An early example of docking stations that utilize these type of connectors is the Eurodocker docking platform [48]. This station was designed as a funnel-type garage, also providing protection to the AUV, charging the device through wet-mate connectors. A similar concept was developed and tested for the REMUS-100 AUV [49]. The dock was designed to operate with external power or from batteries to charge the AUV through underwater electrical wet-mate connectors. Some successful docking runs were conducted in 2005, with docking connections followed by battery recharges. More recently, the Dagon hovering AUV prototype (Figure 1d) was tested in Germany [50]. In this case, the AUV performed a step-by-step alignment with the docking platform with the help of V-shaped guiding structures. The energy transfer was conducted through an underwater-pluggable connector with a power of 210 W.

3. Underwater Wireless Power Transfer

Securely mating wet-mate connectors is challenging and requires high precision [37]. As an alternative, several wireless power transfer methods have been proposed. One of the earliest underwater "contact-less" experiments that can be found in the literature is presented by Kojiya et al. [51]. The proposed system used electromagnetic induction to transfer power wirelessly to safely charge the AUV. These methods can be classified in the following categories:

(i) Far-field methods: Radio frequency waves, optical link and ultrasonic waves.
(ii) Near-field methods: through-wall acoustic waves, capacitive and inductive wireless power transfer.

All these aforementioned alternatives have a transmitter device (Tx) and a receiver (Rx), and they use different methods to transfer power. This section reviews the main methods found in the bibliographical survey (Figure 2).

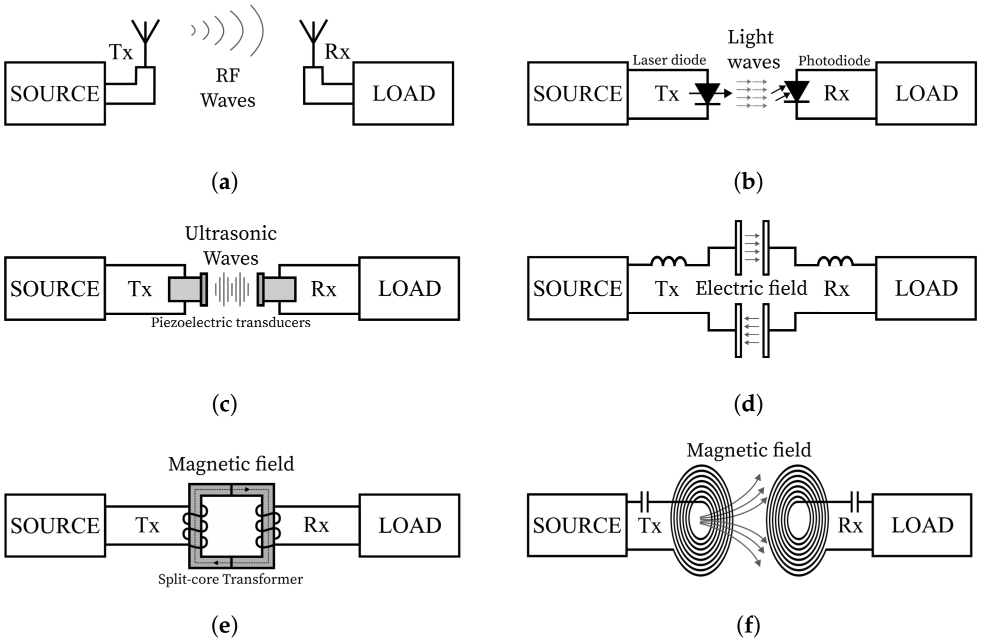


Figure 2. Main wireless power transfer methods [52]. (**a**) Radio-frequency waves. (**b**) Optical link. (**c**) Ultrasonic waves. (**d**) Capacitive. (**e**) Tightly coupled inductive. (**f**) Loosely coupled inductive.

3.1. Radio Frequency Waves

Although radio frequency waves are the most common way to transmit data by air and they have been proposed for contactless long distance power transfer, this is generally not suitable as a charging method. The emitting and receiving antennas operate by the interaction of electromagnetic induction, which is determined by Maxwell's equations [52]. In deep-sea water, radio frequency data communication may have some advantages compared to optical or acoustic transmission, according to [53]. Nonetheless, it is not applicable to submarine electrical power transfer due to an increased attenuation of electromagnetic (EM) waves in seawater. Methods that utilize near-field EM waves are far more suitable.

3.2. Optical Link

Optical links use light to transfer energy between transmitters and receivers. Receivers are light sensitive devices such as solar cells, photo-diodes, or photovoltaic converters, and emitters can be sun or laser powered diodes [52]. These can operate devices and recharge batteries via laser diodes or power remote systems [54]. However, their application is mostly for low power systems that are far from the transmitter. Several applications of this power transfer scheme are reviewed in [55].

Regarding underwater optical link transmission, very few experiments can be found in the literature [56–58]. All of these could achieve power transfers in the mW range, with a power transfer efficiency below 20% for distances over 1 m. Regarding data transfer, in [57], the authors achieved data rates up to 60 Mbps at the receiver side, at a distance of 2.3 m from the emitter. Thus, optical links are not suitable for contactless charging in AUVs due to the low power ratings. However, auxiliary applications such as docking positioning or data transfer could be feasible with this technology.

3.3. Ultrasonic and "Through-Metal Wall" Waves

Acoustic or ultrasonic wireless power transfer technologies use ultrasonic waves that exceed the human hearing limit of 20 kHz to transfer power [52]. It is considered safe, as it uses sound as a propagation medium, making it a suitable option in medical applications. It has been used for low-power data transmission, remote sensing and navigation systems and biomedical implants [59]. A summary of the state of the art for this power transfer method, including data until 2016, can be found in Awal et al. [60].

Regarding underwater applications, very few examples exist in the literature [61–64]. Similarly to optical links, these systems work in the mW range with very low efficiency. For example, in [64] authors tested an experimental prototype applied to the underwater internet of things that had a power transfer efficiency of 4% to 10% for 0.1 W to 1.4 W and 1 m distance. Another experiment yielded results of 20% efficiency at a distance of 10 cm using a modified transducer [63]. These power levels are not enough to charge UUVs.

An alternative that could be suitable for this application is the "through-metal wall" power transfer. It is a near-field application of ultrasonic waves that uses piezoelectric transducers attached to two metal surfaces that are in contact to transfer and receive ultrasonic waves and convert them to electric power [65]. It can be used to transfer power through metal walls such as vehicle armors or sensors within metallic enclosures [66,67]. Most of the applications are in the mW range, as reviewed by Awal et al. [60] and presented in later works such as [68]. However, power transfers in the 1 W range have also been achieved in some studies.

A remarkable example of this technology was presented in 2008 by Sherrit et al. [69] from NASA's Jet Propulsion Laboratory. They designed a 1 kW device that could transfer power with 88% efficiency through a 3.4 mm thick metal wall. Another promising application was also proposed in [70]. The authors were able to simultaneous transfer data and power at 17.37 Mbps and 50 W, respectively, with a power transfer efficiency of 51% through a thicker steel wall of 63.5 mm. Nevertheless, experiments in a seawater environment are required to validate these results.

3.4. Capacitive Wireless Power Transfer

In capacitive wireless power transfer (CWPT), power is transmitted by using a time-varying electric field, using metallic plates on the transmitters and with the receivers working as the two parallel plates of a capacitor. The transfer distance of this system is low and allows the transfer through isolated metal objects.

CWPT has been applied for low-power data transmission in applications such as biomedical implants [71], robots [72] or USB charging [73], among others [74,75]. Higher power applications such as railway applications [76] and the powering of electrical vehicles [77,78] are being recently studied. In the context of railway applications, a 3 kW power transfer system prototype was tested at a distance of 40 mm, yielding an efficiency of 92.5% [76]. The recent designs of large-gap CPT systems intended for EV charging applications are summarized in [79], with distances ranging from 17 mm to 170 mm, power ratings between 0.1 kW and 2.6 kW and efficiencies ranging from 70% up to 92%.

In the field of underwater energy transfer, some CWPT models and prototypes have already been tested in academic studies [80–93]. In most of these works, CWPT systems achieved a power transfer efficiency beneath 70% in seawater environments. However, there are some recent works where this value could be surpassed.

In 2018, Ref. [84] proposed a design method for capacitive couples for fresh water operation. After modeling the system, they constructed a prototype and achieved a power transfer of 400 W with an efficiency of 91.3% for 50 MHz at a transfer distance of 20 mm. Authors also carried out tests for other gaps and frequency values, achieving an efficiency of 80.77% for a 50 mm gap and the same power and frequency values. However, all these tests were conducted in fresh water, and the efficiency in ionized sea water should be tested.

Other works by Tamura et al. [87] present efficiency values up to 91.1% underwater for a CWPT coupler utilizing an electric double layer. By applying this model, they later built a system that could maintain a maximum efficiency of 79% in a seawater environment at 2 MHz [90].

More recently, in a paper by Mahdi et al. [92], authors studied the maximum power capability of a CWPT system by using network theory to then experimentally test it with a prototype in seawater. They were able to achieve an efficiency of 83% for a 100 mm gap and 300 kHz. When the frequency was increased from 300 kHz to 1 MHz, and the separation distance was changed from 100 mm to 300 mm, the power transfer and efficiency decreased.

It is important to remark that CWPT prototypes tested within UUV devices have not been found in the literature. Thus, further research is required to validate its feasibility.

3.5. Inductive Wireless Power Transfer

Inductive wireless power transfer is based on the wireless transfer of power between two coupled coils using a time-varying magnetic field [94]. Depending on the coupling coefficient k between the coils, the system can be loosely or tightly coupled [52]. The system can operate in resonance to achieve higher efficiency. When the distance between coils is constant, the system is considered static, while, if the distance changes, it is considered a dynamic system [95]. IWPT is currently used in consumer electronics, biomedical equipment and vehicle charging. Static IWPT applied to consumer electronics is already a mature technology with commercial standards such as the Alliance for Wireless Power (A4WP) standard, the Qi standard from the Wireless Power Consortium (WPC) and the Power Matter Alliance (PMA) standard [96,97]. The research is underway to improve standardized charging systems [98,99] and design universal charging systems [97,100,101].

In biomedical micro-systems, this technology has been used in endoscopic capsules [102], pacemakers [103], biomedical implants [104] and brain–machine interfaces, among others [105–107]. WPT allows the traditional use of percutaneous cables and implantable batteries to be replaced by rechargeable batteries, reducing the need for surgery and improving system features [105].

For electric vehicles, IWPT is promisingly being studied [108,109], and few commercial products already exist [110]. Two main charging systems are the dominant: the static wireless electric vehicle charging system (S-WEVCS) [111] and the dynamic electric vehicle charging system (D-WEVCS) [112,113]. While static systems function only when the vehicle is stopped and the charger is correctly aligned, dynamic systems are based on a driving path with several coils and a receiver coil in the vehicle [108,114]. In the electric vehicle IWPT charging sector, interoperability and standardization have recently gained significant importance. Standards such as SAE-J2954 [115] have already been published, and certain magnetic couplers have the potential to allow interoperability [116,117]. However, further research is needed in the field of interoperable IWPT systems.

Regarding near-shore applications, IWPT systems have already been tested to be suitable for ship charging. For instance, in [118], the authors were able to conduct laboratory tests with a power transfer of approximately 1 MW for a ship charging application, with its subsequent installation on the Norwegian ferry MS Folgefonn. In the marine environment, many inductive charger prototypes have been tested for underwater recharging of AUVs [119–129] and underwater sensors [130–137]. These charging devices are generally installed in sub-sea docking stations. A sub-sea docking station is a platform that allows underwater power and data transfer for UUVs. It can be directly supported at the seabed, from a ship, or from a buoyed mooring system, or even use their own renewable energy generation.

Apart from transferring power through underwater wet-mate connectors, modern docking stations usually transfer power through wireless power systems, which need to be able to hold the device firmly. These platforms generally have a "landing-type" structure (Figure 3a) or a "funnel-type" structure (Figure 3b). When used for AUV recharging, docking platforms and devices require navigation systems for homing [37] and can use different methods for docking, such as capture, platform or dynamic docking [47].

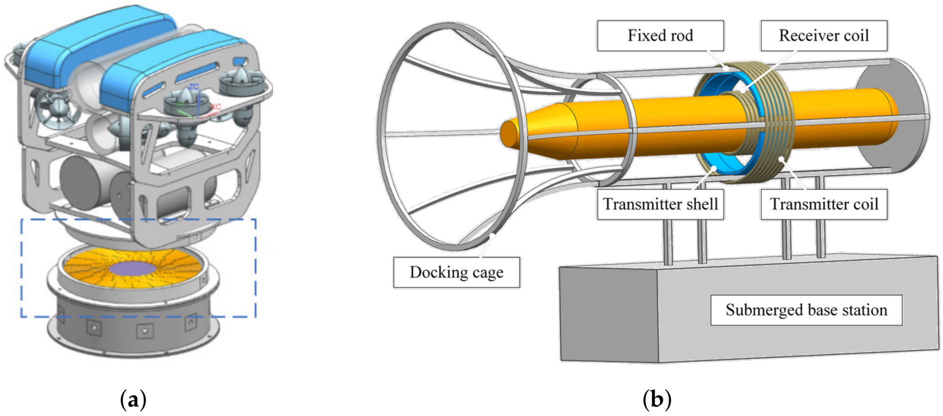


Figure 3. Main UUV docking stations. (**a**) Landing-type UWPT station [138]. (**b**) Funnel-type UWPT station [139].

4. Underwater IWPT Technology

As IWPT seems to be the most promising technology for UUV underwater contactless charging, a introductory chapter on this topic is herein presented.

4.1. IWPT System Components

Underwater IWPT systems are generally divided into two separated devices: the docking station and the UUV. The docking station contains the charger, which is formed by the power source, the input power converter, the transmitter resonant tank and the primary side of the coil. On the other side, the UUV contains the secondary coil, the receiver resonant tank, the output power converter and the battery. The block diagram of a two-coil IWPT is depicted in Figure 4. In the following, key aspects about the constituting elements are provided:

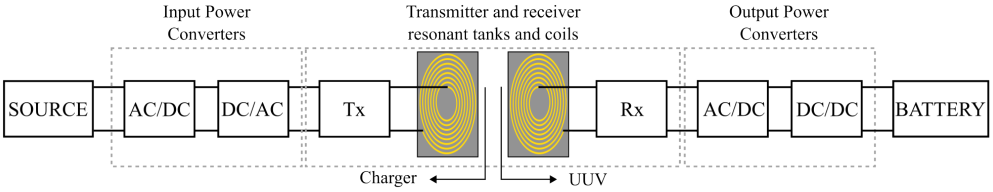


Figure 4. Block diagram of a two-coil IWPT system.

(a) **Input power converters.** Their function is to generate a high frequency AC waveform from the available power source. Depending on the source, power is supplied by an AC/DC or a DC/DC converter to a main DC bus. A full bridge single phase inverter to convert the DC voltage into a high frequency square wave AC voltage waveform is the most extended option [105].

(b) **Transmitter and receiver resonant tanks and coils.** This is the main topic of research and development for IWPT systems. The compensation is essential to cause the coil to resonate at the desired frequency. This is accomplished using different resonant tanks. In order to maximize the efficiency and power capacity of the IWPT system, different coupling structures can be used between the power source and the power receiver or load. The resonant compensation topologies in IWPT can be classified according to the number of compensating capacitors and inductors, their configuration and the type of sources [140]. Generally, four main topologies are used, which, regarding compensating capacitors in the primary and secondary, are series–series (S-S), series–parallel (S-P), parallel–parallel (P-P) and parallel–series (P-S). More complex topologies based on LCC resonant converters such as LCC-S [141,142], LCC-P [143,144], LCC-LCC [145–147] or multi-resonance circuits [147,148] have also been tested in the literature. Using non-resonant (N) IWPT is also possible for low distance and low power transfer with similar efficiency [149]. However, if the transmitting distance and power are increased, resonant IWPT is recommended for optimal power transfer. Thus, resonant IWPT is selected over non-resonant for most applications, including UWPT. The coils consist of various components, usually including copper wire and magnetic cores. These are based on the idea of transformers but with the core split into two parts. These cores are used to shape the path of the magnetic flux and increase inductance, improving the coupling between coils. Metal shields can also be added to reduce electromagnetic interferences and high-frequency magnetic fields [52], which are a source of losses.

(c) **Output power converters.** The function of output converters is to receive and provide stable power to the load or battery. They also can provide feedback information to the transmitter for power regulation according to the load. These are composed of a tuning circuit, power converters and a control unit. The rectifier is the main component in the Rx unit and determines its efficiency. In the output, by connecting batteries or loads to DC/DC converters, stable and regulated power can be provided [105].

(d) **Controller units.** IWPT requires controller units to adjust the output voltage or current in response to load variations during battery charging to maintain efficiency. In electric vehicle charging, three main approaches are employed to manage these variations: transmitter control, receiver control and dual control [108]. Transmitter control and dual control require feedback between the Tx and Rx side, while receiver control utilizes active AC/DC and DC/DC converters to regulate the device from the receiver side. Generally, transmitter control is a more robust option, involving adjustment of the inverter frequency based on feedback from the output. However, in seawater, data sharing between the receiver and transmitter may present challenges, and receiver control or other alternatives may be more suitable [29]. This enables closed-loop control.

4.2. Challenges in Underwater Environments

IWPT has the same structure in water as it has in air. However, it presents some challenges, which are reviewed in this subsection.

4.2.1. Attenuation of Magnetic Fields

The resistance of a coil is the sum of its DC (R_{DC}), AC (R_{AC}) and radiation resistances (R_{RAD}). R_{DC} and R_{AC} depends on its configuration, type of wire and topology. Radiation resistance depends on the permeability and conductivity of the medium and the working frequency of the coils [150]. In air, losses are generally dominated by AC, while R_{RAD} is negligible. However, as seawater is conductive (3–6 S/m), it has to be taken into account.

Several studies have already demonstrated that the radiating losses increase when the operating frequency is increased [151–155], as shown in Figure 5 from [153]. Niu et al. [156], Yan et al. [157] and Zhang et al. [158] also demonstrated that the optimal operating frequency needs to be higher than the resonant one, as seawater causes a detune, and the phenomena of frequency splitting has to be taken into account. Furthermore, as the gap between coils increases, radiation losses also increase, causing an attenuation in the transferred power [29,159].

In addition to radiation losses, eddy current losses (ECL) are a type of AC losses that also depend on conductivity and frequency due to the conductive environment [160]. Eddy currents are loops of induced current that are generated in the surroundings of a conductor, in this case the coils, due to the application of a changing magnetic field. Finding the effect of these losses for different topologies on the system is an important research topic [161–164].

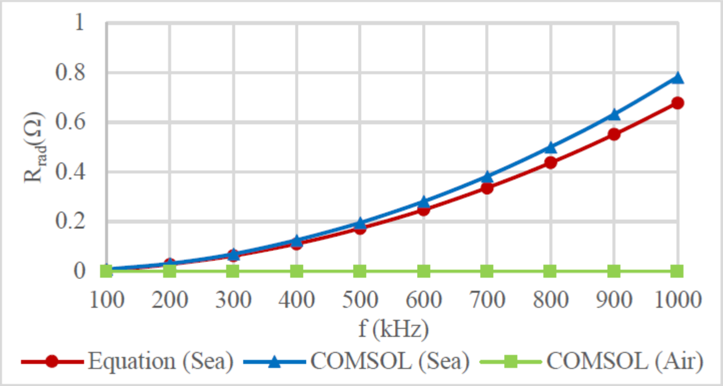


Figure 5. Radiation resistance against frequency, value from equation and from FEM model [153].

As both ECL and radiation losses cause magnetic flux leakage, some possible solutions are being studied to reduce their effects. Using high-permeability materials such as Mn–Zn ferrite as the cores of the coils is the most common approach for frequencies over 100 kHz. However, for frequencies below this value, coreless systems have also been proposed, as AC losses are more prominent than radiation losses, and there is not much difference between seawater and air [153,159]. Higher frequencies allow the construction of more compact devices but increase ECL and R_{RAD}. Therefore, a compromise between compactness and efficiency has to be found in the design of these devices.

4.2.2. Sea Currents and Misalignment

Sea currents are also of significant importance in IWPT losses, as they may cause a misalignment between the transmitter and receiver. When misalignment occur between the coils, coupling is reduced and ECL increase, causing a reduction in efficiency. Several studies have attempted to evaluate these losses [165–167], while others have designed coil topologies that try to address this issue [168–172]. Another possible solution is to achieve this alignment with a mechanical device [143].

The seawater environment makes it difficult to transmit data between Tx and Rx modules due to the attenuation of waves [29]. Therefore, control methods, such as receiver control, that do not require communication between the transmitter and the receiver are highly recommended. In addition to this, its dynamic characteristics cause a variation on the coupling factor Maguer et al. [126]. To solve this problem, control methods based on maximum efficiency tracking have been proposed in the literature [173–175].

4.2.3. Temperature and Biofouling

Regarding temperature, seawater acts as a cooling medium and can increase the thermal limits of coils [176]. However, as temperature dissipates in the coils, a thermal gradient with the environment near the coils can increase marine microbial growth in the coils, causing a phenomena called biofouling.

Biofouling is defined as the accumulation of biotic deposits on a submerged artificial surface [177]. Devices that need to be deployed underwater for a long period of time should consider this issue as it increases the misalignment and gap between coils, which reduces their transfer efficiency [178]. In [178], the authors proposed the use of anti-fouling paint and thermal coating to reduce biofouling. This paper is reviewed with more details in Section 5.4.

4.2.4. High Pressure and Permeability

High pressure in seawater is also an issue for UWPT. As we go deeper in the ocean, pressure is increased approximately by 0.1 MPa per 10 m. Thus, all the equipment needs to be able to stand high pressures, especially in deep sea applications. For a sea depth over a thousand meters, power electronics converters have to be appropriately enclosed with incompressible insulating liquids as a medium [179]. Permeability reduction is also a proven effect of high-pressure environments in ferrite cores. In [180], the authors evaluated permeability as a function of the hydrostatic pressure and presented equations that describe this relation. This reduced permeability leads to a reduction in the magnetic flux shielding, exposing the system to radiation losses.

To evaluate the extension of these losses in IWPT, Li et al. [165] tested a small prototype in a simulated deep water environment of 4000 m by using pressurized salt water. For a frequency of 94.3 kHz and a power transfer of 400 W, efficiency only dropped 2%. This suggests that for low frequency and power values, permeability is not compromised. Another related work is the one by [181], where the authors designed a housing for a wireless charger implemented in an AUV to reduce the effects of the harsh environment and successfully tested it in a hyperbaric chamber at 30 bar (300 m). Their WPT system could reach an efficiency of 75% inside the housing device.

4.2.5. Other Technical Issues

The effects of electromagnetic field emission is an aspect that has not been extensively studied underwater [182]. If the electromagnetic field is contained within the charger and the vehicle and only operates when the vehicle is stationary, it should not pose significant issues for the surrounding marine life. However, its emission could potentially cause interferences in their behavior [182,183]. Regarding its effects in electromagnetic or electronic equipment within the AUV, shielding in AUVs presents a straightforward solution to reduce it [184,185].

Another prevalent topic is interoperability and standardization. These are more challenging for UWPT devices compared to other devices or electric vehicles. This is due to the fact that each application may require a vastly different AUV with varying power ratings, geometries or application ranges. However, for a certain range of applications, it may be possible to design interoperable and standardized devices. Nonetheless, it is a topic that has not been yet addressed in the literature.

5. Review of Underwater IWPT Experiments and Applications

In recent years, the interest in underwater IWPT has increased. Several models and prototypes have been tested. Many are focused on improving efficiency and functionality and reducing the adverse effects of seawater. Some of the main research lines that can be found are related to coupler topologies, compensation schemes, control systems, materials and integration in AUVs and other devices.

5.1. IWPT Prototypes in UUVs and Docking Stations

As previously presented in Section 3.5, IWPT has already been tested for UUV charging in several prototypes. All the IWPT prototypes found in the bibliographical study and other available papers are briefly explained in this subsection. Then, a summary is presented in Table 1, where the power transfer and efficiency of the reviewed AUV charging prototypes are compared.

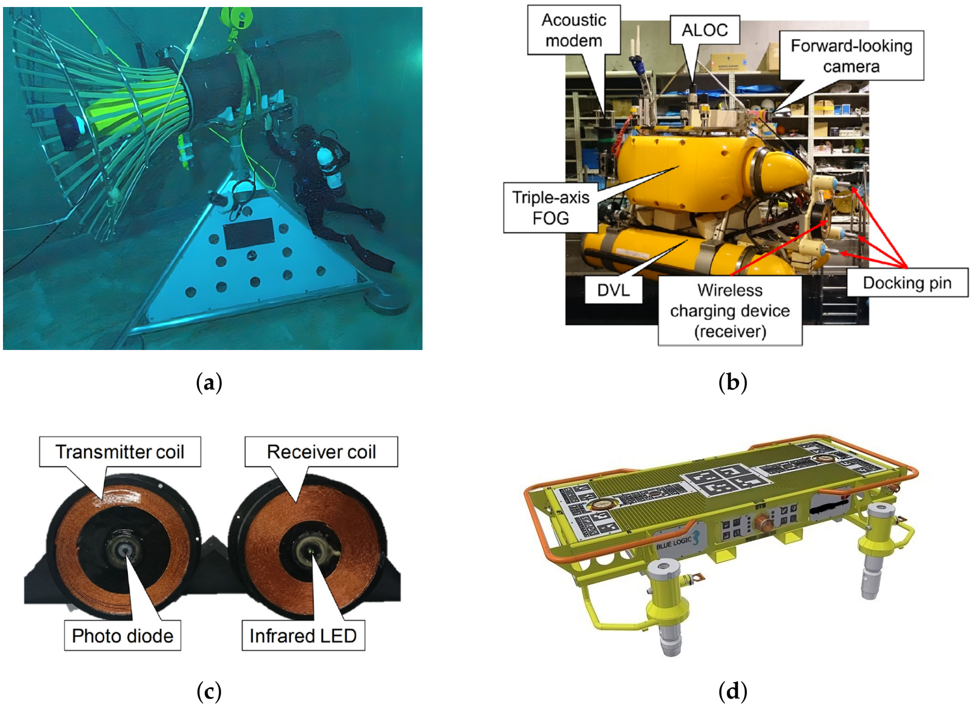
One of the earliest prototypes of a docking platform found for AUV charging is the homing/docking system for the MIT Sea Grant Program Odyssey AUV [119], which was a "funnel-type" docking station. Another early stage WPT-based docking platform was presented in [120]. It was developed for Marine Bird AUV in Japan and had an underwater docking system based on their "landing-on-Base" concept, where the vehicle was caught by robotic arms and latched to wireless connectors at the docking platform.

In 2007, McGinnis et al. [121] designed an IWPT prototype for the ALOHA-MARS mooring system, a deep-ocean sensor network connected to a sea-floor observatory. They installed it to charge their mooring profiler vehicle, the McLane mooring profiler (MMP). The coupler was loosely coupled and had a ferrite core. The system could transfer power of 250 W with a maximum efficiency of 70% for a 2 mm gap. After an experimental phase, the system was successfully deployed in the ALOHA-MARS mooring system in Puget Sound (USA), in June 2007 and for two months.

Table 1. Comparison of IWPT prototypes tested in AUVs.

Authors	Year	Coupling	P_{out} (W)	η (%)	f_r (kHz)	Gap (mm)
Feezor et al. [119]	1997	Funnel-type	N/A	N/A	N/A	N/A
Fukasawa et al. [120]	2003	Landing-type	N/A	N/A	N/A	N/A
McGinnis et al. [121]	2007	Loosely coupled	250	70	N/A	2
Hobson et al. [122]	2007	Funnel-type	1000	88	N/A	N/A
Pyle et al. [123]	2012	Mothership	450	N/A	N/A	N/A
Yoshida et al. [124]	2016	Funnel-type	1000	75	80-90	70
Yoshida et al. [125]	2016	Landing-type	25	65	200	100
Maguer et al. [126]	2018	Funnel-type	500	90	N/A	N/A
Matsuda et al. [127]	2019	Landing-type	188	70	N/A	N/A
Yang et al. [129]	2020	Funnel-type	680	90	35	N/A

The same year, Hobson et al. [122] developed a docking station for a 54 cm diameter Bluefin AUV. Their system was designed to withstand a 4000 m depth seawater environment. The proposed dock had a funnel-type conic design, as shown in Figure 6a. According to the researchers, the inductive charger was theoretically able to transfer 1 kW while maintaining an efficiency of 88%. However, after conducting some docking trials at the Monterey Inner Shelf Observatory (MISO), they were able to transfer 416 W at a global efficiency of 48%.



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

(**c**) (**d**)

Figure 6. AUV and docking station prototypes using IWPT. (**a**) Docking station for Bluefin AUV [122]. (**b**) Tri-TON 2 (TT2) AUV and its parts [127]. (**c**) IWPT coils in Tri-TON 2 AUV [127]. (**d**) Blue Logic SDS 3D model [186].

Pyle et al. [123] described, in 2012, the potential use of a larger underwater vehicle as a "mothership". The Battelle-Bluefin Robotics UUV Docking and Recharging Station (UDRS) project developed and tested a concept for a UUV docking station. The UDRS features inductive charging and wireless data transfer in a wet environment to reduce replenishment time and simplify operational employment. They achieved an inductive power transfer in seawater with a power of 450 W.

In 2016, Yoshida et al. [124] proposed an IWPT system for non-fixed and compact UUV charging in the ocean. They built an IWPT system in an UUV with a spiral planar coil. The size of the Tx coil was of 24 cm × 24 cm × 1.5 cm. They tested it in seawater in a floating charging station. They controlled the UUV to reach the floating station, where it transferred 25 W with an efficiency of 65% and a 10 cm gap. In [125], the authors conceptualized a long-term underwater observation system utilizing an AUV, and they built an IWPT prototype for it. Based on this idea, they built a 2200 × 2200 × 1500 mm^3 IWPT prototype and tested it in the sea. For a frequency of approximately 80–90 kHz and a gap of a few millimeters (<70 mm), they were able to transmit 1 kW of power with an efficiency of 75%.

More recently, Maguer et al. [126] presented an IWPT system integrated in a torpedo UUV. Their prototype was composed of a Tx unit in a funnel-type docking platform called AutoLARS and a Rx unit inside their eFolaga torpedo AUV. The couplers are composed of windings, ferrite core and auxiliary feedback control integrated in a "hockey-puck" shaped housing with a size of 78 mm in diameter and 62 mm in height. Their docking platform was modified to ease the eFolaga's entrance and improve clamping and coupling. The system was capable of transferring 500 W with an efficiency of 90% for a 10 mm gap in laboratory tests. Their work ended in November 2017 by conducting a two-week sea experimental campaign with the AUV deployed in the sea.

In [127], another AUV-integrated resonant IWPT sea test was performed. They built the AUV Tri-TON 2 (Figure 6b) for the monitoring of underwater infrastructure and also a seabed station that serves as a positioning reference and as a charging station. The power transfer was made with circular planar coils in a ferrite core. The Tx coil had a photo-diode implemented in the middle of the device and the Rx an infra-red led for positioning (Figure 6c). This way, the charging system can only be activated when both coils are perfectly coupled. They conducted some sea experiments at the Hiratsuka Fishing Port in Japan in January 2018 [128]. The IWPT could transfer 188 W with an efficiency of 70%.

In 2020, Yang et al. [91] proposed a design procedure to select the optimal underwater operating frequency of the IWPT system, taking into account eddy currents. By applying this procedure, they designed a charging system and conducted some sea-trials with an AUV. They tested it in the Leizhou peninsula in China. They placed the docking station at 105 m depth and powered it from a surface vessel. They charged the AUV for 6 min, achieving a wireless charge of 680 W with an efficiency of 90%.

In recent years, few docking stations with wireless power charging are being commercialized. Subsea docking stations (SDS) by Blue Logic [186] are an example of this. Their designs have already been tested for the landing of several commercially available drones. They have produced three universal and open-standard subsea stations with a power rating of 2 kW, 250 W and 50 W. A 3D model of an SDS is provided in Figure 6d.

Other recent papers have also proposed the integration or combination of renewable energies with WPT devices in docking platforms. The Platform for Expanding AUV exploRation to Longer ranges (PEARL), is an example of this. This device was a floating and solar powered platform with batteries that would provide service to AUVs, including docking and power transfer [187]. Another example of the combination of WPT with wave energy was given in [188]. Here, the authors researched the feasibility of the combination of an AUV charging and docking station powered by a wave energy converter and explained the design process of the whole system.

Other devices such as sensors have also been charged using IWPT. For instance, ocean buoys with monitoring sensors can also be used as charging stations by combining IWPT with renewable energies. In these devices, linear coaxial winding transformers (LCWTs) are usually the preferred choice. These transformers are coaxially aligned transformers that are fixed [130]. In these devices, the buoy is connected to the primary, while the sensors are at the secondary winding. The buoys collect energy through the solar panels and the sensors are charged wirelessly. Some examples of these devices can be found in [16,131].

5.2. Laboratory Prototypes with Coaxial and Planar Coils

In the first stages of development, most of the coils were designed with a planar or coaxial topology, as shown in Figure 7. This happened due to the fact that planar coils are most suitable for landing-type docking stations and coaxial coils for the funnel-type ones. The main focus of the laboratory prototypes has been to optimize the power transfer by testing different frequency values, gaps, models or control schemes while trying to overcome the main challenges presented by seawater. The most usual compensation schemes for these systems were series–series and series–parallel. However, in the last five years, there has been an increasing interest in testing LCC compensating schemes.

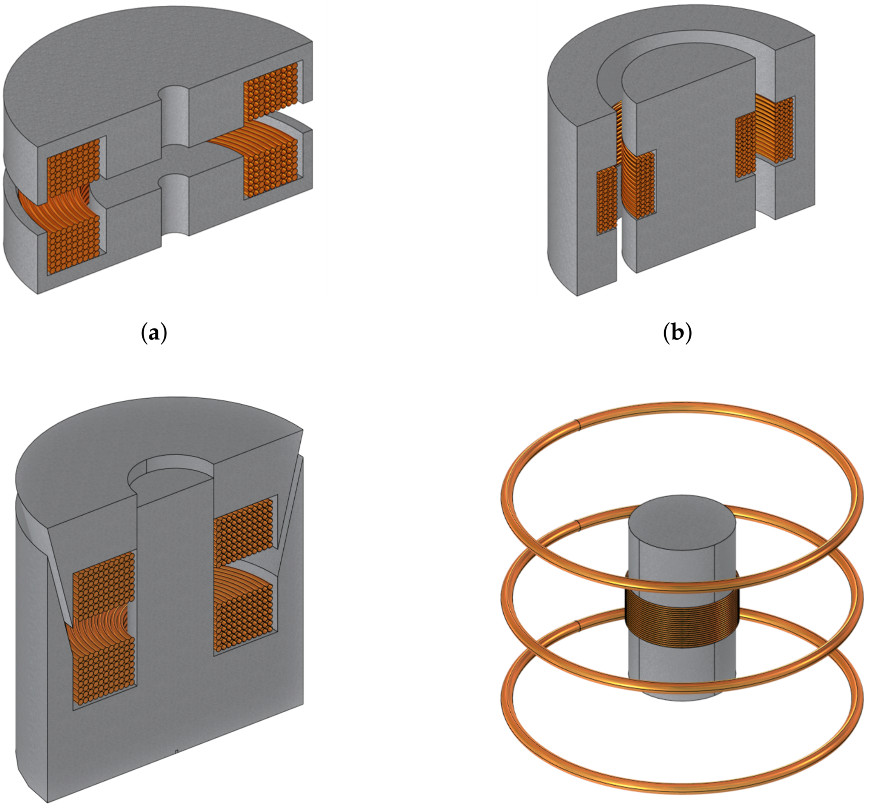

(**a**) (**b**) (**c**) (**d**)

Figure 7. Planar and coaxial coil topologies. (**a**) Planar circular coil with semi-closed core. (**b**) Coaxially coupled coils. (**c**) Self-latching circular coupler model [189]. (**d**) 3 Tx and 1 Rx coaxial IWPT system [190].

In [165], one the earliest laboratory tests for a planar coil was presented. They used planar and semi-closed coils inside of high-pressure (4000 m) salt-water and transferred 400 W. Then, in 2015, a transmission of 10 kW with an efficiency of 92% was achieved by Cheng et al. [151]. In another work by Wu et al. [191], they presented a coreless device that could achieve a maximum load power of 360 W. Yan et al. [157] modeled a coil to obtain its optimal frequency and designed an experimental prototype achieving a 200 W power transfer with 85% efficiency at 504.5 kHz. In [143], the authors achieved a power transfer of 1 kW with an LCC-P compensating circuit. Their peak efficiency was approximately 94%. In [192], the authors constructed a 400 W laboratory prototype with a black-pane ferrite. Liu et al. [193] built a coil mutual inductance model based on an eddy current loss analysis and then tested a 1 kW underwater WPT prototype using an LCC-S compensating method. They achieved an efficiency of 94.05% for a frequency of 100 kHz. In [189], they achieved 92% efficiency on a 3 kW IWPT for a circular resonant coil device. In this case, they designed a self-latching coupling structure that could facilitate AUVs docking and highly reduce misalignment. Their proposal is depicted in Figure 7c.

Regarding coaxial coils, several studies are available in the literature, with efficiency values ranging from 70% up to 90%. Lin et al. [194] designed a coaxially coupled and coreless IWPT system that transferred 300 W. In [195], they proposed a coaxial wireless transfer system for a torpedo-shaped AUV. They designed an impedance matching network that could achieve a 100 W power transfer. In another paper by Guo et al. [196], they designed a coaxial IWPT system with a position adaptive power delivery system to reduce the effect of misalignment with an efficiency of 88% for a 300 W power transfer. In [197], they designed another coaxially aligned IWPT device with high misalignment tolerance and that was compatible with a funnel-type docking station. The authors were able to transfer 2 kW with a 92.7% efficiency. The authors in [167] presented an AUV hull compatible inductive power transfer system with an 80 kW power rating and 93.9% efficiency by using an LCC-S compensation topology, achieving a power transfer of 5180 W in a downscaled prototype. Another coaxially aligned device with a power transfer of 3 kW was presented in [190], which was composed of three Tx devices, as seen in Figure 7d. In the case of the study by Zhang et al. [198], they designed a variable ring-shaped magnetic coupler that improved the transfer efficiency of their coaxial device from 77% to 86.4% for a 800 W power transfer.

In 2023, a coaxial and planar hybrid prototype was proposed by Wen et al. [199]. Here, a solenoid transmitter was tested with a dual planar receiver, achieving an efficiency of 85% for a 401 W power transfer without misalignment. Furthermore, many other planar and coaxial systems that achieved power transfer values below 100 W or did not provide enough information to analyze their parameters can also be found in the literature [159,200–206]. Additionally, some other works present comparisons between planar topologies [207] and planar and coaxial topologies [208].

A summary of the main parameters of the reviewed underwater IWPT system prototypes are collected in Table 2. It is important to note that, in general, the systems operating at higher frequencies have a smaller size than those with lower frequencies.

Table 2. Comparison of resonant IWPT experiments with planar and coaxial topologies.

Authors	Year	Environment	Coil	Core	Comp.	P_{out} (W)	η (%)	f_r (kHz)	Gap (mm)
Li et al. [165]	2010	Salt water	Planar	Semi-closed	S-P	400	90	94.3	2
Cheng et al. [151]	2015	Salt water	Planar	Enclosed	S-P	10340	92.8	38.9	25
Wu et al. [191]	2016	Salt water	Planar	Coreless	S-S	360	90.2	100	1
Yan et al. [157]	2019	Salt water	Planar	Coreless	S-S	200	85	504.5	14
Yan et al. [143]	2019	Air	Planar	Backplane	LLC-P	1000	94	81.6	60
Meşe and Budak [192]	2020	Salt water	Planar	Backplane	S-S	400	86.3	100	50
Liu et al. [193]	2020	Air	Planar	Backplane	LCC-S	1000	94	100	55
Zhou et al. [189]	2021	Salt water	Planar	Self-latch	S-S	3000	92	35.4	5
Lin et al. [194]	2017	Salt water	Coaxial	Coreless	S-P	300	77	52	15
Song et al. [195]	2018	Salt water	Coaxial	Coreless	LCC-S	100	70	214.3	1.6
Guo et al. [196]	2019	Salt water	Coaxial	Enclosed	S-S	300	88	32	5
Liu et al. [197]	2022	Fresh water	Coaxial	Tubular	LCC-S	2000	92.7	200	32
Mostafa et al. [167]	2022	Salt water	Coaxial	Backplane	LCC-S	5180	96.7	200	30
Hasaba et al. [190]	2022	Salt water	Coaxial	Tubular	LCC-LCC	3000	80.7	1.55	770
Zhang et al. [94]	2023	Air	Coaxial	Ring	LCC-S	800	86.4	100	N/A
Wen et al. [199]	2023	Salt water	Hybrid	Coreless	S-S	401	85	100	N/A

5.3. Innovative Topologies and Multi-Coil Systems

In addition to the regular planar and coaxial topologies, in the last five years, there has been a trend towards designing innovative coil topologies to try to improve underwater IWPT characteristics such as integration in AUVs, reduction in size and weight, multiple load charging and misalignment-tolerance. An example of a novel topology is the device presented in 2018 by Cai et al. [209], which used an E-shaped core that followed an arc-shape for AUV applications (Figure 8a). Their design could transmit 605 W with a 91.3% efficiency.

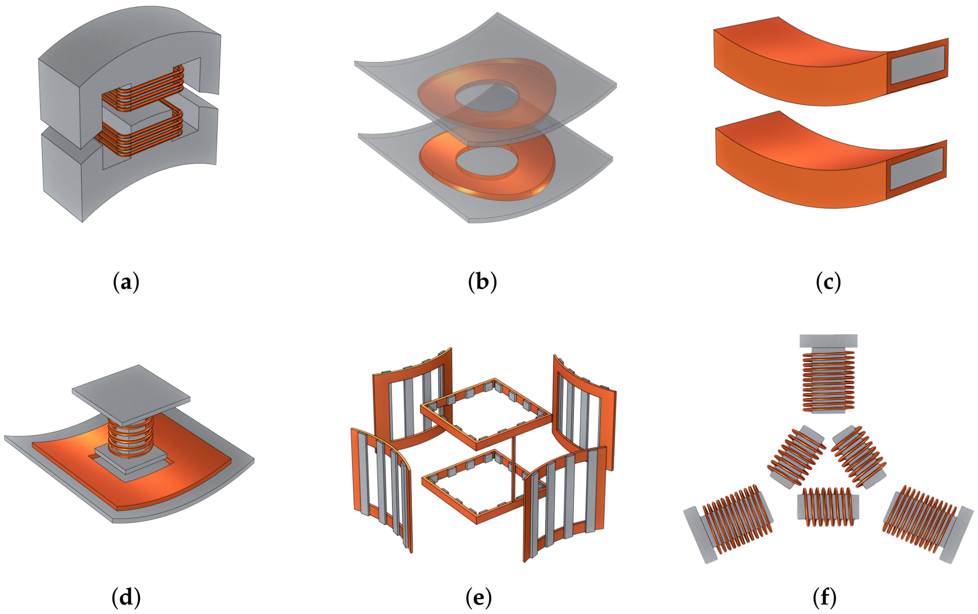


Figure 8. Innovative coil topologies. (**a**) E-shape coil [209]. (**b**) Arc-shaped coil [210]. (**c**) Dipole coil [211]. (**d**) Arc- and H-shaped coil [212]. (**e**) Cuboid and Arc coil [213]. (**f**) Three phase coil [214].

Several other papers have proposed innovative arc-shaped planar topologies that easily adapt to the shape of the AUV and reduce the weight of the IWPT device. In Figure 8b, a general and simplified concept of these topologies is presented. Most of these present an efficiency of approximately 90%. For instance, in [215], the authors designed and tested this coil topology, achieving a power transfer of 1 kW in air. In [141], they integrated the compensation coil and main coil as two unipolar coils on the Tx side for an LCC-S. They achieved power transfer values of around 300 W. In another work by Cai et al. [216], they presented another arc-shaped topology, transferring 1 kW. In [217], they tested a curved coupler with distributed ferrite cores and transferred up to 2.2 kW.

In a similar fashion, Cai et al. [211] proposed an arc-shaped dipole-coil magnetic coupler (Figure 8c). Fe-based nano-crystalline soft magnetic materials were used as coil cores to improve permeability and reduce size and weight. This novel coil topology was constructed and validated in a salt water environment with a 630 W power transfer. Wang et al. [210] proposed the arc-shaped UWPT system from Figure 8b. They also used a a similar alloy material. Their coils could transfer 3 kW of power. In [144], the authors presented an 802.3 W resonant IWPT system with an arc-shaped transmitter and I-shaped receiver (Figure 8d). Xia et al. [218] designed an IWPT device with a coaxial Tx and an arc-shaped Rx that could achieve a stable output power of 575 W. Finally, in [172], they built an arc-shaped transmitter with a pendulum-shaped receiver, transferring up to 3.03 kW when aligned.

Multicoil IWPT systems have also been a dominant topic in the last few years. Most of the works focus on improving the power transfer or reducing misalignment by using more than one coil at the Rx side [213], the Tx side [219–221] or both sides [214,222–224]. Regarding multiple receivers, Zeng et al. [213] proposed a multi-directional magnetic coupler with a cuboid shape as the transmitter for a four arc-shaped receiver system for swarm AUVs (Figure 8e). The system could simultaneously transfer 200 W to four Rx coils.

Regarding multiple Tx devices, Hasaba et al. [219] achieved a 100 W power transfer with a 25.9% efficiency for a distance of up to 10 m. The system was composed of seven bulky Tx coils of 3.4 m in diameter. More recently, in [190], the authors designed an improved coaxial IWPT with three receivers. It allowed a power transfer up to several meters and a maximum efficiency of 80% for a power transfer of 3 kW. The transmitter structure consisted of three circular coils, as shown in Figure 7d, with a diameter of 2000 mm, placed at intervals of 1000 mm. The receiver coil was around a cylindrical aluminum pressure container (emulating an AUV) with a diameter of 460 mm and 1000 mm in length. Finally, in [225], they proposed a free-rotation device with two transmitters and one receiver to reduce misalignment within the system, transferring up to 700 W.

Regarding multiple Rx and Tx devices,Kan et al. [214] proposed the three-phase wireless power transfer system for swarm AUVs in 2017 (Figure 8f), which they constructed and validated for a 1 kW power transfer. Similarly, Yan et al. [222] designed a six-phase prototype where the Tx and Rx devices were inverted. They simultaneously achieved an output power of 500 W for two receivers with a 90% efficiency in air. In addition to these, Sato et al. [224] designed a multiple Tx and two Rx planar circular coupler to improve misalignment and tested a 200 W prototype with success.

Other multi-coil structures that aim to reduce misalignment are the DD and DDQ topologies. These configuration are used to charge only one device and have the advantage of allowing a higher misalignment. Some of the recent studies on these configurations can be found in [226–228]. In [226], they achieved a power transfer of 884 W with a 94.3% efficiency, and in [227], a power transfer of 1.5 kW with an efficiency of 89.8%.

Finally, a comparison between these innovative topologies and some of the most relevant circular and coaxial coils is presented in Table 3.

Table 3. Comparison of resonant IWPT experiments with various topologies.

Authors	**Year**	**Environment**	**Coil**	**Core**	**Comp.**	**P_{out} (W)**	**η (%)**	**f_r (kHz)**	**Gap (mm)**
Li et al. [165]	2010	Salt water	Planar	Semiclosed ferrite	S-P	400	90	94,3	2
Cheng et al. [151]	2015	Salt water	Planar	Enclosed	S-P	10340	92.8	38.9	25
Cai et al. [209]	2018	Air	Circular helical	E-shaped	N/A	606	91.3	50	8
Kan et al. [214]	2017	Air	Three phase	Tx: T-shape Rx: Cuboid	S-S	1000	92.4	465	21
Sato et al. [224]	2019	Salt water	Planar multicoil	Coreless	S-P	200	85	14	10
Yan et al. [215]	2019	Air	Circular arc	Arc	LCC-LCC	1000	95	85	10
Yan et al. [141]	2019	Air	Dual arc	Arc	LCC-S	300	93	85	80
Cai et al. [211]	2020	Salt water	Dipole	Arc	S-S	634	87.9	50	8
Cai et al. [216]	2021	Salt water	Bipolar circular	Arc	LCC-S	1000	95.1	50	8
Zhou et al. [189]	2021	Salt water	Circular planar	Enclosed	S-S	3000	92	35.4	5
Hasaba et al. [190]	2022	Salt water	Coaxial	Backplane	LCC-LCC	3000	80,7	1.55	770
Mostafa et al. [167]	2022	Salt water	Coaxial	Backplane	LCC-S	5180	96.7	200	30
Qiao et al. [144,212]	2022	Salt water	Tx: Arc Rx: H	Tx: Arc Rx: I-shaped	LCC-P	802	91.1	96.2	N/A
Wang et al. [210]	2022	Salt water	Arc	Fe-alloy arc	LCC-LCC	3000	91.9	85	40
Wu et al. [220]	2022	Salt water	Arc	Coaxial multicoil	LCC-LCC	1200	90	85	N/A
Yan et al. [222]	2022	Air	Six-phase	Rx: T-shape Tx: Cuboid	LCC-LCC	2 x 500	90	249	64
Xia et al. [218]	2023	Salt water	Tx: Coax. Rx: Arc	Tx: Coaxial Rx: Arc	S-P	575	92.5	50	8
Zeng et al. [213]	2023	Salt water	Tx: Cage Rx: Arc	Spaced	LCC-S	4 x 200	92.2	249	50
Lin et al. [217]	2023	Salt water	Arc	Distributed	LCC-S	2200	94	35	N/A
Wang et al. [172]	2023	Salt water	Arc Pendulum	Arc Pendulum	LCC-S	3036	95.9	85	50
Yan et al. [225]	2023	Air	Multi Solenoid	Solenoid	LCC-S	700	92	200	N/A
Da et al. [226]	2023	Salt water	DDQ	Backplane	LCC-LCC	884	94.3	85	20
Sun et al. [227]	2023	Salt water	DD-DD	Backplane	S-S	1500	89.9	100	N/A

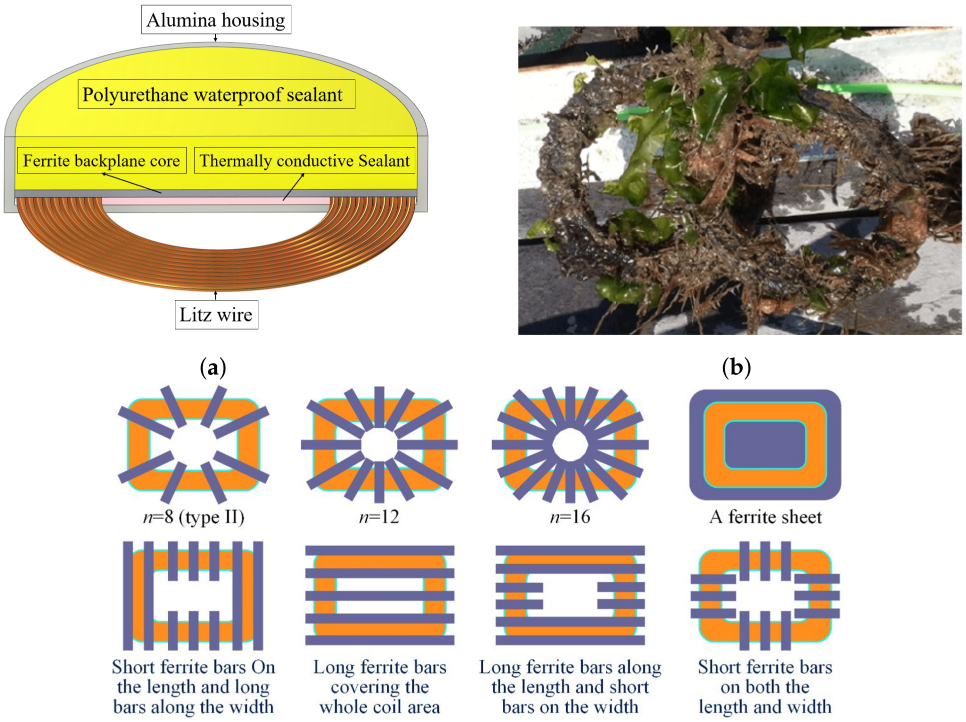
5.4. Novel Core Materials

The research on new materials for various IWPT system parts has been recently addressed in the scientific literature. The main objectives are reducing size and weight, improving permeability, allowing high pressure applications for deep-sea operation, increasing flexibility for a better AUV integration or reducing biofouling.

Within this context, it is important to consider weight and size reduction strategies. One such strategy involves spacing ferrite cores. One of the strategies involving spacing ferrite cores [213,229,230] is an option that does not require research into new materials. For instance, in [229], they modeled a 6.0 kW underwater IWPT system with several *Rx* core distributions that use less ferrite than usual cores, Figure 9c. However, novel materials seem to be a better option, as spaced ferrite cores reduce the performance of the coils. Within this context, Cai et al. [211] and Wen et al. [146] proposed the use of Fe-based nanocrystalline alloys as core materials. In particular, the size and weight of the IWPT were reduced in [146] up to 41.1% and 42.6%, respectively. According to the researchers, these materials have the following advantages:

(a) Magnetic flux density is up to three times higher than Mn-Zn ferrite materials. For the same volume, twice the ferrite core output power can be reached.
(b) Permeability can be more than 10 times that of the Mn-Zn ferrite material.
(c) Strong deformation ability improves integration in round surfaces.

Few other works have focused on using different materials in the windings to reduce eddy currents or improve their coupling. For instance, Kuroda et al. [231] designed and fabricated some underwater antennas covered by a resin sealing layer. This layer was employed to protect the antenna from high pressure and electrically isolate it to reduce ECL. In [159], the authors also proposed covering the coil winding with a polyurethane sealant, as seen in Figure 9a. Another innovative proposal by Hu et al. [232] consists of using Mu Negative metamaterials for the winding, negative permeability materials that could potentially improve coupling.



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

(**c**)

Figure 9. Topologies with novel core materials, distributions and effects of biofouling. (**a**) Planar circular coil with sealant [159]. (**b**) Effect of biofouling in a coil [178]. (**c**) Different ferrite geometries for Rx coils [229].

Some papers have proposed various shielding methods for IWPT devices to reduce the effects of metal hulls in WPT [185]. Regarding AUV hulls, Wen et al. [146] proposed replacing traditional metallic hull materials for silicon–aluminum–oxynitride (SiALON) ceramic ones. According to their research, SiALON could potentially maintain pressure resistance while reducing the interference with the charging system, improve corrosion resistance and avoid structural changes in AUVs, while maintaining the power transfer efficiency. In [184], the authors modeled and tested a prototype that used Nylon6 magnetic shielding to reduce ECL. They could demonstrate that for frequencies over 400 kHz, shielded devices were more efficient than the not shielded ones.

Regarding biofouling resistant materials, Anderson et al. [178] presented a characterization on thermal effects and biofouling in UWPT systems. They prepared eight coils for biofouling tests potted with different materials: two with polyurethane, two with polyurethane and a copper-based anti-foul paint, two with TCE thermal coating and another two with that coating and a copper-based anti-foul paint. They submerged the pots off a pier in San Diego Bay for 45 days. By powering the coils, they generated heat to test the generation of biofouling in each case. One example is shown in Figure 9b. They found out that the anti-fouling paint and thermal coating were effective in reducing coil fouling, and that the combination of both was the optimal option.

5.5. Dual Data and Power Transfer and Innovative Control Systems

The research into innovative control systems and simultaneous power and data transfer is also an increasing trend. As data transfer in seawater can be challenging, control systems that avoid communication between Tx and Rx are being considered to improve overall system feasibility. In addition, the combination of WPT and data transfer could be an effective option to compact the system. Regarding data transfer, some of the previously analyzed AUV prototypes with IWPT systems already incorporated data transfer modules [120,123,124,126]. However, these modules were independent from the power transfer module.

Several hybrid power and data communication systems have been proposed in the literature [15,213,233–237]. In [234], the authors presented a system able to transfer up to 130 W with a 73 mbps full-duplex communication. In [213], a partial Rx coil, a Tx coil and an additional transformer were used to transmit data and power, proving a data transfer rate of 30 kbps at a distance of 5 cm. Wang et al. [235] designed a coaxially aligned underwater IWPT system that could transfer 518 W of power with an efficiency of 92% and 500 kbps/700 kbps full-duplex communication. In [236], they designed a data and power transmission system for a cable-inspecting robot fish with three operating modes: alignment detection, low-speed power transmission and high-speed signal transmission. Cai et al. [238] built a dual prototype with 8.5 kbps data transmission, compact design and a power transfer of 936 W at 94.12% efficiency. Finally, Li et al. [237] achieved a 1-Mbps full-duplex communication link for a 1 kW power transfer.

A number of innovative control approaches have been presented in the literature. Maximum efficiency tracking (MET) control methods are some of the most popular options [29,174,227,239,240], while other papers have proposed different solutions [241–243]. MET control methods focus on finding the variation in the coupling coefficient due to misalignment and adjust the frequency or voltage of one of the sides to maintain an optimal underwater IWPT efficiency. These adjustments are generally achieved by acting on the input or output converters.

Some papers have also developed optimized IWPT models to improve their control [138,244–247]. In [244], a small-signal phasor model was presented, and a control-to-output transfer function was developed, with the output voltage as the regulated variable. In [245], an efficient model for an UWPT system was proposed by using Z-parameters and two port network analysis. Other papers such as [138,246] have very recently presented some mathematical models for underwater IWPT optimization by applying more complex algorithms. In [247], they applied a particle swarm algorithm to adaptively control the output power.

5.6. Bidirectional and Modular IWPT

Another interesting proposal consists of using bidirectional power transfer [248–251]. These type of systems could potentially improve the adaptability of IWPT to any environment [248]. This technology would allow charging an AUV from an underwater power station while also having the ability to charge another device with the same vehicle. In [250], they built a bidirectional IWPT model that could deliver power up to 300 W to a load with an efficiency of 90%, which also could be charged with a power of 51 W and in [251], they achieved a transfer of 519 W with an efficiency of 82.18% and a reverse power of 472 W with 73.63%.

Modularizing IWPT devices is also a recent proposal that very few works like the ones in [252,253] have presented. In [252], the authors designed a small modular vehicle that could be separated into several interchangeable modules, including control and power system. These modules would be provided with data and power through IWPT. On the other hand, Ref. [253] developed a modular housing prototype that sought to adapt the existing IWPT technologies to a marine environment.

6. Conclusions

During recent years, there has been an increasing demand for more efficient and sustainable operation and maintenance UUV devices in the seawater environment. Conventional charging methods are generally more polluting, time-consuming and costly as they require vessels. UWPT devices fed from offshore renewable energy are a great alternative to these. As seen in Appendix A, the interest in UWPT has increased in the last five years, both in academia and in industry, with few commercial devices already available. In this regard, IWPT is the most promising technology, while other near-field technologies such as CWPT or ultrasonic through-wall show potential. On the other hand, far-field technologies have been proven not to be feasible for high power transfer but could be integrated as auxiliary devices and for underwater communication. The combination of renewable energy and UWPT is also a recent proposal that can help to improve the reliability of AUV charging.

In this context, the key conclusions that have been obtained from the comprehensive literature review conducted within this paper can be summarized as follows:

(a) Achieving efficient and reliable underwater UWPT is not a trivial issue. Several challenges such as high-pressures, strong currents or biofouling have to be tackled in subsea docking platforms. In addition to this, the effects of ECL and R_{RAD} need to be reduced to the minimum to maintain efficient IWPT. Regarding these issues, progress has been made in the design of misalignment-tolerant devices and in the characterization of ECL to reduce their effect in the system. Maintaining frequencies below 200 kHz, reducing the gap between the Tx and Rx sides or enclosing the coils are some of the solutions proposed in the literature. On the other hand, very few papers consider the effect of high pressures, biofouling or electromagnetic field emission in underwater wireless technology. These are important issues that warrant attention and should be addressed in the future research.

(b) Due to a lack of standardization, comparing different IWPT systems is difficult. A compromise between size and power often involves low distance, low misalignment, and a frequency range of 50–200 kHz. The latest works have reported efficiency values ranging from 88% up to 93%. However, only a few real-life prototypes have reached up to 90% efficiency. Furthermore, despite sharing the same theoretical background, the experimental results reported in the literature often do not align due to various factors such as different coil shapes, pad designs, ferrite material layouts, shielding techniques, water salinity levels and other factors. This complicates the development of standardized devices, as the optimal configurations may vary depending on the specific application of each AUV. Nonetheless, as the technology matures, there is significant potential to develop general chargers for different types of AUVs.

(c) Power transfer in the range of 1 kW seems already possible, which may suffice for small UUVs, but work-class UUVs require power transfer capabilities with power ratings in the range of 10 kW, which, according to the reviewed literature, seems not to be solved yet today. To meet the power needs of UUVs in industrial applications, further research and improvement of UWPT are essential. One approach is to focus on testing higher power prototypes. By developing and testing prototypes with increased power capabilities, the researchers can assess the feasibility and efficiency of scaling up UWPT technology to meet the demands of work-class UUVs. Furthermore, a collaboration between academia, industry and government agencies can facilitate the exchange of knowledge and resources to accelerate the development and deployment of UWPT technology in real-world settings.

Thus, although significant advances regarding UWPT have been carried out in the last decades, significant research efforts need to be continued to overcome a variety of issues and make UUV charging technologies feasible to, this way, support the autonomous underwater inspection of offshore renewable energy power plants and other offshore and underwater facilities with its added benefits for a more cleaner and sustainable future.

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Abbreviations

AUV	autonomous underwater vehicle
CWPT	capacitive wireless power transfer
D-WEVCS	dynamic electric vehicle charging system
ECL	eddy current losses
EM	electromagnetic
IWPT	inductive wireless power transfer
MET	maximum efficiency tracking
OWT	offshore wind turbine
S-WEVCS	static wireless electric vehicle charging system
SiALON	silicon–aluminum–oxynitride
TMS	tether management system
UUV	unmanned underwater vehicle
UWPT	underwater wireless power transfer
f_r	resonant frequency
k	coupling coefficient
$P-P$	parallel–parallel
$P-S$	parallel-series
R_{AC}	AC resistance

R_{DC}	DC resistance
R_{RAD}	radiation resistance
Rx	receiver
$S-S$	series–series
$S-P$	series–parallel
Tx	transmitter

Appendix A. Bibliographical Study

Appendix A.1. Methodology

In order to characterize the main technologies used in UWPT, a technology intelligence study was conducted by means of a patent and bibliographical search. The existing patents were queried using PATENTSCOPE from WIPO IP in February 2024. The following IPC classification was queried: *H02J-050, Circuit arrangements or systems for wireless supply or distribution of electric power.* Here, multiple sub-fields were included for a more precise decomposition of the corpus:

- H02J 50/05 using capacitive coupling,
- H02J 50/10 using inductive coupling,
- H02J 50/12 of the resonant type,
- H02J 50/15 using ultrasonic waves,
- H02J 50/20 using microwaves or radio frequency waves,
- H02J 50/30 using light, e.g., lasers.

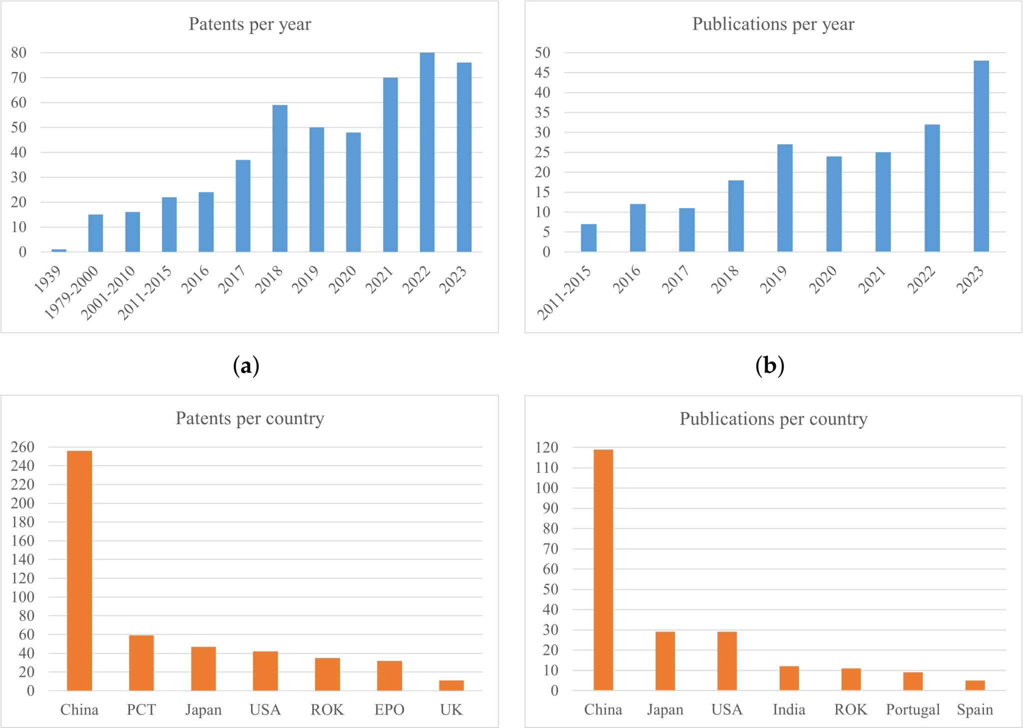
Additionally, *H01F 38/14, inductive couplings* IPC classification and the following keywords were coupled in the search: “underwater”, “submarine”, “AUV”, “autonomous underwater vehicle”, “UUV” or “unmanned underwater vehicle” or ”marine”. This query was conducted in English and repeated in Chinese, Danish, Dutch, French, German, Italian, Japanese, Korean, Polish, Portuguese, Russian, Spanish and Swedish. The search in these languages was carried out after obtaining the translations of English keywords from the cross lingual query search from WIPO PATENTSCOPE.

Regarding scientific publications, the following script was used to query the Scopus database: *(KEY(”wireless charging”) OR KEY (”wireless power transfer”)) AND (TITLE-ABS-KEY(underwater OR subsea OR submarine)).*

Appendix A.2. Patent Corpus

According to the study, a total of 569 patent families have been filed in the field, most of them originating from Asia. The first patent of a wireless underwater transmitter was awarded in 1939 [254]. From that year until 1979, no more patents were found in the study. In the period from 1979 to 2010 few patents were found, with no more than one patent per year on average. Since 2010, the topic has gained increasing interest. The period from 2018 to 2023 has been the most prolific, with an average of 50 patents per year, as seen in Figure A1a.

The increase in patents in the 2016–2023 period is highly due to Chinese applications. The ranking of top applicants is dominated by actors from Asia, though Chinese applicants are mostly academic from Zhejiang university (13 patents), Tianjin university (11 patents) or Harbin engineering university (8 patents), while Japanese patents are from industrial actors such as Panasonic (10 patents), IHI CO (6 patents) or Showa Aircraft ind co LTD (6 patents). On the other hand, western actors mostly come from smaller companies and research organizations, with Finnish company Subsea Energy Oy (6 patents) as one of the most prolific in Europe. Philips is the company with the most patents filed (27) across several patent offices, including the USA, Europe, and China. In the USA, the major patent filers are Panasonic (7 patents) and Philips.



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

(**c**) (**d**)

Figure A1. Derived results from the bibliographical study. (**a**) Patents by year. (**b**) Publications by year. (**c**) Patents by country. (**d**) Publications by country.

Regarding power transfer technologies, the circle chart in Figure A2 shows the percentage of patents in relation to the type of wireless charging technology. This technological decomposition relies on IPC codes, as showcased previously. Inductive coupling technologies are clearly mainstream here, with an approximate 87% of the total, according to the conducted study.

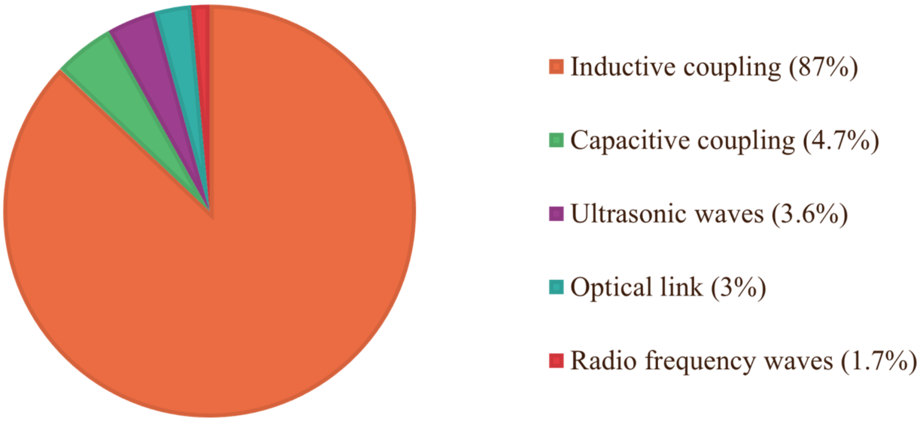


Figure A2. UWPT patents by method.

Appendix A.3. Scientific Publication Overview

In the review carried out for scientific publications, 204 references have been collected on the topic of underwater wireless power transfer since 2011. In a similar fashion to patents, China is the main country of origin, followed by Japan and the United States. In addition to these, India, Portugal and Spain have also shown a significant amount of activity, especially in the last few years (2020–2022), as seen in Figure A1b.

The Northwestern Polytechnical University of Xi'an (China), the Harbin Institute of Technology (China), the San Diego university (United States) and the Toyohashi University of Technology (Japan) appear as the most prolific actors in the field. Additionally, the University of Porto (Portugal) and its Institute for Systems and Computer Engineering, Technology, and Science have also contributed significantly to this topic, along with the Spanish University of Las Palmas, the latter focusing more on publications related to underwater sensor applications [135].

References

1. International Energy Agency (IEA). Ocean Power Generation in the Net Zero Scenario, 2000–2030. 2021. Available online: https://www.iea.org/data-and-statistics/charts/ocean-power-generation-in-the-net-zero-scenario-2000-2030 (accessed on 8 April 2024).
2. International Energy Agency (IEA). Global Energy and Climate Model. 2021. Available online: https://www.iea.org/reports/global-energy-and-climate-model (accessed on 8 April 2024).
3. Hote, K.; Kaushik, R.; Tasnin, W. Global Offshore Wind Scenario: A Review. *ECS Trans.* **2022**, *107*, 11083–11103. [CrossRef]
4. Wang, L.; Kolios, A.; Liu, X.; Venetsanos, D.; Cai, R. Reliability of offshore wind turbine support structures: A state-of-the-art review. *Renew. Sustain. Energy Rev.* **2022**, *161*, 112250. [CrossRef]
5. Li, C.; Mogollón, J.; Tukker, A.; Dong, J.; von Terzi, D.; Zhang, C.; Steubing, B. Future material requirements for global sustainable offshore wind energy development. *Renew. Sustain. Energy Rev.* **2022**, *164*, 1–13. [CrossRef]
6. López, I.; Andreu, J.; Ceballos, S.; Martínez de Alegría, I.; Kortabarria, I. Review of wave energy technologies and the necessary power-equipment. *Renew. Sustain. Energy Rev.* **2013**, *27*, 413–434. [CrossRef]
7. Shetty, C.; Priyam, A. A review on tidal energy technologies. *Mater. Today Proc.* **2022**, *56*, 2774–2779. [CrossRef]
8. Khan, M.; Khan, H.; Aziz, M. Harvesting Energy from Ocean: Technologies and Perspectives. *Energies* **2022**, *15*, 3456. [CrossRef]
9. Ren, Z.; Verma, A.; Li, Y.; Teuwen, J.; Jiang, Z. Offshore wind turbine operations and maintenance: A state-of-the-art review. *Renew. Sustain. Energy Rev.* **2021**, *144*, 110886. [CrossRef]
10. Wang, Z.; Guo, Y.; Wang, H. Review on Monitoring and Operation-Maintenance Technology of Far-Reaching Sea Smart Wind Farms. *J. Mar. Sci. Eng.* **2022**, *10*, 820. [CrossRef]
11. Rémouit, F.; Chatzigiannakou, M.; Bender, A.; Temiz, I.; Sundberg, J.; Engström, J. Deployment and Maintenance of Wave Energy Converters at the Lysekil Research Site: A Comparative Study on the Use of Divers and Remotely-Operated Vehicles. *J. Mar. Sci. Eng.* **2018**, *6*, 39. [CrossRef]
12. Liu, Y.; Hajj, M.; Bao, Y. Review of robot-based damage assessment for offshore wind turbines. *Renew. Sustain. Energy Rev.* **2022**, *158*, 112187. [CrossRef]
13. Wynn, R.; Huvenne, V.; Le Bas, T.; Murton, B.; Connelly, D.; Bett, B.; Ruhl, H.; Morris, K.; Peakall, J.; Parsons, D.; et al. Autonomous Underwater Vehicles (AUVs): Their past, present and future contributions to the advancement of marine geoscience. *Mar. Geol.* **2014**, *352*, 451–468. : 10.1016/j.margeo.2014.03.012 [CrossRef]
14. Wei, X.; Guo, H.; Wang, X.; Wang, X.; Qiu, M. Reliable Data Collection Techniques in Underwater Wireless Sensor Networks: A Survey. *IEEE Commun. Surv. Tutor.* **2022**, *24*, 404–431. [CrossRef]
15. Tibajia, G.; Talampas, M. Development and evaluation of simultaneous wireless transmission of power and data for oceanographic devices. In Proceedings of the SENSORS 2011 Conference, Limerick, Ireland, 28–31 October 2011, pp. 254–257. [CrossRef]
16. Fang, C.; Li, X.; Xie, Z.; Jiayi, X.; Xiao, L. Design and Optimization of an Inductively Coupled Power Transfer System for the Underwater Sensors of Ocean Buoys. *Energies* **2017**, *10*, 84. [CrossRef]
17. Green, R.; Copping, A.; Cavagnaro, R.J.; Rose, D.; Overhus, D.; Jenne, D. Enabling Power at Sea: Opportunities for Expanded Ocean Observations through Marine Renewable Energy Integration. In Proceedings of the OCEANS 2019 MTS/IEEE SEATTLE, Seattle, WA, USA, 27–31 October 2019, pp. 1–7. [CrossRef]
18. Bao, J.; Li, D.; Qiao, X.; Rauschenbach, T. Integrated Navigation for Autonomous Underwater Vehicles in Aquaculture: A Review. *Inf. Process. Agric.* **2019**, *7*, 139–150. [CrossRef]
19. Lee, H.; J.Daehyeonand.; Yu, H.; Ryu, J. Autonomous Underwater Vehicle Control for Fishnet Inspection in Turbid Water Environments. *Int. J. Control. Autom. Syst.* **2022**, *20*, 3383–3392. [CrossRef]
20. Available online: https://www.blueyerobotics.com/products/pro (accessed on 13 April 2023).
21. Available online: https://www.qysea.com/es/products/fifish-v6/ (accessed on 13 April 2023).
22. Available online: https://www.chasing.com/es/chasing-m2.html (accessed on 13 April 2023).
23. Rudnick, D.; Davis, R.; Eriksen, C.; Fratantoni, D.; Perry, M. Underwater Gliders for Ocean Research. *Mar. Technol. Soc. J.* **2004**, *38*, 48–59. [CrossRef]
24. Rudnick, D.; Cole, S. On sampling the ocean using underwater gliders. *J. Geophys. Res.* **2011**, *116*, 1–12. [CrossRef]
25. Waldmann, C.; Kausche, A.; Iversen, M.; Pototzky, A.; Looye, G.; Montenegro, S.; Bachmayer, R.; Wilde, D. MOTH-An underwater glider design study carried out as part of the HGF alliance ROBEX. In Proceedings of the IEEE/OES Autonomous Underwater Vehicles (AUV) Conference, Oxford, MS, USA, 6–9 October 2014; pp. 1–3.
26. Mou, J.; Jia, X.; Chen, P.; Chen, L. Research on operation safety of offshore wind farms. *J. Mar. Sci. Eng.* **2021**, *9*, 881. [CrossRef]
27. Cetin, K.; Suarez Zapico, C.; Tugal, H.; Petillot, Y.; Dunningan, M.; Erden, M. Application of adaptive and switching control for contact maintenance of a robotic vehicle-manipulator system for underwater asset inspection. *Front. Robot. AI* **2021**, *8*, 1–13. [CrossRef]

28. E&T Editorial Staff. Autonomous underwater drones used to maintain offshore wind turbines. *E&T Engineering and Technology*, 23 May 2022.
29. Orekan, T.; Zhang, P.; Shih, C. Analysis, Design, and Maximum Power-Efficiency Tracking for Undersea Wireless Power Transfer. *IEEE J. Emerg. Sel. Top. Power Electron.* **2018**, *6*, 843–854. [CrossRef]
30. Raj, D.; Ko, E.; Yoon, D.; Shin, S.; Park, S.H. Energy Optimization Techniques in Underwater Internet of Things: Issues, State-of-the-Art, and Future Directions. *Water* **2022**, *14*, 3240. [CrossRef]
31. Yang, H.; Lin, C.Y. Promising Strategies for the Reduction of Pollutant Emissions from Working Vessels in Offshore Wind Farms: The Example of Taiwan. *J. Mar. Sci. Eng.* **2022**, *10*, 621. [CrossRef]
32. Chin, C.S.; Jia, J.; Chiew, J.; Toh, W.; Gao, Z.; Zhang, C.; McCann, J. System design of underwater battery power system for marine and offshore industry. *J. Energy Storage* **2019**, *21*, 724–740. [CrossRef]
33. Transeth, A.; Schjølberg, I.; Lekkas, A.M.; Risholm, P.; Mohammed, A.; Skaldebø, M.; Haugaløkken, B.; Bjerkeng, M.; Tsiourva, M.; Py, F. Autonomous subsea intervention (SEAVENTION). *IFAC-PapersOnLine* **2022**, *55*, 387–394. [CrossRef]
34. Viel, C. Self-management of the umbilical of a ROV for underwater exploration. *Ocean Eng.* **2022**, *248*, 110695. [CrossRef]
35. Teague, J.; Allen, M.J.; Scott, T.B. The potential of low-cost ROV for use in deep-sea mineral, ore prospecting and monitoring. *Ocean Eng.* **2018**, *147*, 333–339. [CrossRef]
36. Kapetanović, N.; Krčmar, K.; Mišković, N.; Nad, D. Tether Management System for Autonomous Inspection Missions in Mariculture Using an ASV and an ROV. *IFAC-PapersOnLine* **2022**, *55*, 327–332. [CrossRef]
37. Teeneti, C.R.; Truscott, T.T.; Beal, D.; Pantic, Z. Review of Wireless Charging Systems for Autonomous Underwater Vehicles. *IEEE J. Ocean. Eng.* **2021**, *46*, 68–87. [CrossRef]
38. Jalbert, J.; Baker, J.; Duchesney, J.; Pietryka, P.; Dalton, W.; Blidberg, D.; Chappell, S.; Nitzel, R.; Holappa, K. A solar-powered autonomous underwater vehicle. In Proceedings of the Oceans 2003. Celebrating the Past ... Teaming toward the Future Conference, San Diego, CA, USA, 22–26 September 2003; Volume 2, pp. 1132–1140. [CrossRef]
39. Lu, Z.; Shang, J.; Luo, Z.; Zhu, Y.; Wang, M.; Wang, C. Research on environmental energy-driven intelligent unmanned underwater vehicles and their key technologies. In Proceedings of the 2021 IEEE 4th International Conference on Automation, Electronics and Electrical Engineering (AUTEEE), Shenyang, China, 19–21 November 2021; pp. 564–571. [CrossRef]
40. Driscol, B.P.; Gish, A.; Coe, R.G. Wave-Powered AUV Recharging: A Feasibility Study. In Proceedings of the 2019 International Conference on Offshore Mechanics and Arctic Engineering, Scotland, UK, 9–14 June 2019; pp. 1–8. [CrossRef]
41. Jung, H.; Subban, C.V.; McTigue, J.D.; Martinez, J.J.; Copping, A.E.; Osorio, J.; Liu, J.; Deng, Z.D. Extracting energy from ocean thermal and salinity gradients to power unmanned underwater vehicles: State of the art, current limitations, and future outlook. *Renew. Sustain. Energy Rev.* **2022**, *160*, 1–21. [CrossRef]
42. NOAA/OAR/OER. Mountains in the Sea Expedition 2004. Available online: https://www.flickr.com/photos/noaaphotolib/5424616529/in/photostream/ (accessed on 27 March 2024).
43. Christ, R.D.; Wernli, R.L. Chapter 8—Cables and Connectors. In *The ROV Manual*, 2nd ed.; Christ, R.D., Wernli, R.L., Eds.; Butterworth-Heinemann: Oxford, UK, 2014; pp. 163–220. [CrossRef]
44. Tian, B.; Yu, J. Current status and prospects of marine renewable energy applied in ocean robots. *Int. J. Energy Res.* **2019**, *43*, 2016–2031. [CrossRef]
45. Hildebrandt, M.; Gaudig, C.; Christensen, L.; Natarajan, S.; Carrio, J.H.; Paranhos, P.M.; Kirchner, F. A Validation Process for Underwater Localization Algorithms. *Int. J. Adv. Robot. Syst.* **2014**, *11*, 138. [CrossRef]
46. Song, W.; Cui, W. An Overview of Underwater Connectors. *J. Mar. Sci. Eng.* **2021**, *9*, 813. [CrossRef]
47. Liu, J.; Yu, F.; He, B.; Soares, C.G. A review of underwater docking and charging technology for autonomous vehicles. *Ocean Eng.* **2024**, *297*, 117154. [CrossRef]
48. Brighenti, A.; Zugno, L.; Mattiuzzo, F.; Sperandio, A. EURODOCKER-a universal docking-downloading recharging system for AUVs: Conceptual design results. In Proceedings of the IEEE Oceanic Engineering Society. OCEANS'98. Conference, Nice, France, 28 September–1 October 1998; Volume 3, pp. 1463–1467. [CrossRef]
49. Allen, B.; Austin, T.; Forrester, N.; Goldsborough, R.; Kukulya, A.; Packard, G.; Purcell, M.; Stokey, R. Autonomous Docking Demonstrations with Enhanced REMUS Technology. In Proceedings of the OCEANS 2006 Conference, Boston, MA, USA, 18–21 September 2006; pp. 1–6. [CrossRef]
50. Wirtz, M.; Hildebrandt, M.; Gaudig, C. Design and test of a robust docking system for hovering AUVs. In Proceedings of the 2012 Oceans Conference, Hampton Roads, VA, USA, 14–19 October 2012; pp. 1–6. [CrossRef]
51. Kojiya, T.; Sato, F.; Matsuki, H.; Sato, T. Automatic power supply system to underwater vehicles utilizing non-contacting technology. In Proceedings of the Oceans '04 MTS/IEEE Techno-Ocean '04, Kobe, Japan, 9–12 November 2004; Volume 4, pp. 2341–2345. [CrossRef]
52. Etemadrezaei, M. *22—Wireless Power Transfer*; Butterworth-Heinemann: Oxford, UK, 2018; pp. 711–722. [CrossRef]
53. Saini, P.; Singh, R.P.; Sinha, A. Path loss analysis of RF waves for underwater wireless sensor networks. In Proceedings of the 2017 International Conference on Computing and Communication Technologies for Smart Nation (IC3TSN), Gurgaon, India, 12–14 October 2017; pp. 104–108. [CrossRef]
54. Nguyen, D.H.; Matsushima, T.; Qin, C.; Adachi, C. Toward Thing-to-Thing Optical Wireless Power Transfer: Metal Halide Perovskite Transceiver as an Enabler. *Front. Energy Res.* **2021**, *9*, 1–10. [CrossRef]

55. Ding, J.; Liu, W.; I., C.L.; Zhang, H.; Mei, H. Advanced Progress of Optical Wireless Technologies for Power Industry: An Overview. *Appl. Sci.* **2020**, *10*, 6463. [CrossRef]
56. Kim, S.M.; Choi, J.; Jung, H. Experimental demonstration of underwater optical wireless power transfer using a laser diode. *Chin. Opt. Lett.* **2018**, *16*, 080101. [CrossRef]
57. Kim, S.M.; Kwon, D. Transfer efficiency of underwater optical wireless power transmission depending on the operating wavelength. *Curr. Opt. Photonics* **2020**, *4*, 571–575. [CrossRef]
58. Lin, R.; Liu, X.; Zhou, G.; Qian, Z.; Cui, X.; Tian, P. InGaN Micro-LED Array Enabled Advanced Underwater Wireless Optical Communication and Underwater Charging. *Adv. Opt. Mater.* **2021**, *9*, 2002211. [CrossRef]
59. Basaeri, H.; Christensen, D.B.; Roundy, S. A review of acoustic power transfer for bio-medical implants. *Smart Mater. Struct.* **2016**, *25*, 123001. [CrossRef]
60. Awal, M.R.; Jusoh, M.; Sabapathy, T.; Kamarudin, M.R.; Rahim, R.A. State-of-the-Art Developments of Acoustic Energy Transfer. *Int. J. Antennas Propag.* **2016**, *2016*, 3072528. [CrossRef]
61. Bereketli, A.; Bilgen, S. Remotely Powered Underwater Acoustic Sensor Networks. *IEEE Sens. J.* **2012**, *12*, 3467–3472. [CrossRef]
62. Guida, R.; Demirors, E.; Dave, N.; Rodowicz, J.; Melodia, T. An acoustically powered battery-less internet of underwater things platform. In Proceedings of the 4th Underwater Communications and Networking Conference, UComms 2018, Lerici, Italy, 28–30 August 2018; pp. 1–5. [CrossRef]
63. Zhao, Y.; Du, Y.; Wang, Z.; Wang, J.; Geng, Y. Design of Ultrasonic Transducer Structure for Underwater Wireless Power Transfer System. In Proceedings of the 2021 IEEE Wireless Power Transfer Conference (WPTC), San Diego, CA, USA, 1–4 June 2021; pp. 1–4. [CrossRef]
64. Guida, R.; Demirors, E.; Dave, N.; Melodia, T. Underwater Ultrasonic Wireless Power Transfer: A Battery-Less Platform for the Internet of Underwater Things. *IEEE Trans. Mob. Comput.* **2022**, *21*, 1861–1873. [CrossRef]
65. Yang, H.; Wu, M.; Yu, Z.; Yang, J. An Ultrasonic Through-Metal-Wall Power Transfer System with Regulated DC Output. *Appl. Sci.* **2018**, *8*, 692. [CrossRef]
66. Yang, D.X.; Hu, Z.; Zhao, H.; Hu, H.F.; Sun, Y.Z.; Hou, B.J. Through-Metal-Wall Power Delivery and Data Transmission for Enclosed Sensors: A Review. *Sensors* **2015**, *15*, 31581–31605. [CrossRef]
67. Dai, X.; Li, L.; Li, Y.; Hou, G.; Leung, H.F.; Hu, A.P. Determining the maximum power transfer condition for Ultrasonic Power Transfer system. In Proceedings of the 2016 IEEE 2nd Annual Southern Power Electronics Conference (SPEC), Auckland, New Zealand, 5–8 December 2016; pp. 1–6. [CrossRef]
68. Li, Z.; Zhuang, G.; Wu, Z.; Li, B.; Zhang, X. Modeling of Ultrasonic Wireless Electrical Energy Transfer System. *Huanan Ligong Daxue Xuebao/J. South China Univ. Technol. Nat. Sci.* **2018**, *46*, 72–77. [CrossRef]
69. Sherrit, S.; Bao, X.; Badescu, M.; Aldrich, J.; Bar-Cohen, Y.; Biederman, W.; Chang, Z. KW Power Transmission using Wireless Acoustic-Electric Feed-through (WAEF). In Proceedings of the Earth and Space 2008 Conference, San Diego, CA, USA, 9–11 September 2008; pp. 1–10. [CrossRef]
70. Lawry, T.; Wilt, K.; Ashdown, J.; Scarton, H.; Saulnier, G. A High-Performance Ultrasonic System for the Simultaneous Transmission of Data and Power through Solid Metal Barriers. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **2013**, *60*, 194–203. [CrossRef]
71. Jegadeesan, R.; Agarwal, K.; Guo, Y.X.; Yen, S.C.; Thakor, N.V. Wireless Power Delivery to Flexible Subcutaneous Implants Using Capacitive Coupling. *IEEE Trans. Microw. Theory Tech.* **2017**, *65*, 280–292. [CrossRef]
72. Sarin, A.; Abbot, D.; Revzen, S.; Avestruz, A.T. Bidirectional Capacitive Wireless Power Transfer for Energy Balancing in Modular Robots. In Proceedings of the 2020 IEEE Applied Power Electronics Conference and Exposition (APEC), New Orleans, LA, USA, 15–19 March 2020; pp. 852–859. [CrossRef]
73. Wang, K.; Sanders, S. Contactless USB—A capacitive power and bidirectional data transfer system. In Proceedings of the 2014 IEEE Applied Power Electronics Conference and Exposition—APEC 2014, Fort Worth, TX, USA, 16–20 March 2014; pp. 1342–1347. [CrossRef]
74. Lu, F.; Zhang, H.; Mi, C. A Review on Recent Development of Capacitive Wireless Power Transfer Technology. *Energies* **2017**, *10*, 1752. [CrossRef]
75. Lecluyse, C.; Minnaert, B.; Kleemann, M. A Review of the Current State of Technology of Capacitive Wireless Power Transfer. *Energies* **2021**, *14*, 5862. [CrossRef]
76. Liang, J.; Wu, D.; Yu, J. A Design Method of Compensation Circuit for High-Power Dynamic Capacitive Power Transfer System Considering Coupler Voltage Distribution for Railway Applications. *Electronics* **2021**, *10*, 153. [CrossRef]
77. Machura, P.; Li, Q. A critical review on wireless charging for electric vehicles. *Renew. Sustain. Energy Rev.* **2019**, *104*, 209–234. [CrossRef]
78. Cai, C.; Liu, X.; Wu, S.; Chen, X.; Chai, W.; Yang, S. A Misalignment Tolerance and Lightweight Wireless Charging System via Reconfigurable Capacitive Coupling for Unmanned Aerial Vehicle Applications. *IEEE Trans. Power Electron.* **2023**, *38*, 22–26. [CrossRef]
79. Li, C.; Zhao, X.; Liao, C.; Wang, L. A graphical analysis on compensation designs of large-gap CPT systems for EV charging applications. *CES Trans. Electr. Mach. Syst.* **2018**, *2*, 232–242. [CrossRef]
80. Naka, Y.; Yamamoto, K.; Nakata, T.; Tamura, M. Improvement in efficiency of underwater wireless power transfer with electric coupling. *IEICE Trans. Electron.* **2017**, *E100.C*, 850–857. [CrossRef]

81. Naka, Y.; Yamamoto, K.; Nakata, T.; Tamura, M.; Masuda, M. Verification efficiency of electric coupling wireless power transfer in water. In Proceedings of the 2017 IEEE MTT-S International Conference on Microwaves for Intelligent Mobility, ICMIM 2017, Nagoya, Japan, 19–21 March 2017; pp. 83–86. [CrossRef]
82. Urano, M.; Ata, K.; Takahashi, A. Study on underwater wireless power transfer via electric coupling with a submerged electrode. In Proceedings of the IMFEDK 2017—2017 International Meeting for Future of Electron Devices Conference, Kyoto, Japan, 29–30 June 2017; pp. 36–37. [CrossRef]
83. Gao, Z.; Li, Y.; Jing, Q.; Liu, N. Study on the coupling structure of underwater wireless power transmission system via electric coupling. *J. Hohai Univ.* **2018**, *46*, 366–370. [CrossRef]
84. Tamura, M.; Naka, Y.; Murai, K. Design of capacitive coupler in underwater wireless power transfer focusing on kQ product. *IEICE Trans. Electron.* **2018**, *E101C*, 759–766. [CrossRef]
85. Mohamed, A.; Palazzi, V.; Kumar, S.; Alimenti, F.; Mezzanotte, P.; Roselli, L. Towards subsea non-ohmic power transfer via a capacitor-like structure. *Lect. Notes Electr. Eng.* **2019**, *550*, 349–357. [CrossRef]
86. Gao, Z.; Yu, G.; Liu, N. Design of electric-field coupled underwater wireless power transfer system based on class E amplifier. *J. Hohai Univ.* **2019**, *47*, 560–567. [CrossRef]
87. Tamura, M.; Murai, K.; Naka, Y. Capacitive Coupler Utilizing Electric Double Layer for Wireless Power Transfer under Seawater. In Proceedings of the IEEE MTT-S International Microwave Symposium Digest, Boston, MA, USA, 2–7 June 2019; pp. 1415–1418. [CrossRef]
88. Yang, L.; Ju, M.; Zhang, B. Bidirectional Undersea Capacitive Wireless Power Transfer System. *IEEE Access* **2019**, *7*, 121046–121054. [CrossRef]
89. Zhang, H.; Lu, F. Feasibility Study of the High-Power Underwater Capacitive Wireless Power Transfer for the Electric Ship Charging Application. In Proceedings of the 2019 IEEE Electric Ship Technologies Symposium, ESTS 2019, Washington, DC, USA, 14–16 August 2019; pp. 231–235. [CrossRef]
90. Tamura, M.; Murai, K.; Matsumoto, M. Conductive coupler for wireless power transfer under seawater. In Proceedings of the 2020 IEEE MTT-S International Microwave Symposium Digest, Los Angeles, CA, USA, 4–6 August 2020; pp. 1176–1179. [CrossRef]
91. Yang, L.; Ma, L.; Huang, J.; Fu, Y. Characteristics of Undersea Capacitive Wireless Power Transfer System. In Proceedings of the IEEE 9th International Power Electronics and Motion Control Conference, IPEMC 2020 ECCE Asia, Nanjing, China, 29 November–2 December 2020; pp. 2952–2955. [CrossRef]
92. Mahdi, H.; Hoff, B.; Østrem, T. Optimal Solutions for Underwater Capacitive Power Transfer. *Sensors* **2021**, *21*, 8233. [CrossRef]
93. Su, Y.; Qian, L.; Liu, Z.; Deng, R.; Sun, Y. Underwater Electric-Filed Coupled Wireless Power Transfer System with Rotary Coupler and Parameter Optimization Method. *Diangong Jishu Xuebao/Trans. China Electrotech. Soc.* **2022**, *37*, 2399–2410. [CrossRef]
94. Zhang, B.; Chen, J.; Wang, X.; Xu, W.; Lu, C.; Lu, Y. High-Power-Density Wireless Power Transfer System for Autonomous Underwater Vehicle Based on a Variable Ring-Shaped Magnetic Coupler. *IEEE Trans. Transp. Electrif.* **2023**. [CrossRef]
95. Orekan, T.; Zhang, P. *Underwater Wireless Power Transfer: Smart Ocean Energy Converters*; Springer International Publishing: Berlin/Heidelberg, Germany, 2019. [CrossRef]
96. Lu, X.; Niyato, D.; Wang, P.; Kim, D.I.; Han, Z. Wireless Charger Networking for Mobile Devices: Fundamentals, Standards, and Applications. *Wirel. Commun. IEEE* **2014**, *22*, 126–135. [CrossRef]
97. Ahn, D.; Mercier, P.P. Wireless Power Transfer with Concurrent 200-kHz and 6.78-MHz Operation in a Single-Transmitter Device. *IEEE Trans. Power Electron.* **2016**, *31*, 5018–5029. [CrossRef]
98. Berger, A.; Agostinelli, M.; Sandner, C.; Vesti, S.; Huemer, M. High efficient integrated power receiver for a Qi compliant Wireless Power Transfer system. In Proceedings of the 2016 IEEE Wireless Power Transfer Conference (WPTC), Aveiro, Portugal, 5–6 May 2016; pp. 1–4. [CrossRef]
99. Shah, S.A.A.; Khan, D.; Ain, Q.; Basim, M.; Shehzad, K.; Verma, D.; Kumar, P.; Yoo, J.M.; Pu, Y.G.; Jung, Y.; et al. A Design of Wireless Power Receiver with Gate Charge Recycled Dual-Mode Active Rectifier and Step-Down Converter with 88.2% System Efficiency for Power Management IC. *IEEE Trans. Power Electron.* **2023**, *38*, 1348–1360. [CrossRef]
100. Rooij, M.D.; Zhang, Y. A 10 W Multi-Mode Capable Wireless Power Amplifier for Mobile Devices. In Proceedings of the 2016 International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, Nuremberg, Germany, 10–12 May 2016; pp. 1–8.
101. Park, Y.J.; Jang, B.; Park, S.M.; Ryu, H.C.; Oh, S.J.; Kim, S.Y.; Pu, Y.; Yoo, S.S.; Hwang, K.C.; Yang, Y.; et al. A Triple-Mode Wireless Power-Receiving Unit with 85.5% System Efficiency for A4WP, WPC, and PMA Applications. *IEEE Trans. Power Electron.* **2018**, *33*, 3141–3156. [CrossRef]
102. Basar, M.R.; Ahmad, M.Y.; Cho, J.; Ibrahim, F. An improved resonant wireless power transfer system with optimum coil configuration for capsule endoscopy. *Sens. Actuators A Phys.* **2016**, *249*, 207–216. [CrossRef]
103. Vulfin, V.; Sayfan-Altman, S.; Ianconescu, R. Wireless power transfer for a pacemaker application. *J. Med. Eng. Technol.* **2017**, *41*, 325–332. [CrossRef]
104. Ahire, D.; Gond, V.J.; Chopade, J.J. Coil material and magnetic shielding methods for efficient wireless power transfer system for biomedical implant application. *Biosens. Bioelectron. X* **2022**, *10*, 100123. [CrossRef]
105. Sun, T.; Xie, X.; Wang, Z. *Wireless Power Transfer for Medical Microsystems*; Springer: New York, NY, USA, 2013; pp. 1–183. [CrossRef]

106. Yilmaz, G.; Dehollain, C. *Wireless Power Transfer and Data Communication for Neural Implants: Case Study*; Springer: Berlin/Heidelberg, Germany, 2017; pp. 1–109.
107. Ahire, D.; Gond, V.J.; Chopade, J.J. Compensation topologies for wireless power transmission system in medical implant applications: A review. *Biosens. Bioelectron. X* **2022**, *11*, 100180. [CrossRef]
108. Sagar, A.; Kashyap, A.; Nasab, M.A.; Padmanaban, S.; Bertoluzzo, M.; Kumar, A.; Blaabjerg, F. A Comprehensive Review of the Recent Development of Wireless Power Transfer Technologies for Electric Vehicle Charging Systems. *IEEE Access* **2023**, *11*, 83703–83751. [CrossRef]
109. Rayan, B.A.; Subramaniam, U.; Balamurugan, S. Wireless Power Transfer in Electric Vehicles: A Review on Compensation Topologies, Coil Structures, and Safety Aspects. *Energies* **2023**, *16*, 3084. [CrossRef]
110. Dankov, D.; Prodanov, P.; Madjarov, N. Application of an Inductive Power Transfer System for Charging Modern Electric Vehicles. In Proceedings of the 17th Conference on Electrical Machines, Drives and Power Systems (ELMA), Sofia, Bulgaria, 1–4 July 2021; pp. 1–6. [CrossRef]
111. Zhang, Z.; Pang, H., WPT for High-power Application – Electric Vehicles. In *Wireless Power Transfer: Principles and Applications*; John Wiley Sons, Inc.: Hoboken, NJ, USA, 2023; pp. 275–325. [CrossRef]
112. Zhang, X.; Yuan, Z.; Yang, Q.; Li, Y.; Zhu, J.; Li, Y. Coil Design and Efficiency Analysis for Dynamic Wireless Charging System for Electric Vehicles. *IEEE Trans. Magn.* **2016**, *52*, 1–4. [CrossRef]
113. Tan, Z.; Liu, F.; Chan, H.K.; Gao, H.O. Transportation systems management considering dynamic wireless charging electric vehicles: Review and prospects. *Transp. Res. Part E Logist. Transp. Rev.* **2022**, *163*, 1–17. [CrossRef]
114. Panchal, C.; Stegen, S.; Lu, J. Review of static and dynamic wireless electric vehicle charging system. *Eng. Sci. Technol. Int. J.* **2018**, *21*, 922–937. [CrossRef]
115. Ramakrishnan, V.; Savio A, D.; C, B.; Rajamanickam, N.; Kotb, H.; Elrashidi, A.; Nureldeen, W. A Comprehensive Review on Efficiency Enhancement of Wireless Charging System for the Electric Vehicles Applications. *IEEE Access* **2024**, *12*, 46967–46994. [CrossRef]
116. Ali, R.A.; Latif, M.H.; Usman, M. Existing Coil Topologies for Inductive Power Transfer in EV Charging: A Review. In Proceedings of the 5th International Conference on Energy Conservation and Efficiency (ICECE), Lahore, Pakistan, 16–17 March 2022; pp. 1–13. [CrossRef]
117. Song, K.; Lan, Y.; Zhang, X.; Jiang, J.; Sun, C.; Yang, G.; Yang, F.; Lan, H. A Review on Interoperability of Wireless Charging Systems for Electric Vehicles. *Energies* **2023**, *16*, 1653. [CrossRef]
118. Guidi, G.; Suul, J.A.; Jenset, F.; Sorfonn, I. Wireless Charging for Ships: High-Power Inductive Charging for Battery Electric and Plug-In Hybrid Vessels. *IEEE Electrif. Mag.* **2017**, *5*, 22–32. [CrossRef]
119. Feezor, M.; Blankinship, P.; Bellingham, J.; Sorrell, F. Autonomous underwater vehicle homing/docking via electromagnetic guidance. In Proceedings of the Oceans '97. MTS/IEEE Conference, Halifax, NS, Canada 6–9 October 1997; Volume 2, pp. 1137–1142. [CrossRef]
120. Fukasawa, T.; Noguchi, T.; Kawasaki, T.; Baino, M. "MARINE BIRD", a new experimental AUV with underwater docking and recharging system. In Proceedings of the Oceans 2003. Celebrating the Past ... Teaming Toward the Future Conference, San Diego, CA, USA, 22–26 September 2003; Volume 4, pp. 2195–2200. [CrossRef]
121. McGinnis, T.; Henze, C.P.; Conroy, K. Inductive Power System for Autonomous Underwater Vehicles. In Proceedings of the OCEANS 2007 Conference, Aberdeen, Scotland, 18–21 June 2007; pp. 1–5. [CrossRef]
122. Hobson, B.W.; McEwen, R.S.; Erickson, J.; Hoover, T.; McBride, L.; Shane, F.; Bellingham, J.G. The Development and Ocean Testing of an AUV Docking Station for a 21" AUV. In Proceedings of the OCEANS 2007 Conference, Aberdeen, Scotland, 18–21 June 2007; pp. 1–6. [CrossRef]
123. Pyle, D.; Granger, R.; Geoghegan, B.; Lindman, R.; Smith, J. Leveraging a large UUV platform with a docking station to enable forward basing and persistence for light weight AUVs. In Proceedings of the 2012 Oceans Conference, Virginia Beach, VA, USA, 14–19 October 2012; pp. 1–8. [CrossRef]
124. Yoshida, S.; Tanomura, M.; Hama, Y.; Hirose, T.; Suzuki, A.; Matsui, Y.; Sogo, N.; Sato, R. Underwater wireless power transfer for non-fixed unmanned underwater vehicle in the ocean. In Proceedings of the Autonomous Underwater Vehicles 2016 Conference, AUV 2016, Tokyo, Japan, 6–9 November 2016; pp. 177–180. [CrossRef]
125. Yoshida, H.; Ishibashi, S.; Yutaka, O.; Sugesawa, M.; Tanaka, K. A concept design of underwater docking robot and development of its fundamental technologies. In Proceedings of the 2016 IEEE Autonomous Underwater Vehicles Conference, Tokyo, Japan, 6–9 November 2016; pp. 408–411. [CrossRef]
126. Maguer, A.; Been, R.; Tesei, A.; Alves, J.; Grandi, V.; Biagini, S. Recent Technological Advances in Underwater Autonomy. In Proceedings of the 2018 OCEANS - MTS/IEEE Kobe Techno-Oceans (OTO) Conference, Kobe, Japan, 28–31 May 2018; pp. 1–8. [CrossRef]
127. Matsuda, T.; Maki, T.; Masuda, K.; Sakamaki, T. Resident autonomous underwater vehicle: Underwater system for prolonged and continuous monitoring based at a seafloor station. *Robot. Auton. Syst.* **2019**, *120*, 103231. [CrossRef]
128. Matsuda, T.; Maki, T.; Masuda, K.; Sakamaki, T.; Ohkuma, K. Port Experiments of the Docking and Charging System Using an AUV and a Seafloor Station: Towards Long-term Seafloor Observation. In Proceedings of the 2018 IEEE/OES Autonomous Underwater Vehicle Workshop, Porto, Portugal, 6–9 November 2018; pp. 1–5. [CrossRef]

129. Yang, C.; Lin, M.; Li, D. Improving Steady and Starting Characteristics of Wireless Charging for an AUV Docking System. *IEEE J. Ocean. Eng.* **2020**, *45*, 430–441. [CrossRef]
130. Heeres, B.; Novotny, D.; Divan, D.; Lorenz, R. Contactless underwater power delivery. In Proceedings of the 1994 Power Electronics Specialist Conference—PESC'94, Taipei, Taiwan, 20–25 June 1994; Volume 1, pp. 418–423. [CrossRef]
131. Huang, Y.; Fang, C.; Li, X. Contactless power and data transmission for underwater sensor nodes. *EURASIP J. Wirel. Commun. Netw.* **2013**, *2013*, 81–87. [CrossRef]
132. Lin, C.; Wang, K.; Chu, Z.; Wang, K.; Deng, J.; Obaidat, M.; Wu, G. Hybrid charging scheduling schemes for three-dimensional underwater wireless rechargeable sensor networks. *J. Syst. Softw.* **2018**, *146*, 42–58. [CrossRef]
133. Hwangbo, S.H.; Jeon, J.H.; Park, S.J. Wireless Underwater Monitoring Systems Based on Energy Harvestings. *Sens. Transducers* **2013**, *18*, 113–119.
134. Santana Sosa, G.; Santana Abril, J.; Sosa, J.; Montiel-Nelson, J.A.; Bautista, T. Design of a Practical Underwater Sensor Network for Offshore Fish Farm Cages. *Sensors* **2020**, *20*, 4459. [CrossRef]
135. Santana Abril, J.; Santana Sosa, G.; Sosa, J.; Bautista, T.; Montiel-Nelson, J. A Novel Charging Method for Underwater Batteryless Sensor Node Networks. *Sensors* **2021**, *21*, 557. [CrossRef]
136. Zhang, S.; Huang, X.; Du, Z. Charging path planning algorithm based on multi-parameters in underwater wireless rechargeable sensor network. *J. Phys. Conf. Ser.* **2021**, *1732*, 012077. [CrossRef]
137. Ahluwalia, U.; Chenevert, G.; Pratik, U.; Pantic, Z. System for Wireless Charging of Battery-Powered Underwater Sensor Networks. In Proceedings of the Oceans Conference Record (IEEE) 2022, Hampton Roads, VA, USA, 17–20 October 2022. [CrossRef]
138. Ma, Y.; Mao, Z.; Zhang, K. Optimization Design of Planar Circle Coil for Limited-Size Wireless Power Transfer System. *Appl. Sci.* **2022**, *12*, 2286. [CrossRef]
139. Zhang, B.; Wang, X.; Lu, C.; Lu, Y.; Xu, W. A wireless power transfer system for an autonomous underwater vehicle based on lightweight universal variable ring-shaped magnetic coupling. *Int. J. Circuit Theory Appl.* **2023**, *51*, 2654–2673. [CrossRef]
140. Sohn, Y.H.; Choi, B.H.; Lee, E.S.; Lim, G.C.; Cho, G.H.; Rim, C.T. General Unified Analyses of Two-Capacitor Inductive Power Transfer Systems: Equivalence of Current-Source SS and SP Compensations. *IEEE Trans. Power Electron.* **2015**, *30*, 6030–6045. [CrossRef]
141. Yan, Z.; Zhang, Y.; Zhang, K.; Song, B.; Li, S.; Kan, T.; Mi, C. Fault-Tolerant Wireless Power Transfer System with a Dual-Coupled LCC-S Topology. *IEEE Trans. Veh. Technol.* **2019**, *68*, 11838–11846. [CrossRef]
142. Kong, F.; Qu, X. Low Eddy Current Loss Constant Voltage Wireless Power Transfer System in Seawater. In Proceedings of the 2022 IEEE International Power Electronics and Application Conference and Exposition, Guangzhou, China, 4–7 November 2022; pp. 1342–1347. [CrossRef]
143. Yan, Z.; Zhang, Y.; Song, B.; Zhang, K.; Kan, T.; Mi, C. An LCC-p compensated wireless power transfer system with a constant current output and reduced receiver size. *Energies* **2019**, *12*, 172. [CrossRef]
144. Qiao, K.; Rong, E.; Sun, P.; Zhang, X.; Sun, J. Design of LCC-P Constant Current Topology Parameters for AUV Wireless Power Transfer. *Energies* **2022**, *15*, 5249. [CrossRef]
145. Yan, Z.; Song, B.; Zhang, Y.; Zhang, K.; Mao, Z.; Hu, Y. A Rotation-Free Wireless Power Transfer System with Stable Output Power and Efficiency for Autonomous Underwater Vehicles. *IEEE Trans. Power Electron.* **2019**, *34*, 4005–4008. [CrossRef]
146. Wen, H.; Li, J.; Yang, L.; Tong, X. Feasibility Study on Wireless Power Transfer for AUV with Novel Pressure-Resistant Ceramic Materials. In Proceedings of the 2022 International Power Electronics Conference (IPEC-Himeji 2022- ECCE Asia), Himeji, Japan, 15–19 May 2022; pp. 182–185. [CrossRef]
147. Zhou, Y.; Wang, Q.; Qiu, M.; Zhang, X. Research on Bilateral LCC Compensation Network of Underwater Wireless Charging System with Multi-resonance Point Switching. In Proceedings of the 2023 International Conference on Wireless Power Transfer (ICWPT2023), Weihai, China, 13–15 October 2023; Cai, C., Qu, X., Mai, R., Zhang, P., Chai, W., Wu, S., Eds.; Springer: Singapore, 2024; pp. 298–319.
148. Goncalves, F.; Duarte, C.; Pessoa, L. A Novel Circuit Topology for Underwater Wireless Power Transfer. In Proceedings of the 2nd International Conference on Systems Informatics, Modelling and Simulation, Okinawa, Japan, 24–26 November 2017; pp. 181–186. [CrossRef]
149. Imura, T. Chapter Comparison between Electromagnetic Induction and Magnetic Resonance Coupling; In *Wireless Power Transfer: Using Magnetic and Electric Resonance Coupling Techniques*; Springer: Singapore, 2020; pp. 113–174. [CrossRef]
150. Jenkins, A.; Bana, V.; Anderson, G. Impedance of a coil in seawater. In Proceedings of the 2014 IEEE Antennas and Propagation Society International Symposium (APSURSI), Memphis, TN, USA, 6–11 July 2014; pp. 625–626. [CrossRef]
151. Cheng, Z.; Lei, Y.; Song, K.; Zhu, C. Design and Loss Analysis of Loosely Coupled Transformer for an Underwater High-Power Inductive Power Transfer System. *IEEE Trans. Magn.* **2015**, *51*, 1–10. [CrossRef]
152. Niu, W.; Gu, W.; Chu, J. Experimental investigation of frequency characteristics of underwater wireless power transfer. In Proceedings of the 2018 IEEE MTT-S International Wireless Symposium, IWS 2018, Chengdu, China, 6–10 May 2018; pp. 1–3. [CrossRef]
153. Rozas Holgado, I.; Martínez de Alegría, I.; Kortabarria, I.; Andreu, J.; Martín, J.L. Wireless Power Transfer: Underwater loss analysis for different topologies and frequency values. In Proceedings of the IECON 2020 Conference, Singapore, 18–21 October 2020; pp. 3942–3947. [CrossRef]

154. Li, J.; Liu, K.; Xie, J.; Zhu, C.; Zhang, X. Frequency Optimization Method for Underwater Wireless Power Transfer Considering Coupling Conditions. In Proceedings of the 2022 IEEE Energy Conversion Congress and Exposition, ECCE 2022, Detroit, MI, USA, 9–13 October 2022; pp. 1–6. [CrossRef]
155. Li, W.; Zhu, J.; Wang, Y.; Liu, B. Modeling and Characteristic Analysis of Magnetic Coupling Mechanism in Seawater Environment. *IEEE Trans. Magn.* **2022**, *58*, 1–6. [CrossRef]
156. Niu, W.; Gu, W.; Chu, J.; Shen, A. Frequency splitting of underwater wireless power transfer. In Proceedings of the 2016 IEEE International Workshop on Electromagnetics, iWEM 2016, Nanjing, China, 16–18 May 2016; pp. 1–3. [CrossRef]
157. Yan, Z.; Zhang, Y.; Kan, T.; Lu, F.; Zhang, K.; Song, B.; Mi, C. Frequency optimization of a loosely coupled underwater wireless power transfer system considering eddy current loss. *IEEE Trans. Ind. Electron.* **2019**, *66*, 3468–3476. [CrossRef]
158. Zhang, K.; Ma, Y.; Yan, Z.; Di, Z.; Song, B.; Hu, A. Eddy Current Loss and Detuning Effect of Seawater on Wireless Power Transfer. *IEEE J. Emerg. Sel. Top. Power Electron.* **2020**, *8*, 909–917. [CrossRef]
159. Bana, V.; Kerber, M.; Anderson, G.; Rockway, J.; Phipps, A. Underwater wireless power transfer for maritime applications. In Proceedings of the 2015 IEEE Wireless Power Transfer Conference, WPTC 2015, Boulder, CO, USA, 13–15 May 2015; pp. 1–4. [CrossRef]
160. Mohsan, S.A.H.; Khan, M.A.; Mazinani, A.; Alsharif, M.H.; Cho, H.S. Enabling Underwater Wireless Power Transfer towards Sixth Generation (6G) Wireless Networks: Opportunities, Recent Advances, and Technical Challenges. *J. Mar. Sci. Eng.* **2022**, *10*, 1282. [CrossRef]
161. Zhang, K.H.; Zhu, Z.B.; Song, B.W.; Xu, D.M. A power distribution model of magnetic resonance WPT system in seawater. In Proceedings of the 2016 IEEE 2nd Annual Southern Power Electronics Conference, SPEC 2016, Auckland, New Zealand, 5–8 December 2016; pp. 1–4. [CrossRef]
162. Hayslett, T.; Orekan, T.; Zhang, P. Underwater wireless power transfer for ocean system applications. In Proceedings of the OCEANS 2016 Conference, Washington, DC, USA, 15–16 September 2016; pp. 1–6. [CrossRef]
163. Niu, W.; Ye, C.; Gu, W. Circuit coupling model containing equivalent eddy current loss impedance for wireless power transfer in seawater. *Int. J. Circuits Syst. Signal Process.* **2021**, *15*, 410–416. [CrossRef]
164. Xu, F.; Huang, H. Frequency selection for underwater wireless power transfer based on the analysis of eddy current loss. *AEU—Int. J. Electron. Commun.* **2023**, *163*, 154618. [CrossRef]
165. Li, Z.; Li, D.; Lin, L.; Chen, Y. Design considerations for electromagnetic couplers in contactless power transmission systems for deep-sea applications. *J. Zhejiang Univ. Sci. C* **2010**, *11*, 824–834. [CrossRef]
166. Yan, Z.; Song, B.; Zhang, K.; Wen, H.; Mao, Z.; Hu, Y. Eddy current loss analysis of underwater wireless power transfer systems with misalignments. *AIP Adv.* **2018**, *8*, 1–6. [CrossRef]
167. Mostafa, A.; Wang, Y.; Zhang, H.; Tangirala, S.; Lu, F. An Ultra-Fast Wireless Charging System with a Hull-Compatible Coil Structure for Autonomous Underwater Vehicles (AUVs). In Proceedings of the 2022 IEEE Transportation Electrification Conference and Expo (ITEC), Anaheim, CA, USA, 15–17 June 2022; pp. 279–284. [CrossRef]
168. Goncalves, F.; Pereira, A.; Morais, A.; Duarte, C.; Gomes, R.; Pessoa, L. An adaptive system for underwater wireless power transfer. In Proceedings of the International Congress on Ultra Modern Telecommunications and Control Systems and Workshops, Lisbon, Portugal, 18–20 October 2016; pp. 101–105. [CrossRef]
169. Lopes, I.F.; Coelho, D.C.; Aguilar Bojorge, E.V.; Andrade de Oliveira, L.R.; Oliveira Almeida, A.; Barbosa, P.G. Underwater Wireless Power Transfer with High Tolerance to Misalignments. In Proceedings of the 2021 Brazilian Power Electronics Conference, João Pessoa, Brazil, 7–10 November 2021; pp. 1–5. [CrossRef]
170. Mototani, S.; Yamamoto, R.; Doki, K.; Torii, A. Effect of Angle Offset of the Power Receiving Coil in Underwater Wireless Power Transfer Using a Cone Spiral Coil. In Proceedings of the 2022 International Power Electronics Conference, IPEC, Himeji, Japan, 15–19 May 2022; pp. 167–174. [CrossRef]
171. Zeng, Y.; Rong, C.; Lu, C.; Tao, X.; Liu, X.; Liu, R.; Liu, M. Misalignment Insensitive Wireless Power Transfer System Using a Hybrid Transmitter for Autonomous Underwater Vehicles. *IEEE Trans. Ind. Appl.* **2022**, *58*, 1298–1306. [CrossRef]
172. Wang, D.; Chen, F.; Zhang, J.; Cui, S.; Bie, Z.; Zhu, C. A Novel Pendulum-Type Magnetic Coupler with High Misalignment Tolerance for AUV Underwater Wireless Power Transfer Systems. *IEEE Trans. Power Electron.* **2023**, *38*, 14861–14871. [CrossRef]
173. Kang, L.; Hu, Y.; Zheng, W. Maximum power efficiency tracking on underwater magnetic resonant wireless power transfer system. *Harbin Gongcheng Daxue Xuebao/J. Harbin Eng. Univ.* **2017**, *38*, 829–835. [CrossRef]
174. Lopes, I.; Lacerda Valle, R.; Azevedo Fogli, G.; Ferreira, A.; Gomes Barbosa, P. Low-Frequency Underwater Wireless Power Transfer: Maximum Efficiency Tracking Strategy. *IEEE Lat. Am. Trans.* **2020**, *18*, 1200–1208. [CrossRef]
175. Zheng, Z.; Wang, N.; Ahmed, S. Maximum efficiency tracking control of underwater wireless power transfer system using artificial neural networks. *Proc. Inst. Mech. Eng. Part I J. Syst. Control Eng.* **2021**, *235*, 1819–1829. [CrossRef]
176. Hassnain Mohsan, S.; Islam, A.; Khan, M.; Mahmood, A.; Rokia, L.; Mazinani, A.; Amjad, H. A review on research challenges, limitations and practical solutions for underwater wireless power transfer. *Int. J. Adv. Comput. Sci. Appl.* **2020**, *11*, 554–562. [CrossRef]
177. Flemming, H.C. *Microbial Biofouling: Unsolved Problems, Insufficient Approaches, and Possible Solutions*; Springer: Berlin/Heidelberg, Germany, 2011; Volume 5, pp. 81–109. [CrossRef]
178. Anderson, G.; Bana, V.; Kerber, M.; Phipps, A.; Rockway, J.D. *Marine Fouling and Thermal Dissipation of Undersea Wireless Power Transfer*; Technical Report; Space and Naval Warfare Systems Center Pacific (SPAWAR): San Diego, CA, USA, 2014.

179. Pittini, R.; Hernes, M.; Petterteig, A. Pressure Tolerant Power Electronics for Deep and Ultra-Deep Water. *Oil Gas Facil.* **2011**, *1*, 47–52. [CrossRef]
180. AG, T.E. *The Impact of Pressure on Ferrites*; Technical Report; TDK Electronics AG (Previously EPCOS): Munich, Germany, 2009.
181. Pereira, P.; Campilho, R.; Pinto, A. Application of a Design for Excellence Methodology for a Wireless Charger Housing in Underwater Environments. *Machines* **2022**, *10*, 232. [CrossRef]
182. Nyqvist, D.; Durif, C.; Johnsen, M.G.; De Jong, K.; Forland, T.N.; Sivle, L.D. Electric and magnetic senses in marine animals, and potential behavioral effects of electromagnetic surveys. *Mar. Environ. Res.* **2020**, *155*, 104888. [CrossRef] [PubMed]
183. Hutchison, Z.L.; Gill, A.B.; Sigray, P.; He, H.; King, J.W. Anthropogenic electromagnetic fields (EMF) influence the behaviour of bottom-dwelling marine species. *Sci. Rep.* **2020**, *10*, 4219. [CrossRef] [PubMed]
184. Wang, Y.; Song, B.; Mao, Z. Application of shielding coils in underwater wireless power transfer systems. *J. Mar. Sci. Eng.* **2019**, *7*, 267. [CrossRef]
185. Yang, L.; Zhang, Y.; Li, X.; Feng, B.; Huang, J.; Zhu, D.; Zhang, A.; Tong, X. The Impact of Metal Hull of AUVs for Underwater Wireless Power Transfer System. In Proceedings of the 2022 International Conference on Wireless Power Transfer (ICWPT2022), Chongqing, China, 28–31 October 2022; pp. 218–228. [CrossRef]
186. Subsea Docking Station (SDS). 2019. Available online: https://www.bluelogic.no/news-and-media/subsea-docking-station-sds- (accessed on 13 April 2023).
187. Rolland, E.S.; Haji, M.N.; Weck, O.L. Autonomous Control of a Prototype Solar-powered Offshore AUV Servicing Platform. In Proceedings of the OCEANS 2021 Conference, San Diego, CA, USA, 20–23 September 2021; pp. 1–10. [CrossRef]
188. Sun, X.Y.; Deng, B.; Zhang, J.; Kelly, M.; Alam, R.; Makiharju, S. Reimagining Autonomous Underwater Vehicle Charging Stations with Wave Energy. *Berkeley Sci. J.* **2021**, *25*, 74–78. [CrossRef]
189. Zhou, J.; Yao, P.; Chen, Y.; Guo, K.; Hu, S.; Sun, H. Design Considerations for a Self-Latching Coupling Structure of Inductive Power Transfer for Autonomous Underwater Vehicle. *IEEE Trans. Ind. Appl.* **2021**, *57*, 580–587. [CrossRef]
190. Hasaba, R.; Eguchi, K.; Yamaguchi, S.; Satoh, H.; Yagi, T.; Koyanagi, Y. WPT System in Seawater for AUVs with kW-class Power, High Positional Freedom, and High Efficiency inside the Transfer Coils. In Proceedings of the 2022 Wireless Power Week Conference, Bordeaux, France, 5–8 July 2022; pp. 90–94. [CrossRef]
191. Wu, B.; Liu, J.; Yu, H.; Li, Z.; Chen, Y. Underwater high-power inductive coupling energy transmission system. In Proceedings of the OCEANS 2016 Conference, Washington, DC, USA, 15–16 September 2016; pp. 1–5. [CrossRef]
192. Meşe, H.; Budak, M.A. Efficiency Investigation of a 400W Resonant Inductive Wireless Power Transfer System for Underwater Unmanned Vehicles. In Proceedings of the 2020 IEEE Wireless Power Transfer Conference (WPTC), Seoul, Republic of Korea, 15–19 November 2020; pp. 223–226. [CrossRef]
193. Liu, Z.; Wang, L.; Guo, Y.; Tao, C. Eddy current loss analysis of wireless power transfer system for autonomous underwater vehicles. In Proceedings of the 2020 IEEE PELS Workshop on Emerging Technologies: Wireless Power Transfer, WoW 2020, Seoul, Republic of Korea, 15–19 November 2020; pp. 283–287. [CrossRef]
194. Lin, M.; Li, D.; Yang, C. Design of an ICPT system for battery charging applied to underwater docking systems. *Ocean Eng.* **2017**, *145*, 373–381. [CrossRef]
195. Song, B.; Wang, Y.; Zhang, K.; Mao, Z. Research on wireless power transfer system for Torpedo autonomous underwater vehicles. *Adv. Mech. Eng.* **2018**, *10*, 1–8. [CrossRef]
196. Guo, K.; Zhou, J.; Sun, H.; Yao, P. Design Considerations for a Position-Adaptive Contactless Underwater Power Deliver System. In Proceedings of the 22nd International Conference on Electrical Machines and Systems, ICEMS 2019, Harbin, China, 11–14 August 2019; pp. 1–6. [CrossRef]
197. Liu, P.; Gao, T.; Zhao, R.; Mao, Z. A Novel Conformal Coil Structure Design of Wireless Power Transfer System for Autonomous Underwater Vehicles. *J. Mar. Sci. Eng.* **2022**, *10*, 875. [CrossRef]
198. Zhang, K.; Dai, F.; Li, X.; Yan, Z.; Zhang, F.; Mao, Z.; Hu, A.P. Analysis of Power Transfer Characteristics of IPT System with Near Field Magnetic Coupling. *IEEE Trans. Electromagn. Compat.* **2023**, *65*, 890–899. [CrossRef]
199. Wen, H.; Wang, P.; Li, J.; Yang, J.; Zhang, K.; Yang, L.; Zhao, Y.; Tong, X. Improving the Misalignment Tolerance of Wireless Power Transfer System for AUV with Solenoid-Dual Combined Planar Magnetic Coupler. *J. Mar. Sci. Eng.* **2023**, *11*, 1571. [CrossRef]
200. Shi, J.G.; Li, D.J.; Yang, C.J. Design and analysis of an underwater inductive coupling power transfer system for autonomous underwater vehicle docking applications. *J. Zhejiang Univ.—Sci. C* **2014**, *15*, 51–62. [CrossRef]
201. Shizuno, K.; Yoshida, S.; Tanomura, M.; Hama, Y. Long distance high efficient underwater wireless charging system using dielectric-assist antenna. In Proceedings of the 2014 OCEANS Conference, Washington, DC, USA, 16–17 June 2014; pp. 1–3. [CrossRef]
202. Santos, H.; Pereira, M.; Pessoa, L.; Salgado, H. Design and optimization of air core spiral resonators for magnetic coupling wireless power transfer on seawater. In Proceedings of the 2016 IEEE Wireless Power Transfer Conference, WPTC 2016, Aveiro, Portugal, 5–6 May 2016; pp. 1–4. [CrossRef]
203. Ressurreição, T.; Gonçalves, F.; Duarte, C.; Gonçalves, R.; Gomes, R.; Santos, R.; Esteves, R.; Pinto, P.; Oliveira, I.; Pessoa, L.M. System design for wireless powering of AUVs. In Proceedings of the OCEANS 2017 Conference, New York, NY, USA, 5–9 June 2017; pp. 1–6. [CrossRef]
204. Silva, M.; Duarte, C.; Goncalves, F.; Correia, V.; Pessoa, L. Power Transmitter Design for Underwater WPT. In Proceedings of the OCEANS 2019 Marseille Conference, Marseilles, France, 17–20 June 2019; pp. 1–5. [CrossRef]

205. Dou, Y.; Zhao, D.; Ouyang, Z.; Andersen, M. Investigation and design of wireless power transfer system for autonomous underwater vehicle. In Proceedings of the IEEE Applied Power Electronics Conference and Exposition—APEC, Anaheim, CA, USA, 17–21 March 2019; pp. 3144–3150. [CrossRef]
206. Anyapo, C.; Intani, P. Wireless power transfer for autonomous underwater vehicle. In Proceedings of the 2020 IEEE PELS Workshop on Emerging Technologies: Wireless Power Transfer, WoW 2020, Seoul, Republic of Korea, 15–19 November 2020; pp. 246–249. [CrossRef]
207. Pereira, M.; Santos, H.; Pessoa, L.; Salgado, H. Simulation and experimental evaluation of a resonant magnetic wireless power transfer system for seawater operation. In Proceedings of the OCEANS 2016 Conference, Washington, DC, USA, 15–16 September 2016; pp. 1–5. [CrossRef]
208. Manikandan, J.; Vishwanath, A.; Korulla, M. Design of a 1kW Underwater Wireless Charging Station for Underwater Data Gathering Systems. In Proceedings of the 2018 International Conference on Advances in Computing, Communications and Informatics (ICACCI), Kochi, India, 13–15 September 2018; pp. 211–216. [CrossRef]
209. Cai, C.; Qin, M.; Wu, S.; Yang, Z. A Strong Misalignmentt Tolerance Magnetic Coupler for Autonomous Underwater Vehicle Wireless Power Transfer System. In Proceedings of the 2018 IEEE International Power Electronics and Application Conference and Exposition (PEAC), Shenzhen, China, 4–7 November 2018; pp. 1–5. [CrossRef]
210. Wang, D.; Cui, S.; Zhang, J.; Bie, Z.; Song, K.; Zhu, C. A Novel Arc-Shaped Lightweight Magnetic Coupler for AUV Wireless Power Transfer. *IEEE Trans. Ind. Appl.* **2022**, *58*, 1315–1329. [CrossRef]
211. Cai, C.; Zhang, Y.; Wu, S.; Liu, J.; Zhang, Z.; Jiang, L. A Circumferential Coupled Dipole-Coil Magnetic Coupler for Autonomous Underwater Vehicles Wireless Charging Applications. *IEEE Access* **2020**, *8*, 65432–65442. [CrossRef]
212. Qiao, K.; Sun, P.; Rong, E.; Sun, J.; Zhou, H.; Wu, X. Anti-misalignment and lightweight magnetic coupler with H-shaped receiver structure for AUV wireless power transfer. *IET Power Electron.* **2022**, *15*, 1843–1857. [CrossRef]
213. Zeng, Y.; Lu, C.; Liu, R.; He, X.; Rong, C.; Liu, M. Wireless Power and Data Transfer System Using Multidirectional Magnetic Coupler for Swarm AUVs. *IEEE Trans. Power Electron.* **2023**, *38*, 1440–1444. [CrossRef]
214. Kan, T.; Mai, R.; Mercier, P.P.; Mi, C.C. Design and Analysis of a Three-Phase Wireless Charging System for Lightweight Autonomous Underwater Vehicles. *IEEE Trans. Power Electron.* **2018**, *33*, 6622–6632. [CrossRef]
215. Yan, Z.; Zhang, Y.; Zhang, K.; Song, B.; Mi, C. Underwater wireless power transfer system with a curly coil structure for AUVs. *IET Power Electron.* **2019**, *12*, 2559–2565. [CrossRef]
216. Cai, C.; Wu, S.; Zhang, Z.; Jiang, L.; Yang, S. Development of a Fit-to-Surface and Lightweight Magnetic Coupler for Autonomous Underwater Vehicle Wireless Charging Systems. *IEEE Trans. Power Electron.* **2021**, *36*, 9927–9940. [CrossRef]
217. Lin, M.; Lin, R.; Li, D.; Duan, R. Development of a Radially Coupled Wireless Charging System for Torpedo-Shaped Autonomous Underwater Vehicles. *J. Mar. Sci. Eng.* **2023**, *11*, 1180. [CrossRef]
218. Xia, T.; Li, H.; Yu, H.; Zhang, Y.; Hu, P. A Circular-Arc-Type Magnetic Coupler with Strong Misalignment Tolerance for AUV Wireless Charging System. *J. Mar. Sci. Eng.* **2023**, *11*, 162. [CrossRef]
219. Hasaba, R.; Okamoto, K.; Kawata, S.; Eguchi, K.; Koyanagi, Y. Magnetic resonance wireless power transfer over 10 m with multiple coils immersed in seawater. *IEEE Trans. Microw. Theory Tech.* **2019**, *67*, 4505–4513. [CrossRef]
220. Wu, S.; Cai, C.; Wang, A.; Qin, Z.; Yang, S. Design and Implementation of a Uniform Power and Stable Efficiency Wireless Charging System for Autonomous Underwater Vehicles. *IEEE Trans. Ind. Electron.* **2022**, *70*, 5674–5684. [CrossRef]
221. Zhang, H.; Zhao, Y.; Huang, J.; Zhang, J.; Ji, Y. Propagation Modeling for Underwater Magnetic MISO Wireless Power Transfer. In Proceedings of the 2019 IEEE MTT-S International Wireless Symposium, IWS 2019, Guangzhou, China, 19–22 May 2019; pp 1–3. [CrossRef]
222. Yan, Z.; Zhang, K.; Qiao, L.; Hu, Y.; Song, B. A Multiload Wireless Power Transfer System with Concentrated Magnetic Field for AUV Cluster System. *IEEE Trans. Ind. Appl.* **2022**, *58*, 1307–1314. [CrossRef]
223. Zhang, K.; Zhang, X.; Zhu, Z.; Yan, Z.; Song, B.; Mi, C. A new coil structure to reduce eddy current loss of wpt systems for underwater vehicles. *IEEE Trans. Veh. Technol.* **2019**, *68*, 245–253. [CrossRef]
224. Sato, N.; Kifune, H.; Komeda, S. A coil layout of wireless power transfer systems based on multicoil arrangement for underwater vehicles. *Electr. Eng. Jpn. Engl. Transl. Denki Gakkai Ronbunshi* **2019**, *207*, 38–48. [CrossRef]
225. Yan, Z.; Wu, M.; Zhao, C.; Hu, Q.; Zhu, L.; Qiao, L.; Wang, L. Free-Rotation Wireless Power Transfer System Based on Composite Anti-Misalignment Method for AUVs. *IEEE Trans. Power Electron.* **2023**, *38*, 4262–4266. [CrossRef]
226. Da, C.; Wang, L.; Li, F.; Tao, C.; Zhang, Y. Analysis of Undersea Simultaneous Wireless Power and 1Mbps Data Rate Transfer System Based on DDQ Coil. *IEEE Trans. Power Electron.* **2023**, *38*, 11814–11825. [CrossRef]
227. Sun, A.; Zhu, J.; Wang, F.; Liu, B. Modeling and efficiency optimized control of DD Orthogonal wireless power transfer system. In Proceedings of the 2023 IEEE 6th International Electrical and Energy Conference (CIEEC), Hefei, China, 12–14 May 2023; pp. 2306–2311. [CrossRef]
228. Cai, T.; Lyu, F.; Wang, T.; Huang, F. Design of a Highly Compatible Underwater Wireless Power Transfer Station for Seafloor Observation Equipment. *J. Mar. Sci. Eng.* **2023**, *11*, 1205. [CrossRef]

229. Niu, S.; Zhao, Q.; Chen, H.; Yu, H.; Niu, S.; Jian, L. Underwater Wireless Charging System of Unmanned Surface Vehicles with High Power, Large Misalignment Tolerance and Light Weight: Analysis, Design and Optimization. *Energies* **2022**, *15*, 9529. [CrossRef]
230. Xu, Y.; Yang, J.; Zeng, M.; Dong, L. Wireless Power Transfer System of AUV Based on Improved Coil Structure with Stable Output Power and Efficiency. In Proceedings of the 17th IEEE Conference on Industrial Electronics and Applications ICIEA 2022, Chengdu, China, 16–19 December 2022; pp. 561–565. [CrossRef]
231. Kuroda, J.; Ogawa, M.; Yamaguchi, I.; Sato, R.; Sogo, N.; Matsui, Y. Design of underwater power transfer antenna coverd with resin sealing layer. In Proceedings of the 2018 OCEANS - MTS/IEEE Kobe Techno-Oceans (OTO) Conference, Kobe, Japan, 28–31 May 2018; pp. 1–6. [CrossRef]
232. Hu, Y.; Kang, L.; Zheng, W.; Bai, J. Impedance matching control method for an underwater magnetic resonance-based wireless power transfer system with metamaterials. *J. Electromagn. Waves Appl.* **2016**, *30*, 2003–2019. [CrossRef]
233. Ogihara, M.; Ebihara, T.; Mizutani, K.; Wakatsuki, N. Wireless power and data transfer system for station-based autonomous underwater vehicles. In Proceedings of the OCEANS 2015 Conference, Washington, DC, USA, 5–6 October 2015; pp. 1–5. [CrossRef]
234. Shi, J.; Li, F.; Peng, S.; Cai, W.; Pan, M.; Yu, H. Design and analysis of a noninsert wet mateable connector for underwater power and data transfer. *Mar. Technol. Soc. J.* **2020**, *54*, 65–78. [CrossRef]
235. Wang, Y.; Li, T.; Zeng, M.; Mai, J.; Gu, P.; Xu, D. An Underwater Simultaneous Wireless Power and Data Transfer System for AUV with High-Rate Full-Duplex Communication. *IEEE Trans. Power Electron.* **2023**, *38*, 619–633. [CrossRef]
236. Chen, G.; Sun, Y.; Huang, J.; Zhou, B.; Meng, F.; Tang, C. Wireless Power and Data Transmission System of Submarine Cable-Inspecting Robot Fish and Its Time-Sharing Multiplexing Method. *Electronics* **2019**, *8*, 838. [CrossRef]
237. Li, T.; Sun, Z.; Wang, Y.; Mai, J.; Xu, D. An Underwater Simultaneous Wireless Power and Data Transfer System with 1-Mbps Full-Duplex Communication Link. *IEEE Trans. Ind. Inform.* **2023**, *20*, 2620–2631. [CrossRef]
238. Cai, C.; Li, J.; Wu, S.; Qin, Z.; Chai, W.; Yang, S. A Bipolar and Unipolar Magnetic Channel Multiplexed WPT System with Simultaneous Full-Duplex Communication for Autonomous Underwater Vehicles. *IEEE Trans. Power Electron.* **2023**, *38*, 15086–15090. [CrossRef]
239. Xu, J.; Li, X.; Li, H.; Xie, Z.; Ma, Q. Maximum Efficiency Tracking for Multitransmitter Multireceiver Wireless Power Transfer System on the Submerged Buoy. *IEEE Trans. Ind. Electron.* **2022**, *69*, 1909–1919. [CrossRef]
240. Zheng, Z.; Wang, N.; Ahmed, S. Decoupling Control Scheme Bridging Frequency Tracking and DC Output Stabilizing for Wireless Charging System of Autonomous Underwater Vehicles. *Int. J. Control. Autom. Syst.* **2022**, *20*, 1099–1110. [CrossRef]
241. Yang, L.; Zhang, B.; Ju, M. A fast dynamic response regulation method for undersea wireless power transfer system. In Proceedings of the 14th IEEE Conference on Industrial Electronics and Applications, ICIEA 2019, Xi'an, China, 19–21 June 2019; pp. 1162–1166. [CrossRef]
242. Siroos, A.; Sedighizadeh, M.; Afjei, E.; Fini, A. Comparison of different controllers for wireless charging system in AUVs. In Proceedings of the 13th Power Electronics, Drive Systems, and Technologies Conference, PEDSTC 2022, Tehran, Iran, 1–3 February 2022; pp. 155–160. [CrossRef]
243. Pang, S.; Xu, J.; Li, H.; Ma, Q.; Li, X. Dual-frequency modulation to achieve power independent regulation for dual-load underwater wireless power connector. *IEEE J. Emerg. Sel. Top. Power Electron.* **2022**, *11*, 2377–2389. [CrossRef]
244. Bagchi, A.C.; Wang, H.; Saha, T.; Zane, R. Small-Signal Phasor Modeling of an Underwater IPT System in Constant Current Distribution. In Proceedings of the 2019 IEEE Applied Power Electronics Conference and Exposition (APEC), Anaheim, CA, USA, 17–21 March 2019; pp. 876–883. [CrossRef]
245. Kim, J.; Kim, K.; Kim, H.; Kim, D.; Park, J.; Ahn, S. An Efficient Modeling for Underwater Wireless Power Transfer Using Z-Parameters. *IEEE Trans. Electromagn. Compat.* **2019**, *61*, 2006–2014. [CrossRef]
246. Liang, B.; Mao, Z.; Zhang, K.; Liu, P. Analysis and Optimal Design of a WPT Coupler for Underwater Vehicles Using Non-Dominated Sorting Genetic Algorithm. *Appl. Sci.* **2022**, *12*, 2015. [CrossRef]
247. Xia, T.; Zhang, X.; Zhu, Z.; Yu, H.; Li, H. An Adaptive Control Strategy for Underwater Wireless Charging System Output Power with an Arc-Shaped Magnetic Core Structure. *J. Mar. Sci. Eng.* **2023**, *11*, 294. [CrossRef]
248. Sanborn, G.; Phipps, A. Standards and methods of power control for variable power bidirectional wireless power transfer. In Proceedings of the 2017 IEEE Wireless Power Transfer Conference (WPTC), Taipei, Taiwan, 10–12 May 2017; pp. 1–4. [CrossRef]
249. Kerber, M.; Offord, B.; Phipps, A. Design considerations for an active rectifier circuit for bidirectional wireless power transfer. In Proceedings of the Wireless Power Transfer Conference—WPTC 2017, Taipei, Taiwan, 10–12 May 2017; pp. 1–4. [CrossRef]
250. Lin, M.; Zhang, F.; Yang, C.; Li, D.; Lin, R. Design of bidirectional power converters coupled with coils for wireless charging of AUV docking systems. *J. Mar. Sci. Technol.* **2022**, *27*, 873–886. [CrossRef]
251. Dongye, Z.; Mei, W.; Yuan, J.; Li, T.; Yuan, Q.; Diao, L. Bidirectional Inductive Power Transfer for Unmanned Underwater Vehicles. In Proceedings of the 2023 IEEE 6th International Electrical and Energy Conference (CIEEC), Hefei, China, 12–14 May 2023; pp. 2411–2416. [CrossRef]
252. Tolstonogov, A.Y.; Chemezov, I.A.; Kolomeitsev, A.Y.; Storozhenko, V.A. The Modular Approach for Underwater Vehicle Design. In Proceedings of the Global Oceans 2020 Conference, Singapore, 5–31 October 2020; pp. 1–7. [CrossRef]

253. Agostinho, L.; Ricardo, N.; Silva, R.; Pinto, A. A Modular Inductive Wireless Charging Solution for Autonomous Underwater Vehicles. In Proceedings of the 2021 IEEE International Conference on Autonomous Robot Systems and Competitions, ICARSC 2021, Santa Maria da Feira, Portugal, 28–29 April 2021; pp. 68–73. [CrossRef]
254. Vaughan, C.H. A System for the Transmission of Electrical Energy to or from a Submerged Body. United Kingdom, Patent number: GB499037 1937. Available online: https://patents.google.com/patent/GB499037A/en?oq=GB499037#citedBy (accessed on 8 April 2024).