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Review

Enabling Underwater Wireless Power Transfer towards Sixth Generation (6G) Wireless Networks: Opportunities, Recent Advances, and Technical Challenges

Syed Agha Hassnain Mohsan [1], Muhammad Asghar Khan [2], Alireza Mazinani [3], Mohammed H. Alsharif [4] and Ho-Shin Cho [5,*]

1 Ocean College, Zhejiang University, Zheda Road 1, Zhoushan 316021, China
2 Department of Electrical Engineering, Hamdard Institute of Engineering & Technology, Islamabad 44000, Pakistan
3 School of Electronic and Information Engineering, Beihang University, Beijing 100000, China
4 Department of Electrical Engineering, College of Electronics and Information Engineering, Sejong University, Seoul 05006, Korea
5 School of Electronic and Electrical Engineering, Kyungpook National University, Daegu 41566, Korea
* Correspondence: hscho@ee.knu.ac.kr

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Abstract: In recent decades, wireless power transfer (WPT) has gained significant interest from both academic and industrial experts. It possesses natural electrical isolation between transmitter and receiver components, ensuring a secure charging mechanism in an underwater scenario. This groundbreaking technology has also enabled power transmission in the deep-sea environment. However, the stochastic nature of the ocean highly influences underwater wireless power transmission and transfer efficiency is not up to that of terrestrial WPT systems. Recently, the research fraternity has focused on WPT in the air medium, while underwater wireless power transfer (UWPT) is challenging and yet to be explored. The major concerns are ocean current disturbance, bio-fouling, extreme pressure and temperature, seawater conductivity and attenuation. Thus, it is essential to address these challenges, which cause a substantial energy loss in UWPT. This study presents a comparison between various WPT techniques and highlights the research contributions in UWPT in recent years. Research and engineering challenges, practical considerations, and applications are analyzed in this review. We have also addressed influencing factors such as coil orientation, coil misalignment and seawater effects in order to realize an efficient and flexible UWPT system. In addition, this study proposes multiple-input and multiple-output (MIMO) wireless power transmission, which can significantly improve the endurance of autonomous underwater vehicles (AUVS). This idea can be applied to the design of an underwater wireless power station for self-charging of AUVs.

Keywords: underwater wireless power transfer; WPT; AUV; 6G; MIMO; self-charging

1. Introduction

The extensive research activities and rapidly growing market of electrical vehicles [1,2] and implantable devices [3,4] have reinvigorated the demand for wireless technologies. Wireless communications are considered one of the most successful technological innovations in modern history. To date, five (5) generations of wireless cellular communications are deployed and marketed by telecommunication operators, with the recent generation being the fifth generation (5G) wireless network [5]. Figure 1 presents the evolution of wireless cellular communications.

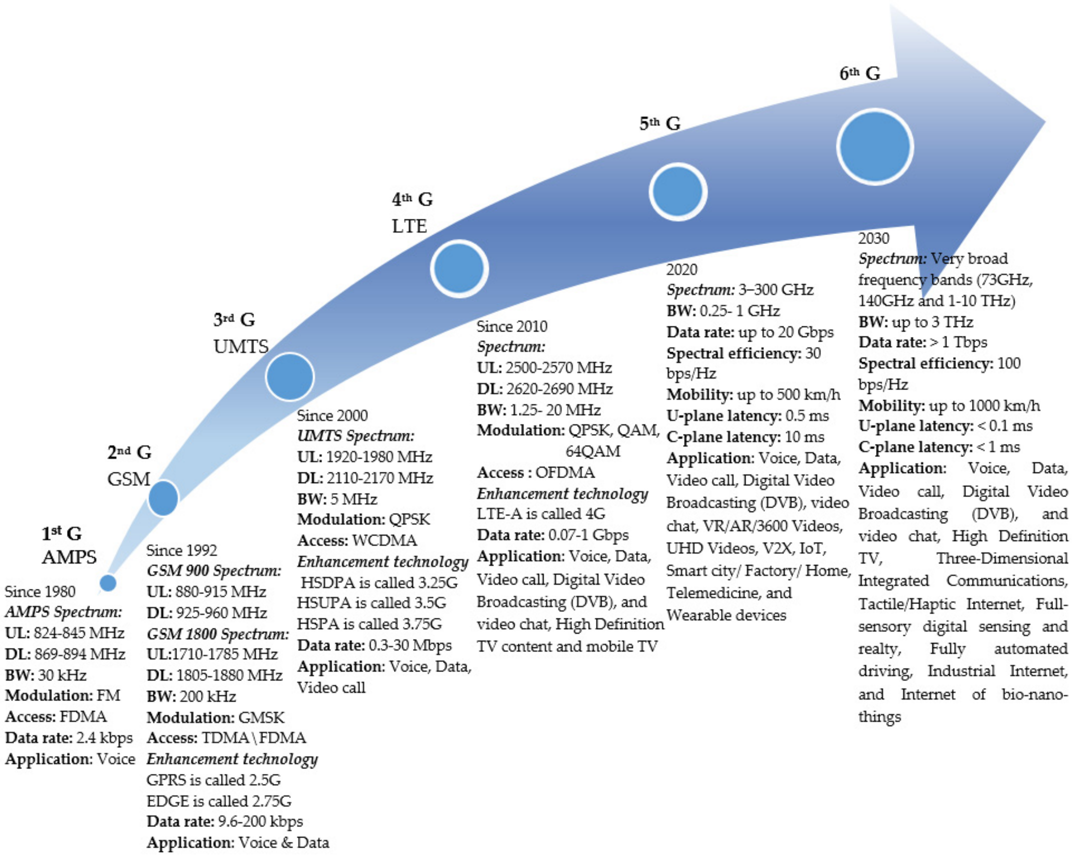


Figure 1. Evolution of wireless mobile technologies.

As 5G has entered into the commercialization phase, researchers around the globe have started focusing on future 6G technology which is expected to be launched in the 2030s [6–8]. Progress in 5G yields the conceptualization of 6G with the capability to unleash the promises of ample autonomous services. Specifically, 6G is envisaged to offer innovative promising wireless techniques and novel network design perspectives. 6G can bring a remarkable advancement in wireless technology with ultra-low latency in microseconds and data rates up to 1 Tbps. Its capacity is envisioned to be 1000 times higher than 5G with spatial multiplexing and THz frequency communication. Moreover, 6G will provide haptics communication, quantum machine learning, and energy harvesting technologies that will have a profound impact, helping to realize future sustainable green networks. More precisely, it has the capability for high-precision communications for tactile services to enable the desired sensing experience at various steps, such as smell, touch, vision, and listening [7,8]. However, one key objective of 6G is to feature ubiquitous coverage by incorporating underwater wireless communications to support global coverage [9,10]; one of the challenges facing underwater wireless communications is the delivery of high energy performance, most especially from the perspective of pervasive utilization of the global coverage wireless communications and with an eco-system of many minute sensors. Furthermore, extending the battery-recharge capacity of IoT devices and sensor networks underwater must be addressed in line with the notion that their capabilities and abilities to deal with sophisticated multimedia signal processing rise in quantum leaps as their power consumption increases [11–13]. Thus, energy-efficient underwater wireless communications are considered a hot research topic for the coming years. The underwater Wireless Power Transfer (WPT) is considered a key technology to support underwater systems and applications, which is the scope of this study.

Wireless Power Transfer

A critical demand for WPT has emerged to support underwater systems and applications with excessive power requirements including autonomous underwater vehicles (AUVs), underwater sensor nodes and ocean monitoring objects. AUVs play an irreplaceable role in marine applications with a complex intelligent control system like that of aircraft [14,15]. Research into extending the monitoring and navigation range of AUVs is becoming popular for purposes of ocean exploration. AUVs have the advantages of superior intelligence, safety and mobility. These underwater objects are deployed in several underwater applications including underwater resource exploration, underwater observation, monitoring underwater species, oceanic data collection, underwater rescue, bathymetry profiling and oceanographic sampling. In most cases, these electronic objects and sensors are used on remotely operated vehicles (ROVs) and AUVs. However, AUVs offer more potential benefits as they have an exception from the need for a support vessel for ongoing underwater missions. Apart from this appealing benefit, there are some disadvantages such as distance range and mission time, which are severely constrained by limited battery endurance. AUVs generally carry heavy loads and high-power instruments, which consume more energy. The demand for periodically recharging AUVs emerges due to these factors. The traditional technique to charge these electronic objects is time-consuming which results in limited operation range and disrupted service. In order to overcome these limitations, extensive research contributions on AUVs are needed. Although WPT system can possibly charge AUVs, its bulky design is challenging for smaller AUVs. Thus, researchers should address these challenges, which can open a new era of research to extend the lifetime and operational range of AUVs. In this regard, one potential solution is to develop an underwater docking station [16,17]. Underwater docking stations are more affordable, intelligent and convenient as compared to surface vessels. However, traditional cabled methods are not useful to transmit energy in UW environments due to docking precision and high expenses [18,19]. Therefore, such systems require high cost and maintenance periodicity. These systems are only applicable for near shore scenarios. These systems are usually used for monitoring of water parameters, weather reporting, oceanography studies and SARS operations. Noncontact and wet-mateable connectors are used to recharge AUVs. Although these connectors offer the benefits of high efficiency and small size, they need appropriate alignment between AUV and dock. Thus, WPT has emerged as a viable solution. Most of the studies on WPT only address terrestrial applications. These studies have proposed different methods to enhance WPT system efficiency including impedance matching, intermediate field repeaters and frequency tuning. In 2016, W. Niu et al. [20] proposed metamaterials to improve air-based WPT system efficiency. However, WPT systems for underwater systems are still in their infancy and researchers are trying to investigate different ways to revolutionize WPT in the underwater medium. There are several challenges in underwater wireless power transfer (UWPT) such as:

- What is the impact of a highly conducting water environment on the electrical parameters of the WPT system?
- How does seawater affect coil radiation resistance?
- What are the losses incurred in UWPT and what are the possible mitigative solutions?
- In the case of highly frequency dependent loss, how to choose the operating frequency to empower an efficient UWPT system?

Apart from these challenging issues, mobility is another major concern in UWPT system due to the dynamic characteristics of ocean leading towards a varying coupling coefficient, which is a key parameter of any WPT system. Hence, there is a need to introduce optimized design to overcome these variations. Other critical elements to surpass are high electrical permittivity and high losses in ocean. It is worth noting that both permeability and permittivity parameters for air medium are different from underwater medium [21,22]. All of these factors impose severe constraints on UWPT systems. In addition, control mechanisms in air-based WPT systems require a communication path to check system parameters, while these methods seem unviable for UWPT systems. Thus, it is crucial to design a control mechanism without requiring a communication link. It is foreseeable that extensively growing research activities can empower this research domain. Similarly, it is envisaged that MIMO strategy will be implemented in WPT to simultaneously charge multiple devices [23]. Figure 2 presents an overview of underwater wireless charging system for unmanned underwater vehicle (UUV).

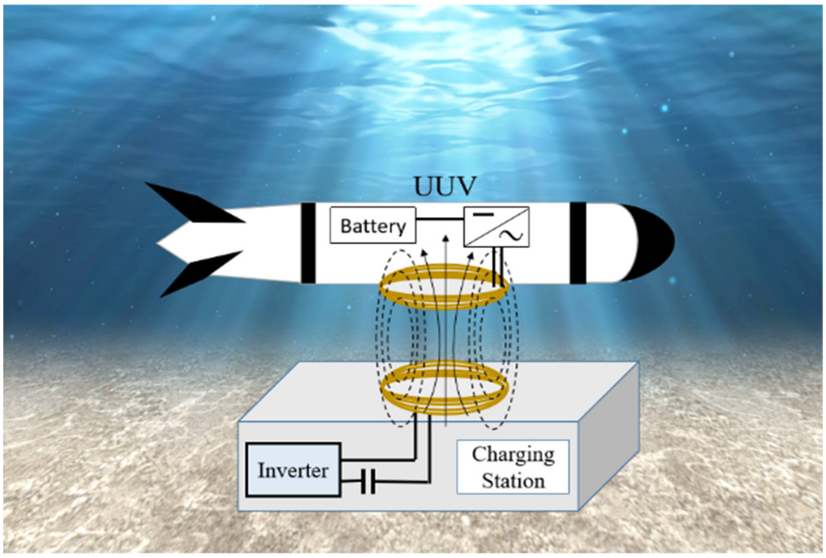


Figure 2. Overview of UWPT system to charge UUV.

To enable an efficient WPT system, three conditions must be met: (i) large air gap; (ii) high power; and (iii) high efficiency [24]. The efficiency of a WPT system is different for various WPT techniques such as optical wireless power transfer (OPWT) and magnetic resonant coupling, etc. Figure 3 shows transfer efficiencies of near and far field region based WPT techniques [24]. It can be seen that 70–90% transfer efficiency is possible through inductive coupling, while moderate 40–60% efficiency can be achieved through magnetic resonance coupling. Microwave and laser support efficiency is below 30%. It is worth noting that these transfer efficiencies decrease with increasing distance. The organization of this study is presented in Figure 4.

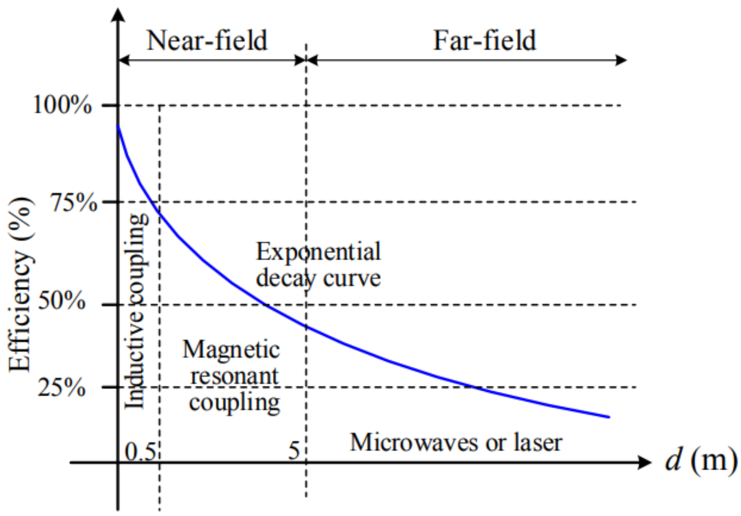


Figure 3. Transfer efficiencies for different WPT techniques [24].

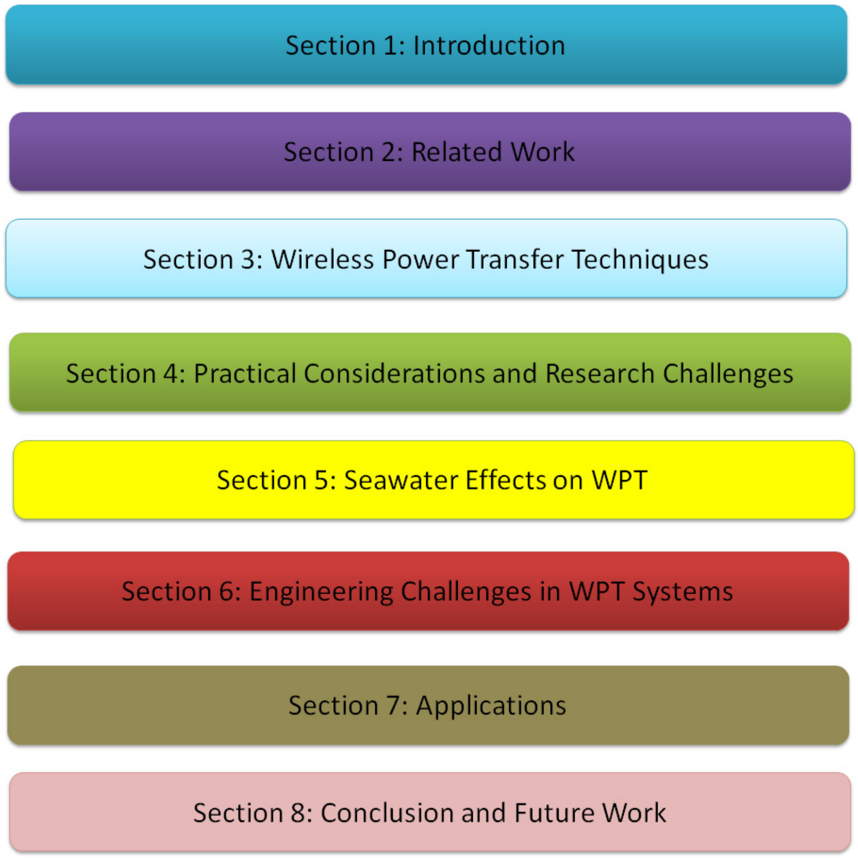


Figure 4. Organization of this study.

2. Related Works

The current ongoing research mainly focuses on terrestrial applications [25]. Frequency tuning has been implemented for maximum system efficiency [26,27]. Various other techniques such as use of metamaterial [28,29], impedance matching and intermediate field repeaters [30–33] have been investigated to improve air-based WPT system efficiency. In recent decades, the research fraternity has made significant contributions in impedance matching, optimization designs and modelling analysis. Tsai et al. [34] have designed a directional antenna to generate higher flux density. However, WPT in seawater is still a challenging issue. Several research studies have been focused on controlling load power and improving UWPT system efficiency. The research work by Yoshida et al. in 2016 [35] outlines UWPT applications. M. Urano et al. [36] have investigated some techniques on the basis of coil winding and resonator circuits to overcome difficulties in WPT systems in salt water. Recently, the authors in [37] proposed a multi objective design mechanism for UWPT system for AUVs. F. Goncalves et al. have discussed underwater target recognition by using WPT [38]. An adaptive system is proposed in [39] which removes additional wireless interfaces. In another study [40], the authors have highlighted eddy current losses and addressed coil structure to overcome these losses. In [41], the authors studied high efficiency WPT for undersea environment. Zhengchao Yan et al. [42] carried out an analysis of eddy current losses for various frequencies and misalignments. An efficient model is proposed in [43] by considering Z-parameters for UWPT. Insightful discussion is provided in [44] to design a UWPT system. In [45], the authors have comprehensively reviewed AUV-based WPT systems and docking techniques. This study presents a practical overview of developing an AUV IWPT system. We have summarized an overview of WPT and UWPT studies and research contributions in Table 1.

Table 1. Research studies on UWPT.

Reference	Year	Research Contributions
[46]	2014	This study outlines the electrical characteristics of a coil in sea water for UWPT system. It presents a comparison between Wait and Kraichman's expression for coil resistance in seawater. This study also reports a comparison for a circular coil submerged in ocean and a glass sphere. The results reveal low resistance for a coil located directly in glass sphere as compared to seawater.
[41]	2015	This study aims at enhancement of power transfer efficiency of UWPT using saltwater. The authors introduced a novel coil structure of 4 layered spiral coil and reported enhanced transfer efficiency by considering dense winding of litz wire.
[30]	2016	This article proposes an adaptive system for underwater wireless applications. The output voltage is regulated through wireless power link without requiring any additional wireless interface. The authors demonstrated experiments using class-D drive considering a series-series resonant topology in saline water to deliver 1.6 and 2.4 W power.
[47]	2016	This study highlights some challenges and mitigative solutions to overcome the challenges that a WPT faces in salt water medium. The authors investigate that addition of resonator circuits and proper coil winding enhances transfer efficiencies. They briefly discuss best coil shape, parasitic resistance, capacitance and self-inductance.
[36]	2017	This study reports WPT systems for internet-of-things (IoT) devices. The authors studied WPT using electric coupling for system in water using the impact of large dielectric constant of water. One electrode was exposed while other was isolated from water. The authors reported an overall transfer efficiency of above 75%.
[38]	2017	This study proposes a novel topology for the matching networks of UWPT system. The authors presented analytical derivation and demonstrated the proposed design with an example. They reported a good performance comparison with conventional methods such as series-parallel and series-series networks for power delivery and efficiency considering a wide load range.
[48]	2017	This article addresses the load modulation for WPT in underwater medium. The authors analyzed a voltage-mode class-D in a series-series resonance topology to investigate WPT working along with impact of load on the primary coil.
[42]	2018	This study presents an analytical model for the eddy current loss of WPT system in seawater considering misalignment through Maxwell's equations. The authors derived the theoretical expressions for eddy current loss for different frequencies and misalignments and electric field intensity. They reported a stable efficiency in seawater around 215.5 kHz to 248.4 kHz.
[43]	2018	This study presents a strong misalignment tolerance magnetic coupler design using finite element analysis (FEA). The authors demonstrated a prototype of 600 W and experimental results showed agreement withtheoretical analysis and strong misalignment tolerance.
[49]	2018	This study simplifies the complicated analytical expression of EFI to the product of coil turns, current, frequency and a coefficient to analyze the eddy current loss (ECL). The authors also presented an optimization flow chart and a prototype system with the capacity to deliver 100 W at 90% efficiency considering 107.1 kHz frequency and a gap of 30 mm.
[50]	2018	This study proposes a CWPT system for fresh water application. It also discusses the design technique for the capacitive coupler for fresh water medium. The authors reported 91.3% transfer efficiency at a distance of 20 mm through experimental demonstration.

Table 1. *Cont.*

Reference	Year	Research Contributions
[23]	2019	This study proposes an efficient model for UWPT through Z-parameters. Using the two port and EM analysis, the authors derived an impedance model of coils taking conductivity and frequency of seawater. This designed impedance model can be considered for equivalent circuit design of UWPT system. The authors reported a good agreement between simulation and measured results.
[40]	2019	This study introduces a coil structure using two transmitter coils located adjacent to receiving coils. The authors arranged coils as $1 \times 1 \times 1$ structure, which gives reduced eddy current loss and improved power transfer efficiency by nearly 10%.
[44]	2019	This study proposes a power inverter design for UWPT system using magnetic resonance coupling considering saltwater as a transmission medium. The authors used series capacitors on both sides of coupled coils. The proposed structure uses impedance of load and resonant coupling coils to develop class-DE scenarios in a full-bridge inverter.
[45]	2019	In this study, the authors proposed a highly efficient and lightweight coupler design for UWPT system. They briefly discussed the pivotal parameters which enhance the coupling coefficient of the proposed coupler.
[51]	2019	This article provides in-depth insight into the design of UWPT system. The authors proposed an optimized coil design to improve the power transfer efficiency. In addition, they proposed a new maximum power-efficiency tracking (MPET) technique which considers k-nearest neighbors to find the coupling coefficient and traces the peak efficiency above 85% using an adaptive converter control.
[52]	2019	This article reviews the state-of-the-art IWPT system for underwater applications. It discusses design and engineering challenges for IWPT system. This study also presents a comprehensive review of IWPT control mechanism, compensation networks, AUV energy storage and docking strategies. It also explains technical challenges such asincorporation of IWPT system into an AUV hull, stability, docking station sinking, retention issues, alignment and interoperability along with battery operation, data transfer and pressure-tolerant charging electronics.
[53]	2019	In this study, the authors proposed a UWPT system considering a curly coil which can integrate with cylindrical hull of the AUVs. They optimized unipolar and bipolar curly coils to reduce the weight of the receiving side. They stated that weight of unipolar curly coil has a light receiver than bipolar coil structure. However, the EM field strength in AUV of unipolar curly coil is greater than bipolar.
[54]	2019	This work proposes an omnidirectional planar AUV charging system to ensure stable charging performance of AUV regardless of its direction and position. The authors considered a single layer planar coil array with moderate overlaps and ferrite core. They reported reduced material cost, high misalignment tolerance along with 95% decrease of the downside eddy current loss. This study also shows agreement between theoretical results and underwater experiment.
[55]	2020	This study presents a technique to enhance the transfer efficiency of a low frequency WPT system for AUV using inductive power transfer. The proposed system utilizes a split-core transformer (SCT) to transmit power from the docking station to the AUV without requiring any electrical contact.
[37]	2021	This study proposes a multi-objective technique of UWPT system for AUVs considering a DC/DC converter and a cooperative design of compensation network to reduce the electrical stress of the inverter and enhance the efficiency of UWPT system.

Table 1. *Cont.*

Reference	Year	Research Contributions
[56]	2021	This article investigates three solutions to attain maximum power, maximum efficiency and conjugate-matching. Each equation expresses the efficiency and load power of CPT system and expresses the desired admittance for the source and the load. The demonstrated experiments reveal a decrease in available power and efficiency after increasing frequency from 300 kHz to 1 MHz and transmission distance from 100–300 mm. The authors reported maximum efficiency of 83# at 300 kHz considering distance of 100 mm.
[57]	2022	This study proposes a new open-type magnetic coupler with a high self-inductance stability, strong misalignment performance, lightweight and a simple design for the arc-shaped shell of AUV. The proposed design uses an arc-shaped transmitter and the receiver employs an H-shaped ferrite core to empower close coupling of magnetic flux in the vertical direction.
[58]	2022	This study proposes a power-supply strategy by designing an underwater bidirectional wireless power transmission (UBWPT) system. In order to enhance the efficiency of the proposed system in the underwater medium, the power converters coupled with coils are developed by analyzing the parasitic jumper capacitor and eddy current loss in seawater. The transceiver converters are made with two separate controllers so that power flow can be controlled underwater.
[59]	2022	This study proposes an arc-shaped UWPT magnetic coupler for AUV's curved shell. In the proposed magnetic coupler design, the magnetic core is Fe-based nanocrystalline alloy soft magnetic material. In the proposed design, both weight and volume of the receiver are minimized as compared to the conventional Mn-Zn ferrite material.
[60]	2022	This article proposes an underwater wireless power and data transfer (WPDT) system considering a shared channel. The signal and power can be transferred over the same channel utilizing time division multiplexing technique. It transmits power in the first half switching cycle and transfers power in the second half switching cycle. The authors used frequency-shift keying (FSK) modulation for the signal of 240 kHz.
[61]	2022	This study proposes a new hybrid transmitter comprised of planar spiral and conical coil which highly enhances the transfer performance and the misalignment tolerance for the UWPT system.

3. Wireless Power Transfer Techniques

According to [62], it is envisaged that WPT will generate 12,000 million US dollars of revenue in 2020. This prediction can be seen in Figure 5. It is due to diverse applications in the electronics industry with several key benefits in terms of safety, convenience, reliability and a fully automated charging mechanism. These benefits can be attained through different WPT techniques. Another key feature of WPT is that it is very much needed in different environments where wired power transfer techniques are dangerous, difficult or impossible such as underwater environments and high voltage power applications. The research fraternity has been exploring trade-offs and evaluated different WPT techniques. These techniques are categorized as: radiative electromagnetic (EM) and non-EM techniques. Figure 6 shows these WPT techniques which are further divided into 5 categories. In non-EM, power is transferred using acoustics or optical sources such as lasers. EM is further classified into radiative far-field, non-radiative and mid-field radiative and non-radiative. RF is used for power transmission in radiative techniques, with capacitive coupling; inductive coupling and magnetic resonance coupling are used in non-radiative processes. Currently, these WPT techniques are commercially available for different applications such as smart phone charging and charging implantable medical devices, etc., and are still being developed for different applications. Next, we have highlighted some WPT techniques and research contributions to UWPT.

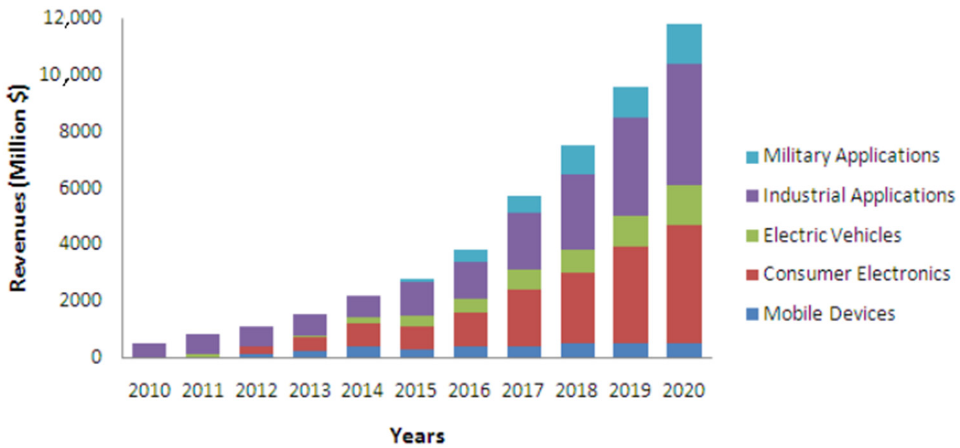


Figure 5. Predicted values of WPT technology in 2020 [62].

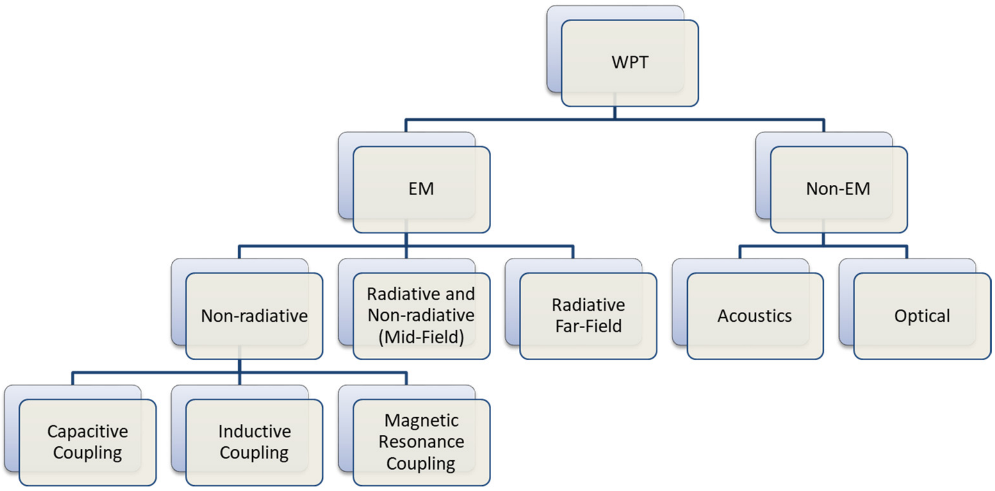


Figure 6. Different wireless power transfer techniques.

3.1. Radiative WPT

Among these technologies, Radiative WPT is usually termed as far-field WPT. It commonly uses RF or microwaves. Microwave WPT enables power transmission up to a few meters to tens of meters and uses 300 MHz to 300 GHz range. This technique converts microwave power into DC power using rectenna or energy harvesting antenna. Both transmitter and receiver components are equipped with antennas. The receiver antenna is used to intercept received RF energy and forwards it to the rectifier circuit, which converts this energy into electrical signals. N. Shinohara et al. utilized microwave WPT for the near field region through a flat beam pattern [63]. It is notable that this technology greatly suffers from attenuation at high frequencies in seawater. In [64], researchers have demonstrated underwater wireless power transfer (UWPT) by using radio waves, however the power transfer efficiency is low.

3.2. Optical Wireless Power Transfer (OWPT)

To increase the transmission distance, optical wireless power transfer (OWPT) can be a promising solution. OWPT is a WPT technology which involves a light source as a power transmitter. OWPT is one of the suitable approaches which can extend transfer distance with simple system components. In OWPT, a light source such as a light emitting diode (LED) or laser diode (LD) is used on the transmitter site which converts electrical power into optical power. A solar cell or photovoltaic cell or photodiode (PD) is used on the OWPT receiver site, which converts optical power into electrical power. Researchers in [65] have successfully implemented OWPT underwater by using a laser diode. The authors have reported transfer efficiency of 4.3% for back-to-back OWPT with a PD receiver. Laser based OWPT allows a narrow cross sectional beam. It has various advantages over other domains such as compact size, large coverage and no interference with existing radios. Although microwave systems are used for solar power satellites, laser power transfer (LPT) based systems have emerged as an alternative technology owing to their growing development. As compared to an RF beam, the power and size of a laser beam can be maintained at a larger distance. Thus, the transfer efficiency of an OWPT system based on LD does not significantly degrade with distance. Moreover, it does not create electromagnetic interference (EMI) for radio communications. Many researchers think laser-based WPT is not realistic due to laser hazards, interference caused by ambient noise and its low efficiency.

3.3. Acoustic Power Transfer (APT)

Acoustic power transfer (APT) is a non-EM wireless power transfer technique and it is considered as an emerging competitor against nonradiative inductive coupling (NRIC) due to its power transfer efficiency (PTE) performance. In this technique, energy is transferred wirelessly through ultrasound waves at frequencies above 20 kHz. In an APT system, two piezoelectric transducers are used to transmit energy in the form of ultrasound waves using tissue to any implanted object where it is converted into electrical signals. Figure 7 gives an overview of APT system with an ultrasonic oscillator T. Electrical excitation is enabled to generate surface vibrations which result in acoustic signals around 200 kHz to 1.2 MHz frequency range. This pressure field is directed to the transducer R. We can also achieve better directivity by using arrays of transducers at the expense of low beam penetration. The transducer R is inserted in the body for harvesting piezoelectric energy. It is located in the main radiation lobe of T to change acoustic waves into electrical signals.

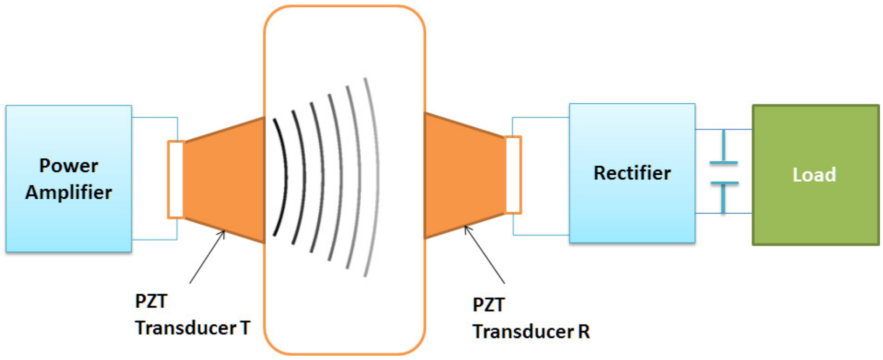


Figure 7. Acoustic power transfer.

3.4. Nonradiative WPT

Generally, Nonradiative WPT (NRWPT) is categorized into short or mid-range on the basis of spacing between primary and secondary coils. In mid-range NRWPT, the distance between these coils is greater than the radius of the coils. In this WPT technique, the power transmission using electric or magnetic fields is limited to shorter distances up to tens of centimeters. The NRWPT technique uses capacitive coupling, inductive coupling or magnetic resonance coupling to transfer energy. The capacitive wireless power transmission is associated with submerged electrodes which are separated by water medium. In capacitive-WPT (CWPT), water is considered as a lossy dielectric medium. However, CWPT is not preferred because of missing galvanic isolation and low coupling capacitance. CWPT requires a high operating frequency. Efficiency in inductive WPT (IWPT) can be increased by increasing coil diameter or number of turns [66,67]. Better performance of IWPT can be achieved by involving shield materials such as ferrite material [68]. Currently, IWPT is preferred to transmit data on station in seawater or power in hovering underwater. Another key advantage is that EM induction possesses a stronger coupling effect between coils than magnetic induction. Thus, research studies mostly consider EM induction for nonradiative WPT systems.

3.5. IWPT

In this section, we will discuss the matured IWPT technique. IWPT is associated with near-field magnetic coupling using coils. IWPT is regarded as more handy for the underwater environment as it is safer, efficient and utilizes lower frequencies than CWPT. In the 19th century, Nikola Tesla demonstrated the very first IWPT system through EM resonance [69]. He developed resonance for high voltages for successful WPT implementation at longer distances, while the latest WPT techniques have proliferated through more advanced solutions to charging electronic objects. Nowadays, IWPT systems can be found commercially to charge electric vehicles (EVs), electronic gadgets and implantable biomedical devices. IWPT is considered as more effective system as it is less affected by misalignment factors. Several research studies have addressed IWPT for underwater robotics [70–72], ships [73], underwater sensing nodes [74] and autonomous underwater vehicles [75,76]. For AUVs, IWPT can significantly reduce operation cost. IWPT has the potential to minimize leakage currents and can eliminate bio-fouling issues and corrosion. Several leading research institutes have been focusing on IWPT systems and standardization. The standards include shielding, system design, power levels, operating frequency range and several other characteristics. A well-known Qi standard is operating at frequencies below 250 KHz; however it has a limited power up to 15 W. Similarly, AirFuel resonant standards operate at 6.78 MHz for industrial, scientific research and medical applications. These standards can be directly integrated in underwater applications; they are severely affected by high attenuation at higher frequencies in seawater. Table 2 summarizes various IWPT systems and Table 3 summarizes different WPT systems for underwater applications.

Table 2. Comparison of various IWPT systems.

Parameter	Resonant IWPT	Loosely Coupled Transformer	LCWT
Operating frequency	Very high	High	Medium
Hysteresis losses	No	Yes	Yes
Misalignment tolerance	High	Medium	Low
Efficiency	Medium	High	Medium
Leakage flux	High	Medium	Low
Air gap	High	Medium	Very low
EMF cancellation	Required	Not required	Not required
Multiple receiver	Possible	Not possible	Possible
Coupling coefficient	<0.25	>0.5	~1
Eddy current losses	High	Considerable	Low
Copper loss	Low	Low	Very High

Table 3. Research work in WPT.

Reference	Coupling Coefficient	Power Level	Efficiency (%)	Gap (cm)	Experiment Setup/Application
[77]	N/A	250 W	70	0.2	AUVs
[69]	0.54	10 kW	70.45	2.5	Underwater applications
[75]	N/A	200 W	79	N/A	AUVs
[78]	N/A	N/A	80	7.5	Coil submerge in water tank
[79]	0.49	600 W	80	8	AUVs
[80]	N/A	3 kW	80	26	Halogen lamp
[50]	N/A	400 W	80.7	2	AUVs
[81]	0.43	N/A	82	0.5	AUVs

Table 3. *Cont.*

Reference	Coupling Coefficient	Power Level	Efficiency (%)	Gap (cm)	Experiment Setup/Application
[82]	0.25	N/A	82.13	4	Coils submerge in water tank
[83]	0.74	45 W	84	0.9	Underwater vehicle docking
[84]	0.64	300 W	85	0.5	Ocean observation
[85]	N/A	75 W	85	N/A	AUV charging
[44]	N/A	80 W	86	4	Underwater applications
[86]	0.16	745	86.19	N/A	Lightweight AUVs
[87]	N/A	500	88	0.6–1	AUVs
[88]	0.765	400 W	90	0.2	Deep sea applications
[89]	0.64	1 kW	90	0.6	Underwater vehicles
[90]	N/A	680 W	90	N/A	AUV docking station
[91]	0.1385	1 kW	92.41	2.1	Charging AUVs

3.6. MIMO WPT

A notable challenge in far-field WPT is to enhance the DC power level at the rectenna output without enhancing the transmission power, as well as to recharge devices which are placed far away from the transmitter. To tackle this shortcoming, most of the technical contributions in the literature have been dedicated to the development of efficient rectenna [92]. Another alternative solution to enhance the output DC power level is to develop efficient WPT signals [93]. In [94], authors carried out analysis and simulation of a multisine signal excitation in order to improve the DC power and RF-to-DC conversion efficiency. In [95], authors performed systematic analysis, design and optimization of WPT waveforms. Those waveforms were adaptive to channel state information (CSI) by considering rectenna nonlinearity, frequency-selectivity of the channel and beamforming gain in order to enhance the harvested DC power. After that, various studies have been devoted to minimizing design complexity and proposing large-scale multi-antenna multi-sine WPT and powering multiple devices [96]. By introducing multiple antennas at the transmitter and receiver side, a MIMO WPT system is formed. In [97], authors proposed beamforming optimization for a MIMO WPT system. They considered the nonlinearity of the rectenna to maximize the output DC power along with RF combining approach. Authors in [98] considered the linearity of rectenna to maximize the output DC power. In [99], the researchers utilized several power combiners and splitters for MIMO WPT systems. However, it is not preferable for low power WPT systems. It is worth mentioning that proper distribution of electromagnetic (EM) energy and maximizing the power transfer efficiency (PTE) are the major critical concerns for designing any MIMO WPT systems. Several studies have already proposed magnetic induction (MI) beamforming to improve the PTE for the MIMO WPT systems. However, conventional magnetic beamforming in WPT systems usually requires accurate magnetic channel estimation, in both amplitude and phase control of the charging source, which is mostly hard in an extreme environment such as underwater medium. According to some studies, the circuit composition of MIMO is more flexible and the input impedance is affected by multiple coils, which are entangled together, making it complex to calculate the input impedance and analyze the impedance matching (IM) for MIMO. IM in MIMO has yet to be fully investigated.

4. Practical Considerations and Research Challenges

Besides all these appealing benefits, several technical challenges still exist in WPT systems. As such, in terms of system design, high-order and variable nonlinearities occur if we increase the number of loads. It is also worth noting that different loads and their power requirements also vary. For instance, computers, smart phones, and desk lamps involve the same WPT surface, but these electronic devices have different power requirements. Hence, it is crucial to fulfil the power requirements criteria of these loads. Moreover, WPT system parameters indicate that a high impact on receiving power exists because of the spatial positions of electrical objects. It is also possible to integrate new loads while operating in a multi-load WPT system. This integration can cause power stability and overall efficiency problems for the WPT system.

Several research studies have focused on multi-load WPT systems in order to enhance system efficiency by controlling load power. In Shi et al. [83] demonstrated a multi-load WPT system using a series-to-series compensation topology. Their proposed system uses load coils as relay coils and same energy is given to various loads located at different distances. In another study, coupled-mode theory was considered to carry out analysis of S-S compensation topology [38]. In this proposed mechanism, researchers used dynamic control of impedance matching to empower tunable power allocation. Similarly, Goncalves et al. [39] made a contribution to enhancing multi-load WPT system efficiency using impedance matching in S-S compensation topology.

Apart from the above issues, another critical factor in WPT systems is distance between transmitter and receiver coils. The distance factor plays a pivotal role in WPT applications. The power transfer distance range varies for different applications; there can be *mW* for biomedical implants, while for EV charging the range can be in *kW*. Several research studies have been dedicated to increasing WPT distance range along with overall efficiency. It can be noticed in most of the research studies that WPT follows the phenomenon of EM induction. When current I flows through any coil then it induces a magnetic field **H** which is related to magnetic flux density **B**, as can be seen in Figure 8.

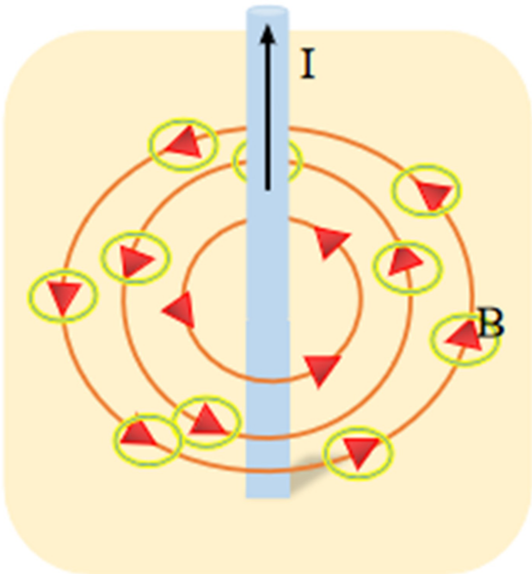


Figure 8. An illustration of electromagnetic induction.

Mathematical expression for magnetic field **H** is provided in Equation (1). It is clear from Equation (1) that a magnetic field is directly proportional to current intensity, while it is inversely proportional to the distance [39].

$$\mathbf{H} = \frac{i}{2\pi r} \quad (1)$$

$$\mathbf{B} = \mu\mathbf{H} \quad (2)$$

In order to check the impact of distance, we used MATLAB simulation to plot magnetic flux density **B** for different values of current by considering Equation (2). The results provided in Figure 9 clearly show a decrease in magnetic flux density when the distance increases.

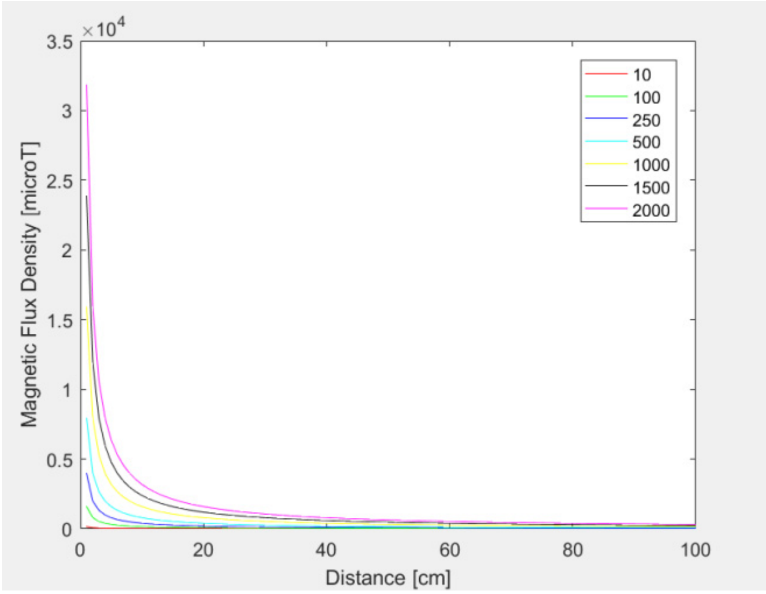


Figure 9. Magnetic field for different values of currents.

4.1. Coil Characteristics

One critical issue in UWPT is misalignment between transmitter and receiver coils. Although some studies have reported stagger-tuning method, UWPT still suffers from high variations in underwater environments. The impact of angular or lateral misalignment between coils can significantly reduce output voltages. Therefore, proper design is needed to overcome these challenges. Thus, the research fraternity must find coordination and optimization techniques for WPT. In this section, we briefly discuss the impact of coil shape, orientation, topology and number of turns on the WPT systems.

4.1.1. Coils Shape

Coil shape has a good impact on WPT system. Less material is required to design a coil with circular geometry and it also occupies least space. Coils with circular shape offer high misalignment tolerance and less leakage flux. In contrast, rectangular coils have more leakage flux and more material is needed to design such coils. Rectangular coils give high coupling variations in case of coil misalignment. Thus, circular coils are preferred and suitable for WPT applications. Table 4 summarizes a comparison of different parameters between circular and rectangular coils.

Table 4. Coil Characteristics Comparison.

Parameter	Rectangular Coil	Circular Coil
Polarity	Polarized	Unipolar
Flux Distribution	Non-uniform	Uniform
Vertical Tolerance	More	Less
Horizontal Tolerance	Less	More
Leakage Flux Direction	Bottom	Horizontal
Leakage Flux	More	Less
Required Material	More	Less

We have focused on circular coils and investigated parasitic effects by calculating coil impedance using an impedance analyzer. We calculated self-resonance shift and coupling coefficient for circular coils of 15 turns and an inner diameter of 40 mm. The coupling coefficient was 0.44 at transmission distance of 20 mm. We found that the coupling coefficient decreases as we increase the transmission distance between coils, as shown in Figure 10.

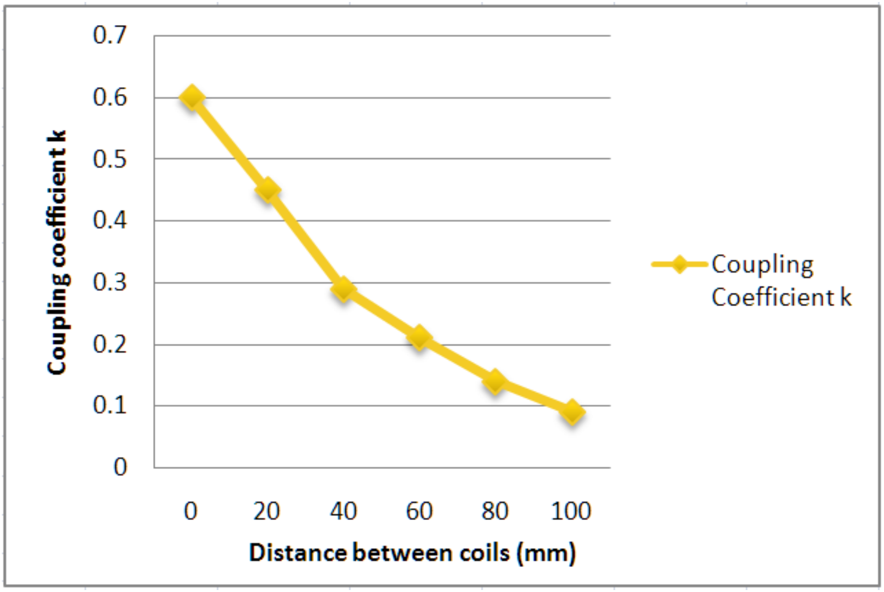


Figure 10. Coupling coefficient variation across distance.

4.1.2. Coil Orientation

We have also investigated the impact of mutual inductance on impact on the coupling coefficient as compared to coil selection. The coupling coefficient is highly associated with the coils' orientation and the relative distance between coils. Figure 11 shows the three spatial degrees of freedom which impact the coupling coefficient of WPT systems. We can say that accurate relation between distance and coupling coefficient is a complex subject. In this regard, researchers should carry out analyses of the magnetic field strength and shape.

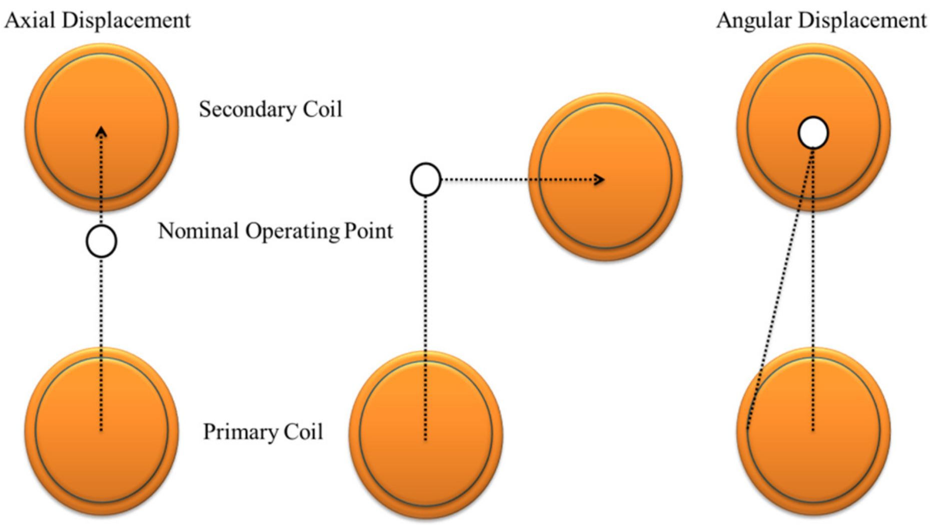


Figure 11. An overview of coil orientation.

4.1.3. Coil Topology

For UWPT, it is important to select the most suitable coil topology. For this purpose, we have focused on coil design parameters which should be taken into consideration to design any coil. Traditionally there are two ways to design any coil: solenoid coil and flat coil. Figure 12 presents different coil designs reported in various studies.

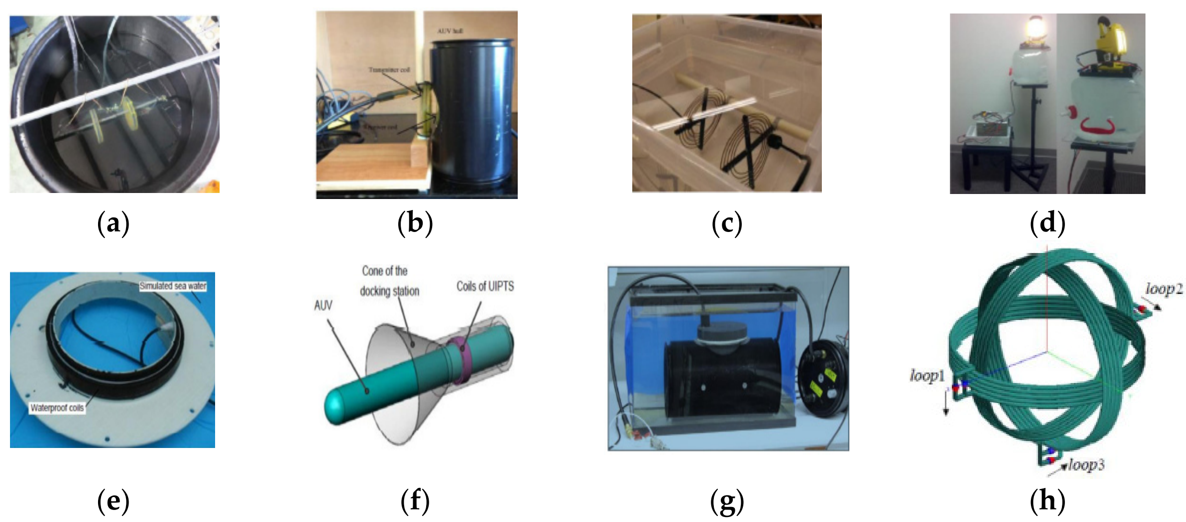


Figure 12. IWPT systems using coils investigated by: (**a**) Askari et al. [78]; (**b**) James et al. [79]; (**c**) Santos et al. [82]; (**d**) WiTricity [80]; (**e**,**f**) Shi et al. [83]; (**g**) Bana et al. [85]; and (**h**) He et al. [100].

We have investigated the effect of coil size, shape, orientation and coupling coefficient. Besides these, another important factor is coil winding or number of turns which has a great impact on an efficient coupling [40]. Considering coils' shape, distance and number of turns, we have noticed that the coupling coefficient of a spiral coil is higher than of a helix coil. In a recent study, Z. He et al. [100] demonstrated a three dimensional omnidirectional topology for underwater operations. In another study, X. Shi et al. [101] stated that the efficiency of a spiral coil is better as compared to a helix coil as the distance between the coils increases. Surprisingly, the coupling coefficient for a helix coil decreases while for spiral coil it increases by increasing the number of turns, as shown in Figure 13. Hence, the coupling coefficient is a key element for designing of any coil [41].

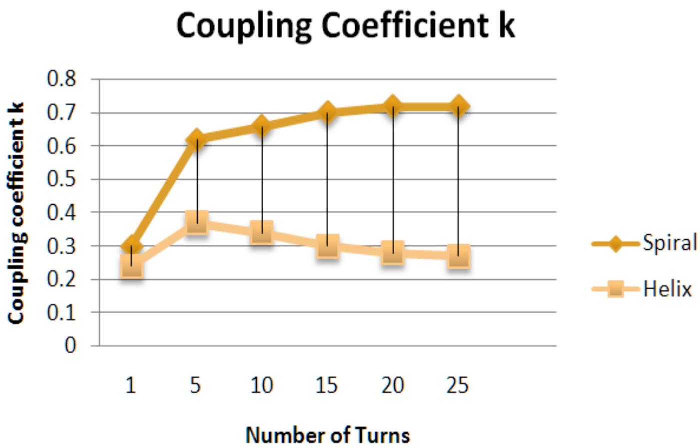


Figure 13. Coil effect on coupling coefficient.

In another study reported on WPT [102], D. Patil et al. found that coils with a lesser number of turns showed good performance at longer distances due to lower reactance. However, coils with a greater number of turns showed better performance at shorter distances, as can be noticed in Figure 14 [102]. Hence, researchers should keep these trade-offs into consideration while designing any WPT system. Table 5 provides a comparison of various coupling mechanisms.

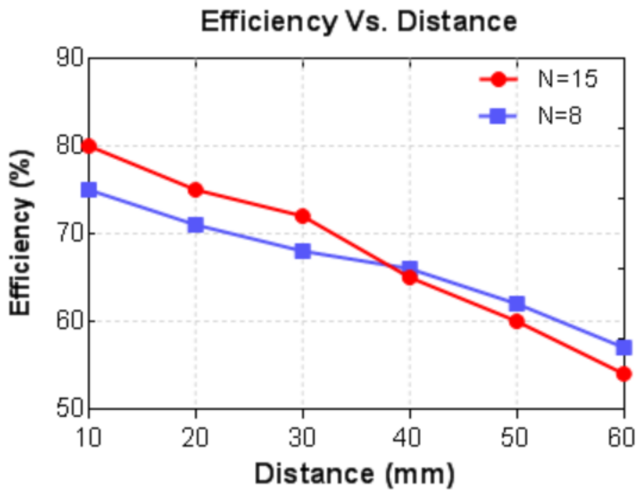


Figure 14. Effect of coil turns on efficiency.

Table 5. Comparison between different coupling mechanisms.

Reference	Coupling Mechanism	System Performance
[103]	3D orthogonal dipole coils	It provide a stable output of more than 10 W while rotating to any angle.
[84]	Fan-shaped ferrite core	It ensures transmission of 1 kW power at 88% efficiency with 5 mm gap.
[104]	Magnetic couplers based on dipole coils	It provides transfer of 630 W with 89.7% DC-DC efficiency.
[105]	Three phase coil design	Transmits 1 kW of power with DC-DC efficiency of 92.41%
[106]	Conical magnetic core	Transfers 500 W of power at an efficiency of 96%
[107]	Cylindrical winding	It ensures 60% transfer efficiency with 5–10 cm gap.

4.2. Frequency Tracking

The operating frequency has a significant impact on transfer power and system efficiency. Frequency tracking can realize consistency between output frequency, receiving frequency and resonant frequency, along with efficiently enhancing the transfer power and efficiency. Frequency tracking can efficiently enhance the output power under constant transfer system parameters, ultimately maximizing overall transfer efficiency of the system. Several studies have proposed solutions based on resonant cavity structures and closed-loop control based adaptive frequency tracking control mechanisms. In [108], authors suggested a structure of maximum efficiency point tracking control along with configuring the output voltage to improve the overall performance of the system. By adjusting the operating frequency at the resonant frequency of the receiver component and controlling the input voltage and load resistance, respectively, the proposed system can enable dynamic tracking of the maximum efficient point over constant output voltage points. It is worth mentioning that when the transmission of the system changes, the frequency tracking technique can efficiently compensate for the efficiency decrease occurred by a reduction in the coupling coefficient. The efficiency of a traditional WPT system decreases with increasing the transmission distance; however, an adaptive frequency tuning method can compensate for the efficiency reduction due to the changes in the distance or direction of the coupling method.

5. Seawater Effects on WPT

In this section, we address the impact of different seawater parameters, e.g., water conductivity, temperature, pressure, ocean currents and biofouling, etc., on WPT systems.

5.1. Water Conductivity

The presence of salt increases seawater conductivity which results in eddy currents [109]. These eddy currents have a strong impact on magnetic fields and significantly reduce the field strength of WPT. Ultimately, this degrades the overall performance and efficiency of the WPT system. This efficiency loss is directly associated with seawater conductivity. We can conclude that high inductance requires high dependency on conductivity which creates a strong magnetic field. Additionally, it also shows dependency on compensation techniques; for example, when power flows in a low voltage then it will create a strong magnetic field. Thus, it results in high dependence on seawater conductivity. In 2016, Santos et al. [109] illustrated a relation between transfer efficiency and conductivity as presented in Figure 15.

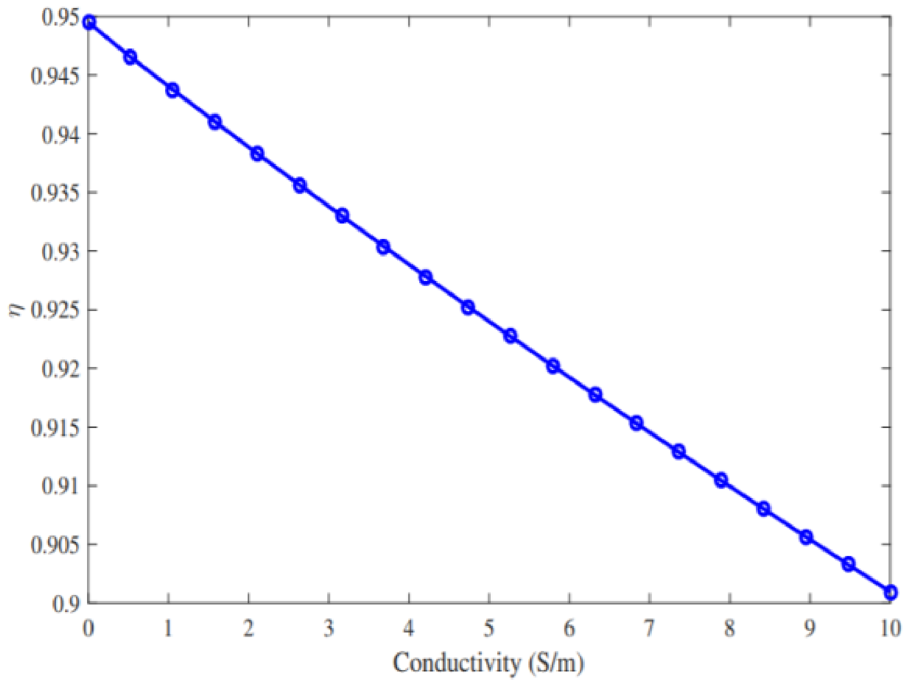


Figure 15. Water conductivity effect on efficiency.

5.2. Ocean Current Disturbance

The seawater currents severely affect the performance of WPT systems. These currents introduce misalignment between transmitter and receiver coils. In a study [89], T. Kojiya et al. stated that electromotive force (EMF) is useful to stabilize AUVs. Lee et al. [110] and Wang et al. [111] briefly discussed coil topologies and shielding effects for UWPT. Several studies have focused on designing couplers to overcome seawater currents. Conventional structures or WPT couplers contain solenoid, bipolar, circular, rectangular and DD pad structures. Figure 16 presents different inductive and magnetic coupler designs. However, extra shielding and fixing is needed as these conventional structures are vulnerable to ocean currents. Thus, current structures must be improved to tolerate ocean currents and overcome misalignment along with handling cost, weight and complexity of WPT systems. Table 6 provides a comparison between different couplers for UWPT.

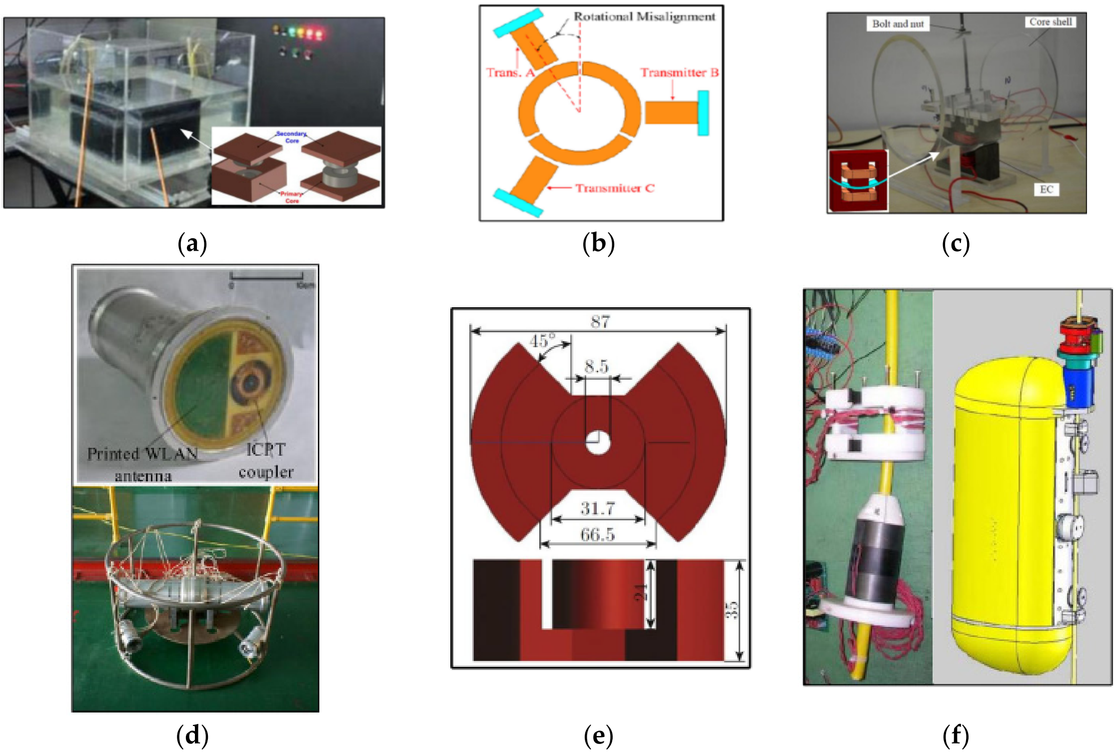
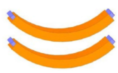
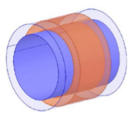


Figure 16. Different magnetic and inductive couplers proposed by: (**a**) Cheng et al. [68]; (**b**) Kan et al. [81]; (**c**) Yan et al. [81]; (**d**) Zhou et al. [84]; (**e**) Wang et al. [87] and (**f**) McGinnis et al. [77].

Table 6. Comparison between different couplers for UWPT.

Magnetic Coupler Structure	Electromagnetic Compatibility	Operating Frequency	Display View	Design Angle of Receiver	Power Level	Hydrodynamic Characteristics	Efficiency	Reference
Arc shaped	Excellent	85 kHz		80	3 kW	Excellent	91.9	[59]
Dipole arc shaped	Excellent	50 kHz		About 56	630 W	Excellent	89.7	[104]
3 phase ring shaped	Low	465 kHz		360	1 kW	Good	92.41	[91]
Ring shaped	Low	52 kHz		360	300 W	Low	77	[112]
Embedded shaped	Medium	20 kHz		/	10 kW	Low	91	[68]

5.3. Loss and Biofouling

Another critical challenge in WPT systems is bio-fouling in marine environments. It occurs because of the amassed marine microorganisms existing on the water surface. Moreover, temperature elevation can exacerbate marine microbial growth [113] as shown in Figure 17. Unchecked microbial growth causes misalignment and a wider gap between coils, consequently reducing the efficiency of the WPT system. In [114], Anderson et al. reported that heat generated in WPT coils can lower the fouling. In this regard, external heating and antifoul paints are being used which can significantly control fouling. Thus, heat dissipation should be kept into account while implementing any UWPT system. For this purpose, coating materials are considered as a good heat dissipating medium.

Figure 17. UWPT coil bottom after 45 days [115].

Another major concern in UWPT is power loss. The total loss contains copper loss due to coil resistance, magnetic loss in ferrite, eddy current loss in seawater, loss in compensation capacitor and switching loss in rectifier and inverter. Figure 18 presents total losses in UWPT system. Power electronics losses may constitute up to 1–2% of total loss. Power losses can be decreased through coaxial winding and Litz wire.

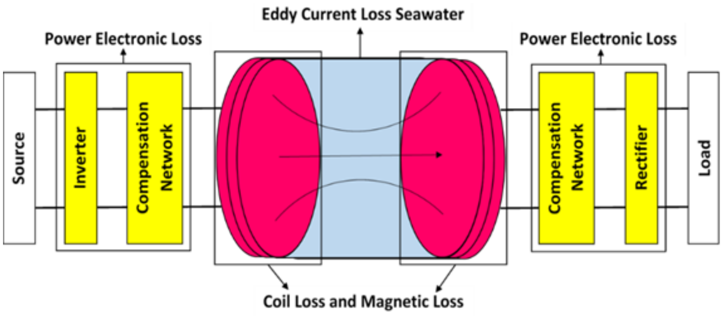


Figure 18. Various power losses in UWPT.

5.4. Temperature and Pressure

Generally, seawater is considered as a cooling medium which can improve the thermal limit of coils. D. Patil et al. [102] reported an increase from 600 W to 1 kW from air to underwater medium. Moreover, potting or shielding material also play a major role in heat dissipation in coils. Similarly, pressure also impacts an UWPT system. In [88], the authors investigated high hydrostatic pressure impact on WPT system efficiency. They reported a decreased efficiency at a depth of 4 km with 40 MPa pressure. The authors stated that this decreased efficiency was caused by low permeability under high pressure which reduces magnetic inductance. Results presented in Figure 19 show that magnetizing inductance decreases with increasing pressure [54,88]. Reactance also becomes dominant with an increase of gap length between transmitter and coil as permeability is determined through gap length. As a result, a little effect on magnetizing inductance is noticed by high pressure.

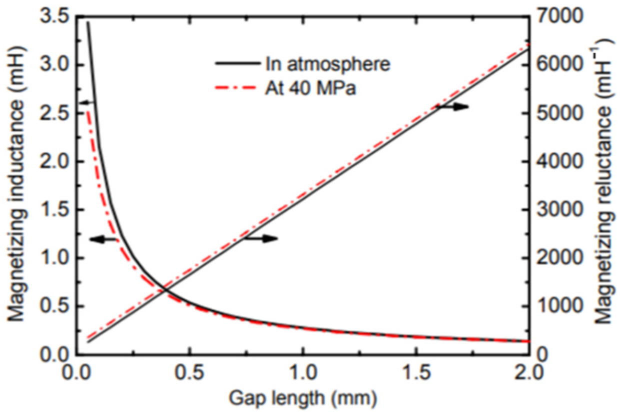


Figure 19. Gap length effect on EM coupler.

6. Engineering Challenges in UWPT Systems

UWPT technology is confronted with many technical challenges as follow:

6.1. IWPT System for AUV

AUVs are currently being used for several oceanographic missions such as ocean observation, monitoring and exploration. Matsuda et al. [116] discussed an AUV based system for deep-sea applications. The mission time span of these underwater objects is limited due to battery challenges. The incorporation of AUV and WPT system without damaging its shape and hydrodynamic mechanics is crucially important. In [83], In 2014, J. G. Shi et al. integrated a secondary coil on an AUV's hull, which creates a high magnetic flux. In other studies [75,76,88], researchers focused on AUV shape which causes high impact on hydrodynamic performance.

6.2. Pressure-Tolerant Electronics

High ocean pressure can severely damage electrical objects in AUVs. In case of a strong EM field, UWPT can generate intense high-frequency EM waves radiated in all directions. As the internal layout of AUVs is compact, so generated EM waves can affect the normal operation of its equipment or even completely damage it if generated EM waves are not properly controlled. That is why the safety of these electronic objects becomes a challenging issue in underwater missions. It is essential to take EM compatibility design and suppression measures into account in order to reduce the severe impact of high-frequency EM waves on components. For this purpose, these electrical objects are encapsulated in high compressible material to overcome high ambient ocean pressure [117]. This material can be fluid such as insulating oil or solid such as urethane. Thus, pressure tolerant system design should involve smart selection of electronic objects. Previously, some studies [118,119] have briefly discussed selection of pressure tolerant electronics.

The WPT system submerged in ocean must deal with challenging issues such as temperature, pressure, water conductivity, ocean currents, fluctuation and corrosive salts. Researchers should find a watertight design which can halt intrusion and is sturdy enough to combat wave motion. Another pivotal constraint is the physical dimension of transceiver coils. Smaller coils offer limited throughput power while larger coils can be cumbersome to incorporate. Thus, the research fraternity should investigate an intelligent and optimized design through proper simulation and experimental trials.

6.3. Retention and Alignment

For an efficient WPT system, an appropriate alignment is required. A docking station is needed in order to maintain AUV stability under turbulent seawater conditions. Due to AUV docking maneuvers, misalignment occurs which reduces the coupling coefficient and results in lower efficiencies. Different methods have been investigated to stabilize AUVs, including hooks, poles, conical guides, magnetic switches and moving carriages.

We performed some experiments on UWPT and demonstrated the effect of misalignment on coupling coefficients as displayed in Figure 20. The graph shows almost symmetrical behavior which indicates that misalignment can occur on any side of a coil. In a recent study [120], Lopes et al. presented two transformers with high tolerance to misalignment for battery charging application of AUVs. These transformers are comprised of two topologies which are commonly used in WPT systems: Solenoid-Planar Spiral and Solenoid-Solenoid.

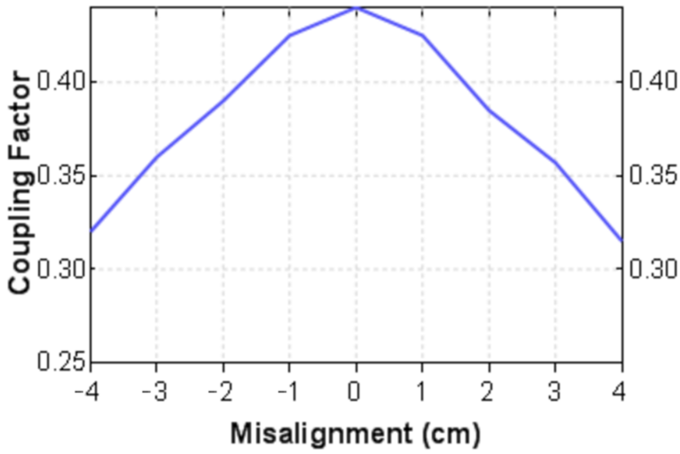


Figure 20. Effect of coil misalignment on coupling coefficient.

6.4. Angle Coverage

Another crucial factor in WPT is the positioning angle between transmitter and receiver coil, which can impact WPT system efficiency. We changed the positioning angle of the receiver coil from 0 to 90° according to the transmitter, as illustrated in Figure 21. We performed some experiments of UWPT and calculated efficiency variation at 0°, 30°, 60° and 90°. Our results indicate that maximum efficiency decreases as the angle varies from 0–90°. We conclude that system efficiency will be lower at greater angles between transmitter and receiver coils. We can see that angles greater than 30° highly impact the transfer efficiency. There is a drastic drop in efficiency at angles above 60°. This positioning angle may impact the charging distance as well. At higher angles, the charging distance will be much less. Our results validate that the placement angle should be lower than 30° to attain high efficiency and larger charging distance.

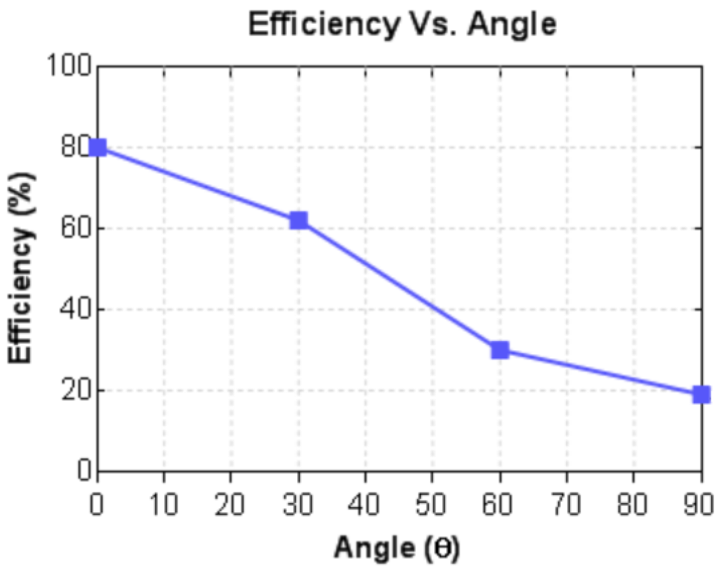


Figure 21. Efficiency variation across angles.

6.5. Transmitter and Receiver Distance

In an UWPT system, a drastic decrease in transmission efficiency is noticed with the increase of transmission distance. This is due to the permeability and permittivity of water which is hundred times higher than air medium. In complicated ocean environments, the transmission distance is limited to several millimeters due to induced eddy current losses. The eddy current losses in the ocean are of high concern in UWPT systems. Meanwhile, a UWPT system is more vulnerable to distance as transmission distance is further reduced after waterproofing and pressure resistance packaging. Research should focus on design of a magnetic coupler with minimum magnetic flux leakage. Important design concerns must be involved in corresponding parameters' optimization. Table 7 shows conductivity, relative permeability and relative permittivity values for vacuum, air, seawater and fresh water, which greatly impact performance of WPT systems. Transmission distance is also a critical concern in wireless charging of AUVs. In that scenario, it is closely linked with the size of the coupling mechanism. Therefore, it is important to investigate an optimal halfway point between coupling mechanism and transmission distance in order to accurately determine the application range of AUVs [121].

Table 7. EM parameters comparison of different media.

Medium	Conductivity (S/m)	Relative Permeability	Relative Permittivity
Vacuum	0	-	1
Air	0	1	1.0006
Fresh Water	0.01	0.99	78.50
Seawater	4	0.99	81.50

6.6. Docking Station Stability

Positioning, orientation and leveling must be maintained during deploying the docking station in an underwater environment. B. W. Hobson et al. [122] used heavy railroad wheels to maintain dock leveling. The authors demonstrated additional pumping to mitigate inadequate angle impact while deploying cone docks. Cone-shaped docks under ocean currents have been used in [123]. Similarly, some studies reported a hooking concept, where the entire docking process must be repeated.

6.7. Harsh Envirnment

In deep-sea applications, wireless power transfer systems suffer from low temperatures, which cause unpredictable saturation and severely degrade the performance of ferrites. Power modules and magnetic couplers must be provided with extra protection to face these challenges as they are the most crucial components in WPT systems. Particularly, the configuration of a magnetic coupler determines its applicability, while its design parameters and optimization strategies influence the overall efficiency of a WPT system. For efficient charging for an AUV and suitability for its curved shell, the authors in [59] designed an arc-shaped UWPT coupler. In addition, ocean currents also affect the precise positioning of UWPT systems. Fixing and clamping equipment are used to stabilize power transfer between transceivers.

6.8. Battery Charging Rate

The battery operation depends on ambient temperature, operation rate and thermal conditions. It seems hard to secure rapid AUV charging as charging and discharging rate is highly influenced by lower ambient temperature. Therefore, mission time delay is often reported in commercially available batteries. In [124], the authors reported that increased pressure has a negligible impact on the resistance and capacity of a battery, while lower ambient temperature results in increased resistance and decreased battery capacity. Y. Ji et al. [125] carried out analysis on low temperature effects on Li-ion batteries.

6.9. Security and Pollution Issues

Magnetic leakage and heat generation are two key security concerns in UWPT systems. High temperatures not only affect bio-fueling but also affect the insulation ageing of devices. Researchers should consider heart dissipation design while using the UWPT system. Electromagnetic pollution can harm marine life, so shielding effect analysis must be taken to protect the biological environment. Similarly, the EM stealth of the AUV is a critical concern whenever it is deployed for military or naval operations. Considering a power supply component for military equipment, the EM radiations generated during power transfer must be minimized along with absorbing the detection waves emitted by the radar. Hence, considerable EM compatibility and stealth performance are crucial factors for safe, secure, reliable, and stable operation of AUVs in practice [121].

6.10. Auxiliary System Improvement

With the rapidly expanding research and development activities on AUV's WPT techniques, several new challenges arise along with innovative applications of this technology. Fast, safe and accurate charging of these marine objects is a crucial concern in practical applications. The research fraternity is focusing on smooth and reliable charging processes along with incorporating advanced navigation systems [121]. Furthermore, as AUVs are required to operate in harsh, dynamic, and high-pressure undersea environments, a major problem is to tackle the challenge of sealing the equipment. Cost-efficient and new material designs which can withstand high-pressure are worthy of further exploration.

6.11. Accurate Measurement of Eddy Current Losses in Seawater

When the WPT system operates in undersea environment, it is accompanied by inevitable eddy current losses. Although the difference between eddy current loss in air and pure water is small, however, it is obviously larger in an undersea environment and severely degrades the performance of the WPT system. Eddy current loss (ECL) increases with an increase in frequency and coil current. Thus, it is important to find strategies to overcome ECL such as accurate measurement of ECL of UWPT systems to support a theoretical basis for the enhancement of transmission efficiency. Several coil structures, frequency optimization and current control techniques, and equivalent circuit models [126] of the ECL have been proposed as well.

6.12. Ambiguity of WPT in Underwater Electric-Field Coupled Power Transfer (ECPT)

There is ambiguity which makes it difficult to accurately compute coupling capacitance, since the conductive properties of electric fields in seawater are still unclear. It is difficult to realize a precise energy loss model for underwater ECPT due the complexity of the energy loss [127]. It is also unclear how the operating frequency of ECPT impacts output current or voltage and even power transfer or overall system efficiency. According to recent studies, the operating frequency of ECPT ranges from tens of kHz to tens of MHz; however, there is a clear lack in regulation of operating frequency for underwater ECPT. In addition, considering the couple capacitance as the indicator of coupling strength is yet to be further explored. Similarly, the resistance enhanced by piezoelectric effects cannot be ignored in deep-sea environments. All these challenges must be further studied.

6.13. Difficulty of Parameters Configuration in Compensation Net

Compensation net is often required in ECPY systems, to minimize the imaginary power and enhance the power transfer capability of the coupler. The parameters of the compensation net must be accurately configured to coordinate with the couple capacitance at the resonant frequency. However, there exists a contradiction in that the estimation of equivalent couple capacitance is hard due to the harsh sea environment. The load of ECPT is variable, and the components reactance in a compensation network can cause manufacturing problems. All these above-listed issues lead to critical challenges of parameters configuration in a compensation net.

6.14. Insufficient Power Transfer Efficiency and Intensity

Power transfer efficiency and intensity has a relationship with power compensation topology, operating frequency and couple capacitance. These parameters can be mutually controlled or restricted, making it hard to coordinate these parameters. Power intensity mostly cannot be available due to the restriction of breakdown voltage and operating frequency of couple capacitors. On the other hand, energy losses in ECPT can include leakage of power from the coupler, energy consumption by parasitic resistances, switching loss in components and eddy current loss. All these energy losses lead to a substantial reduction in the efficiency of underwater ECPTs. In addition, it is also challenging to precisely control the operating frequency due to parameter changes in uncertain sea water and significant distribution of capacitance in the sea environment. These factors will finally impact the stability and efficiency of the whole system. Thus, it is hard to optimize the transmission power and efficiency of the ECPT system.

7. Applications

7.1. Mother Ship Charge to AUV

In 2001, WHOI and MIT originated the concept of WPT in underwater vehicles incorporated in an autonomous ocean sampling network (AOSN). Sorrell and Feezor designed an underwater robot MIT/WHOI Odyssey II which could be wirelessly charged at seafloor level. The system was deployed at 2000 m in the deep sea and provided 79% transfer efficiency to transfer 200 W power [128,129]. Later, underwater vehicles Bluefin 21, REMUS 100 and REMUS 600 [130] were designed for underwater wireless charging as can be seen in Figure 22. Similarly, Kawasaki has started working on AUVs in order to tackle the expanding demand for pipeline inspection and maintenance in the offshore oil and gas industry [131]. SPICE is the world's first ever AUV equipped with a robotic arm to perform uninterrupted continuous underwater pipeline monitoring, designed based on a fusion of industrial robotic technologies and submarine-oriented technologies. SPICE has the feature of recharging its battery and forwarding collected data to the support vessel after returning to the docking station.

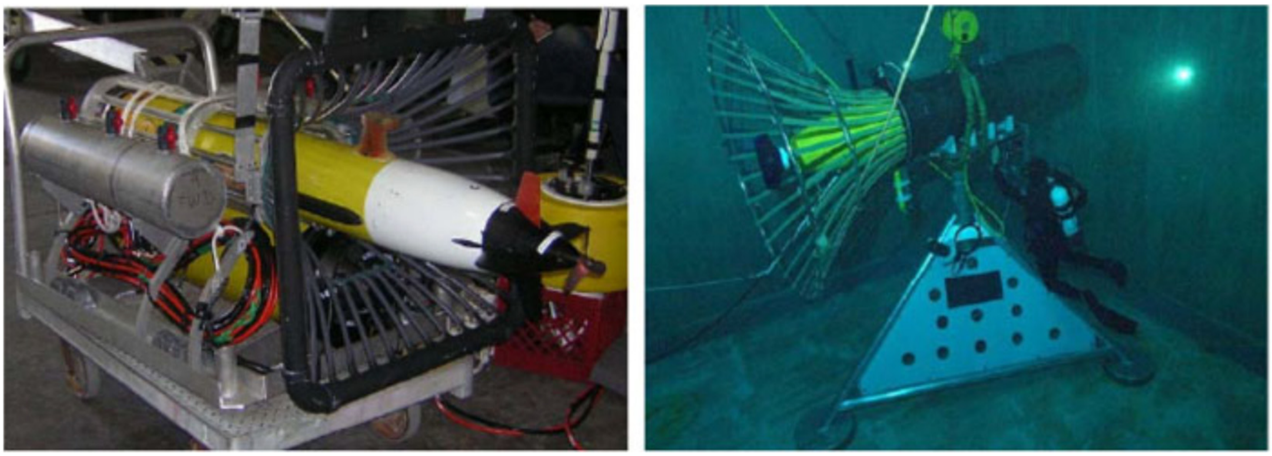


Figure 22. Overview of AUV **(left)** and docking station (**right**) [128].

An unmanned underwater vehicle (UUV) named "Marine Bird" was designed by Kawasaki Heavy Industries. In this project, a base station is used to wirelessly charge UUVs through electromagnetic induction [117,132]. Tohuku University collaborated with NEC company to design a wireless charging system for AUVs as shown in Figure 23. They achieved 90% transfer efficiency to transfer 500 W power. The designed system was stable with no vulnerability to disturbance [35,89].

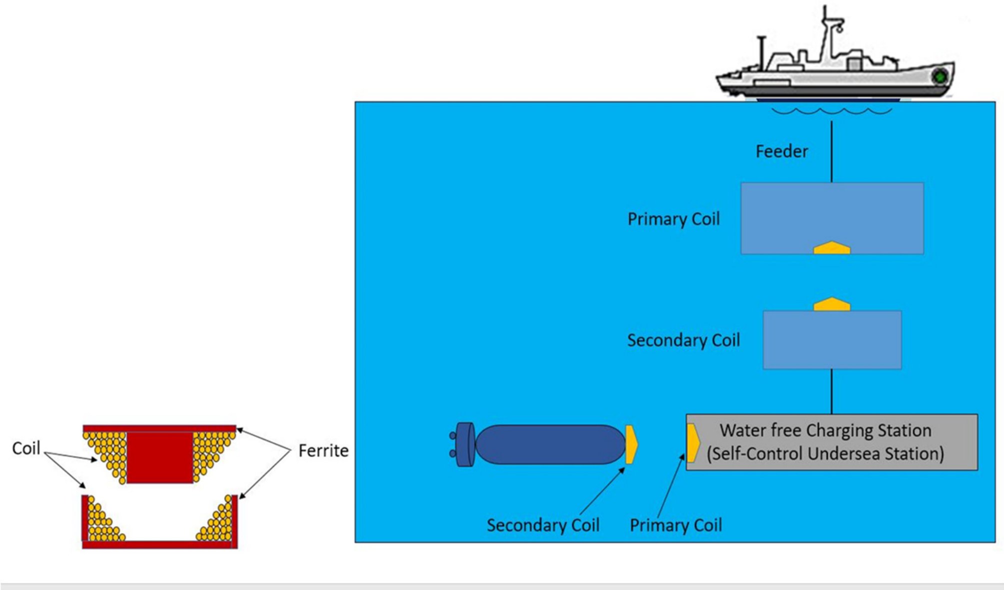


Figure 23. WPT System by Tohuku University and NEC company.

7.2. Designing UWPT for Smart Ocean Energy Systems Applications

Taofeek Orekan in University of Connecticut, USA presented a methodology to optimize coil design to enhance the transfer efficiency of an UWPT system. In this research work, the authors proposed a novel maximum power-efficiency tracking (MPET) technique [51]. An adaptive convertor control was utilized in tracking the maximum efficiency. Results validated the robustness and effectiveness of the MPET approach and design to obtain maximum WPT efficiency under an unpredictable and dynamic undersea environment.

The systematic techniques outlined in this research work have empowered a new era of research and opportunities in smart ocean systems. Advanced control strategies, unique topologies for power electronics and multiple source ocean energy systems will offer better estimation features in MPET. A smart ocean energy system at UConn Power Lab can be seen in Figure 24. It is capable of UWPT, smart wave energy conversion, cyber security and tidal energy generation.

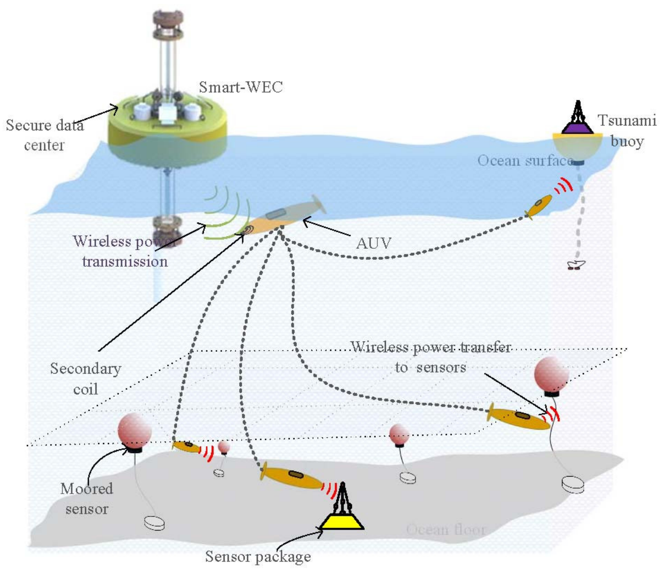


Figure 24. Concept of Smart Ocean Energy Systems [133].

7.3. Ocean Observation Network

A WPT system for seabed observatory system ALOHA-MARS was designed in Washington University by Professor McGinni. They achieved 70% transfer efficiency for 250 W power. A German based MESA company designed a rotatable UW charging system to provide power to microprocessors, EVs, lighting devices and sensors. MESA had designed INPUD DON series devices for deep-sea regions and INPUD CAN series devices for coastal waters as shown in Figure 25. It allows 2500 rmp rotary speed and 90% efficiency for 10 W power [134]. A Japanese TRITON company also designed a buoy system to achieve power and data transmission simultaneously. Researchers from Tianjin University, China have developed an IPT system which is able to provide power to underwater sensors [135].

Figure 25. INPUD DON100 HE30 Underwater equipment [136].

7.4. Smart Wave Energy Converter (WEC)

Marine renewable energy (e.g., salinity gradient, thermal gradient, ocean, tidal or wave current) can revolutionize underwater power transfer techniques and sea observing capabilities. To achieve efficient renewable energy supply, smart wave energy converters are single body point converters which can oscillate in heavy motion as shown in Figure 26. These converters offer unique features of underwater WPT, cyber security and intelligent control such as MLCT, MPC and MPET [137]. In the foreseeable future, smart WECs will be used to deploy distributed ocean systems and can provide power solutions in ocean space. In [138], the authors proposed underwater wireless power and data transfer systems with a shared channel which is powered by renewable system.

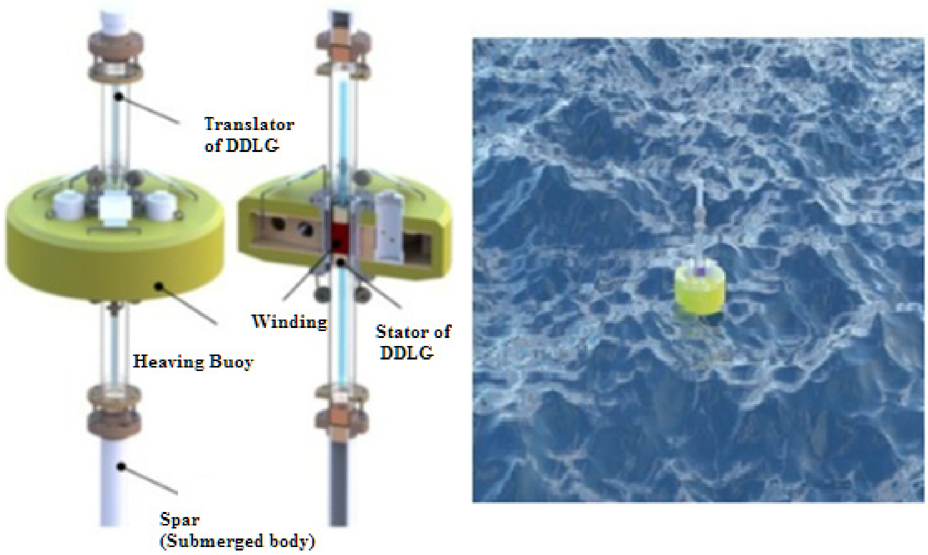


Figure 26. Smart wave energy converter [133].

7.5. Torpedo AUVs

In Torpedo AUV, a transmitter is incorporated within docking cage. Power is transferred as the AUV comes into the docking station and transceiver coils are aligned. Figure 27 shows IPT system which contains two coaxial solenoids. The receiver coil is wound on the AUV's hull while a transmitter coil is assembled on the submerged base station [139,140]. The power transmission is made from base station to AUV [141].

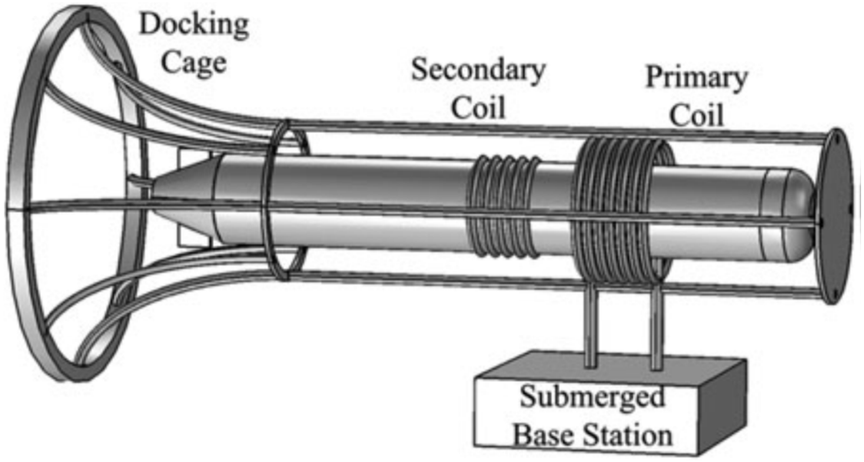


Figure 27. Concentric Circular Structure for AUVs [86].

Torpedo AUV has gained attention as it has less liquid resistance and provides more room. A torpedo AUV prototype and experiment is shown in Figure 28. However, battery storage limits the endurance of the AUV. It is suggested to design an undersea docking station to increase its cruising ability [142]. This docking station can guide the AUV into dock [143,144]. The docking station can collect and store energy from both wave and tide [145]. In case of low energy levels, the AUV moves towards the nearest docking station to recharge. Although traditional cable methods are not preferable to supply energy, still WPT appears as a good alternative to charge AUVs. A comparison of existing docking stations is presented in Table 8.

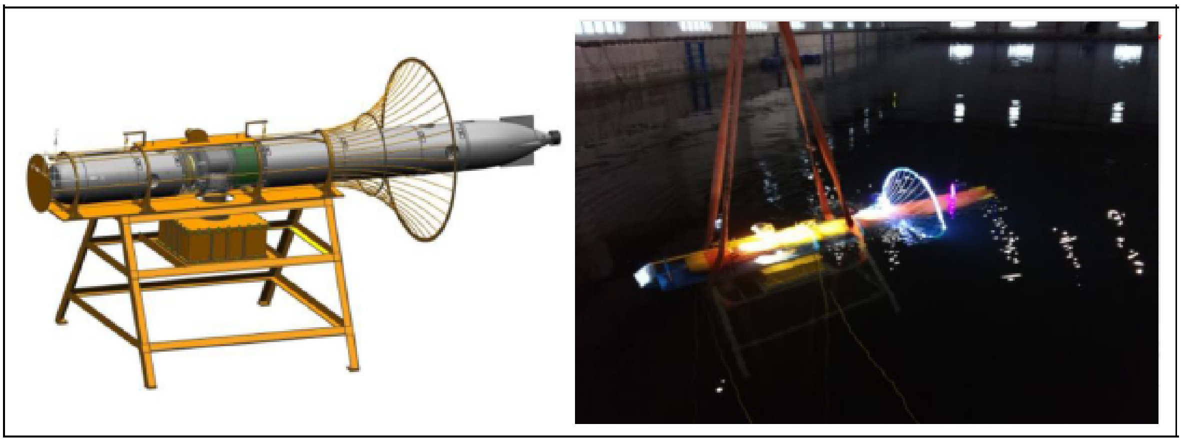


Figure 28. Experimental demonstration of Torpedo AUV Prototype [146].

7.6. Deep-Sea Power and Communication Links

The Sensor Systems Lab and the UW Applied Physics Lab are jointly working on UWPT and communication. They have collaborated with Bob Michimato and David Dyer to recharge a power base station which is located at 1000 m depth below sea-level. They carried out experiments for both fresh water and seawater. They have concluded that WPT losses can be minimized through modifying coil size and various other parameters. Their experiments include a test tank shown on the left side of Figure 29, a data logger containing

4 buoys in the middle and underwater coil on the right side. An underwater inductive link is utilized to communicate data from the base to the buoys.

Table 8. Comparison of existing docking stations [123].

AUV Type	Type Characteristics	Docking Device Structure	Docking Device Structure	Reference
Marine-bird	V-shaped guide rail, two grasping arms	Cushioning locking mechanism type underwater docking platform	Electricity supplementation, data exchange	[147]
Bluefin-21	Maximum diving depth of 4500 m Has a sealed recovery chamber diameter of 0.53 m	Round gradual locking cage box	Electricity supplementation, data exchange	[148]
REMUS-100	A square cage as the guiding mechanism, maximum diving depth of 100 m, diameter of 0.19 m,	Compact splicing device, square progressive locking cage box	Electricity supplementation, data exchange	[130]
DAGON	V-shaped clamping mechanism and captured rod	Round construction with locking mechanism	Electricity supplementation, data exchange	[149]
Odyssey II	V-shaped titanium latch body and rotatable titanium rod	Round construction with locking mechanism	Electricity supplementation, data exchange	[150]

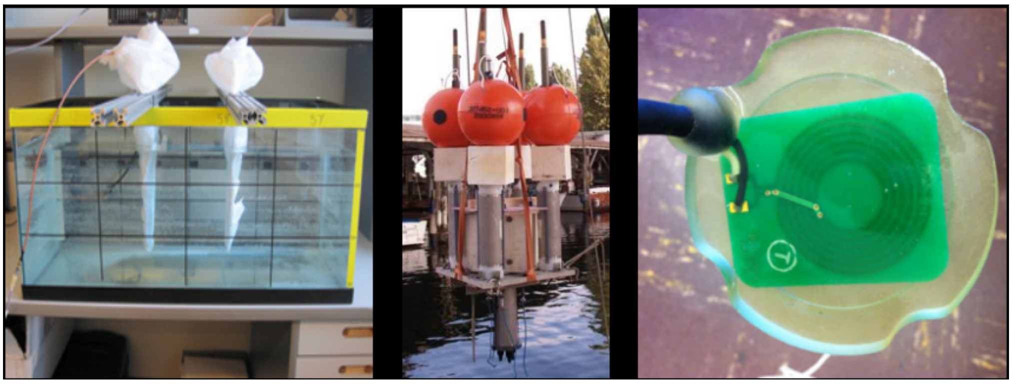


Figure 29. Deep-sea power and communication experiment [151].

8. Conclusions and Future Work

This study focuses on WPT research contributions for the seawater environment. Research and engineering challenges, practical considerations, and applications in underwater wireless power transfer (UWPT) are highlighted in this review, providing a reference and guidance for researchers and engineers to improve the efficiency of UWPT systems. We have also addressed the impact of coil orientation, coil misalignment and seawater effects on the UWPT system and suggested measures to improve UWPT efficiency. In addition, this study proposes multiple-input and multiple-output (MIMO) wireless power transmission, which can significantly improve the endurance of autonomous underwater vehicles (AUV). This idea can be applied to designing an underwater wireless power station for self-charging of AUVs. Since we know that underwater environments are unstructured, uncertain and dynamic in nature, so we encounter several challenges while deploying any system in this harsh environment. Researchers are making efforts to overcome these challenges with efficient data and power transmission in underwater applications. A notable approach is to use an adaptive control mechanism to achieve maximum efficiency besides frequent change in coupling coefficients because of stochastic nature of seawater. In future, the efficiency of any UWPT system can be improved by integrating the MIMO concept. Introducing MIMO signal processing and optimizing WPT can bring promising results. Another key benefit of the MIMO technique will be the enhanced area of charging station and distance range. In such an UWPT system, an AUV can be guided to visit the nearest charging station to charge itself as can be seen in Figure 30.

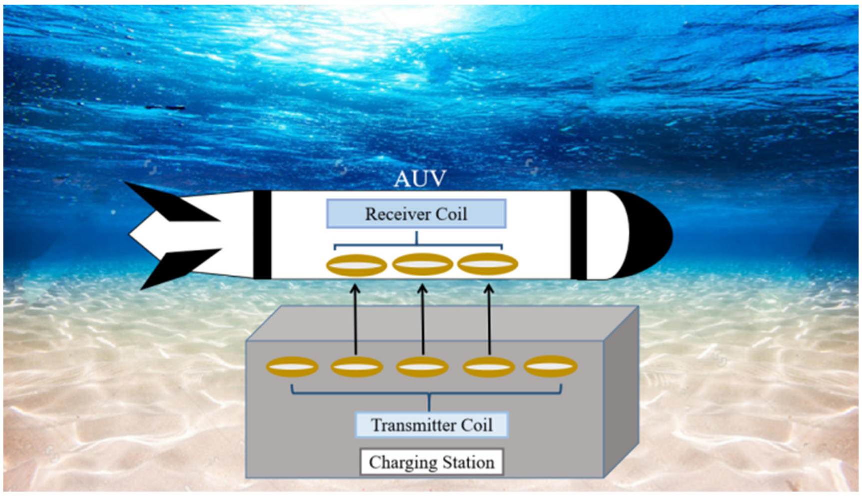


Figure 30. MIMO UWPT for self-charging of AUV.

UWPT systems are not only influenced by effective medium constraints such as permeability, permittivity and conductivity but also affected by salinity, ocean currents, pressure, temperature and adherent microorganisms. All these factors severely impact the performance of UWPT systems. In future, the research fraternity should address multiple environmental factors as current studies only focus on temperature, salinity and misalignment. Researchers should investigate efficient design of housing, shielding and sealing of EM couplers for deep-sea applications where high pressure is a critical concern. In addition, transmission distance is also crucial in deep-sea applications. Deep-sea devices are usually compact and it is not practical to enhance coil size to extend transmission distance. Thus, researchers should investigate novel designs to attain a wide range of transmission distance without requiring excessive device size or volume. Future studies should also carry out analyses for material selection and design structure in order to protect housing and sealing of materials from corrosion. Significant research focus is also needed to investigate electromagnetic interference (EMI) challenges. In future, mu-near-zero (MNZ) metamaterials, multiple coil switching techniques and issues of coil size disparity must be addressed to improve WPT system efficiency.

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