ACCELERATING THE ADVANCEMENT OF WAVE ENERGY DESALINATION TECHNOLOGIES

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Executive Summary

As the global population increases, meeting the basic needs of all becomes more challenging. One of the most basic needs for humans is access to clean water. Many people across the globe either live in water-stressed areas or lack access to potable water which is suitable for human consumption. In areas with limited access to clean water, desalination systems are being proposed as a solution. However, the desalination process is energy-intensive and the use of non-renewable energy resources to power such systems presents negative impacts on the natural environment. Therefore, the use of renewable energy sources such as wave, solar, and wind are now being deployed to power desalination technologies to generate clean water in a more sustainable manner.

This report provides a background on the wave energy and desalination sectors, specifically, and how these technologies can address the global water issue. It also highlights the present status of both fields, including the different types of systems available and the potential to integrate both together. Challenges and opportunities within the wave energy sector are also highlighted with an aim to capitalize on the opportunities while addressing the challenges.

The Waves to Water prize presents an opportunity to promote the development of desalination technologies powered by a low carbon energy source. The goal of this prize is to accelerate the development of wave-powered desalination technologies for remote island communities and disaster relief scenarios. The $3.3 million USD prize is awarded throughout the competition to teams that advance to the next prize stage. The winning team will have had to successfully create a desalination system powered by renewable wave energy which is small enough to fit into a palletized container, is modular to allow for scalability, and is also cost-competitive. This competition has five stages, spanning over three years, to support innovators from initial concept to a fully functional prototype - CONCEPT (Stage 1), DESIGN (Stage 2), ADAPT (Stage 3), CREATE (Stage 4), and DRINK (Stage 5). The last stage is ongoing, and the winner is expected to be announced in April 2022.

As a partner supporting the prize, Engineering for Change (E4C) has provided engineering support and market analyses for both the development and implementation of the competing technologies. Driving development and innovation in this emerging sector will require investment across a number of dimensions including, but not limited to:

- Increased funding opportunities for individuals and groups working on these technologies
- Collaboration with academia, industry, nonprofits, and government entities for a holistic approach in developing these technologies for widespread adoption
- Collaboration with diverse organizations representing end-user needs for wave-powered desalination design
- A robust procurement pathway for products with growth of the innovation ecosystem attracting diverse entrepreneurs via platforms such as prizes (ex. Waves to Water Prize) to facilitate funding and networking

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Wave Energy and Desalination Technologies

Global Water Needs, Challenges, and Solutions

As the global population rises, so does the need for clean and safe water. In 2020, approximately 2 billion people (around 26% of the world's population) did not have access to properly and safely managed water-related services. Another 733 million people live in countries containing regions that are classified as highly water-stressed.[1] These problems are exacerbated by climate change, making it even more difficult for people to gain access to clean water, particularly within rural communities across the globe.

Children and women within these rural communities are the ones who are impacted the most. Studies have found that an estimated 200 million women and girls are often faced with the burden of carrying water for their families for long distances, especially within the African continent.[2] The lack of access to clean and safe water can result in severe diseases and even death in some instances. To prevent the occurrence of such consequences, it is vital that this global issue be addressed, one method of which is through sustainable innovation.

Although approximately 70% of the earth's surface is covered by water, the majority of this water is unsuitable for direct human consumption. This is mainly due to the salt concentration of the seawater (about 35,000 PPM of salt ~ 35 g of salt per liter of water). One solution is to develop sustainable desalination systems. Desalination is the process through which freshwater is obtained either from seawater or brackish water. As the desalination process can be energy intensive (~2.5-4 kWh/m^3)[3], renewable sources of energy are preferred over non-renewables to minimize the carbon footprint.

Solar, wind, and wave-powered technologies provide clean, renewable energy resources that can be used to power desalination. By using renewable energy sources instead of non-renewable energy sources to power the relevant desalination technologies, the harmful impacts to the natural environment associated with fossil fuel energy can be reduced. By doing so, both the Sustainable Development Goals 6 (Clean Water and Sanitation) and 7 (Affordable and Clean Energy) can be addressed simultaneously. Identifying the most appropriate renewable energy resource for this application depends on many factors including potential for useful energy output and the location of implementation.

Communities living in the coastal vicinity would largely benefit from wave energy-powered technologies that can provide them with clean electricity as well as clean water through the integration of desalination technologies. One particular benefit of wave energy for this application is that it can generate pressure to pump water through desalination devices directly without having to convert the energy to electricity first. Promoting and enabling more research and development for renewable energy-powered desalination systems can help address the water scarcity issue while simultaneously conserving our natural environment.

In Sri Lanka the first ever seawater reverse osmosis (SWRO) project is currently underway in the Northern province. The design and development of the entire plant is carried out by the "Suez" group of companies.[4] The

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[1] UN, Summary Progress Update 2021: SDG 6 — Water and Sanitation for All, 2021
[2] World Vision, Global Water Crisis - Water Scarcity Facts & How To Help, 2021
[3] LiVecchi, A., Copping, A., Jenne, D., Gorton, A., Preus, R., Gill, G., ... & Spence, H. (2019). Powering the blue economy; exploring opportunities for marine renewable energy in maritime markets. *US Department of Energy, Office of Energy Efficiency and Renewable Energy. Washington, DC*, *207*.
[4] Suez Group, First SWRO Plant in Sri Lanka, 2021

system will have a capacity of 10,000 m^3/day.[4] It is estimated that the system will deliver clean and safe water for a population of approximately 300,000 living in the vicinity.[4] Although the exact energy resource used to power the desalination plant is unknown, it is likely to be either powered by wind or solar energy technologies since "Suez" specializes in seawater reverse osmosis plants powered by these two renewable energy resources.[5]

State of the Field

Wave Energy Converters

History of Wave Energy

Wave energy technologies date back to the 20th century. The first physical wave energy converter was developed by Yoshio Masuda in Japan who was a former naval commander. The wave energy converter system he developed later came to be known as an "oscillating water column" device, developed based on the principle of floating. Research in wave energy was rejuvenated in the 1970s and 80s around the time of the oil crisis. Since then, wave energy technologies have evolved through innovation into different types of wave energy converters (WECs).[6]

Types of Wave Energy Converters

Wave energy converters (WECs) are the systems that are used to harness the energy from waves. These WECs can be categorized based on the following:

1. location of operation: onshore, near-shore, or offshore.
2. operating principle/mechanism: point absorber system, surface attenuator, oscillating water column, oscillating wave surge converter, and the overtopping device.

Point absorber system: Also known as "wave activated bodies", the system can either be submerged below the water (relies on pressure differential) or it can be used as a floating structure. The generator is either fixed onto a support underwater generator, is on top of the buoy, or is out of the water, and the harnessed energy is transferred to the shore via underwater cables. The main advantages of the point absorber type of WECs are that they do not depend on the direction of the wave, the design is simple, and they are more cost effective (comparatively) in terms of manufacturing, installation, and maintenance.[7] One example of a point absorber system is the Ocean Power Technologies' PowerBuoy.[8]

Surface attenuator: A mechanical wave energy converter that consists of numerous floating bodies which are linked together by joints. These types of wave energy converters are used in offshore locations. The system is aligned parallel to the incoming wave motion. The rise and fall of the waves are then used to create a flexion motion that is either converted to rotational motion or drives hydraulic pumps to generate electricity. This type of WECs is always placed on the surface of the ocean rather than being submerged like point absorber WECs.[7] One example of a surface attenuator is Sea Wave Energy Ltd's Waveline Magnet.[9]

Oscillating water column: This can be used in either onshore or offshore locations. If the system is to be used for an onshore location, it is a "terminator wave energy converter device" and if it is offshore then it will act like a "point absorber system". This type of WEC consists of a chamber that has an opening to the ocean below the

[5] Suez Group, Desalination by Reverse Osmosis, 2021
[6] Aderinto, T., & Li, H. (2018). Ocean wave energy converters: Status and challenges. *Energies*, *11*(5), 1250
[7] Koyuncu, B., Mahmood, M., & Myderrizi, I. Theory and Applications of Wave Energy Converters: A Review
[8] Ocean Power Technologies, PowerBuoy
[9] Sea Wave Energy Ltd, SWEL Breakthrough Results

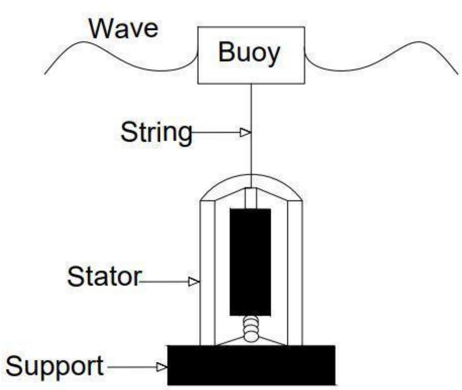
waterline. This forms an enclosed area of air on the top of the water column. Wave energy is received by the air chamber opening which is converted into compressed air. This air is then passed through the turbine situated in the power take-off (PTO) mechanism. This energy passing through the turbine is then converted into mechanical energy and ultimately into electrical energy through the generator.[7] One example of an oscillating water column is the Pico Powerplant on the Island of Pico/Azores.[10]

Oscillating wave surge converter: This wave energy converter typically uses a deflector to power a piston-based system that produces electricity or can be used for direct use. Waves hit the deflector causing forwards and backward movements which results in the activation of the piston system used to produce the output energy.[7] One example of an oscillating wave surge converter is Wave$_2$O^{TM} by Resolute Marine.[11]

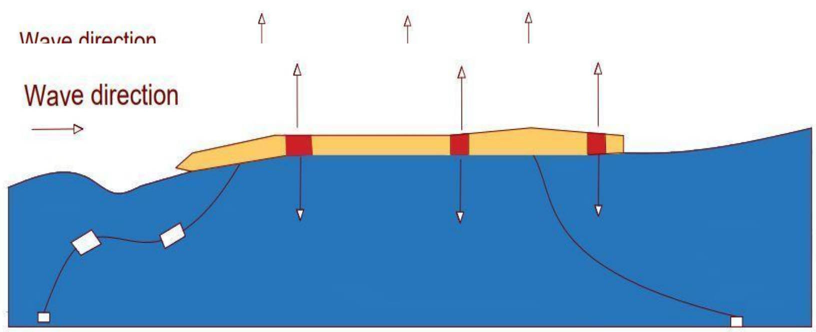
Overtopping device: The theory of operation of this type of wave energy converter is similar to that of a hydropower plant. A water storage reservoir placed above the sea level captures the wave energy and the turbine outlet releases the water back to the ocean.[7] One example of an overtopping device is the WavePlane.[12]

The following figures illustrate the different wave energy converters used in the present (recreated[7,13]):

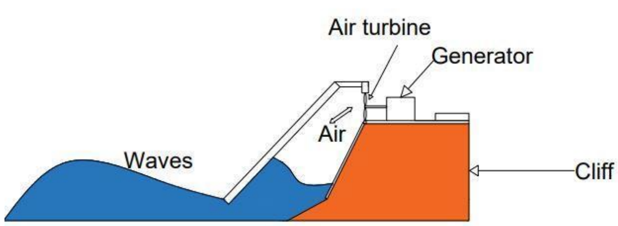
1. Point Absorber System



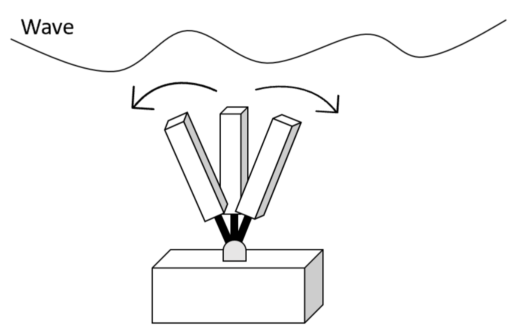
2. Surface Attenuator type WEC



3. Oscillating water column WEC

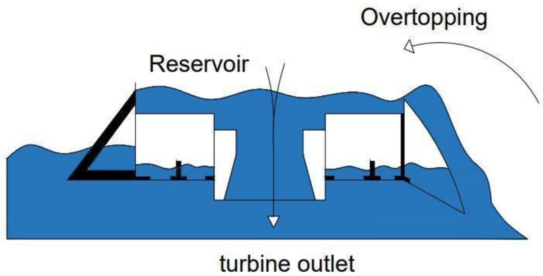


4. Oscillating Wave Surge Converter



[10] Pico OWC, OWC Pico Power Plant
[11] Resolute Marine, Technology
[12] WavePlane Production, WavePlane
[13] The European Marine Energy Centre Ltd, Wave Devices

5. Overtopping device



Desalination Technologies

History of Desalination Technologies

Prior to Yoshio Masuda's time, desalination technologies were first introduced during the end of the 18th century by the UK's Royal Navy. The first desalination unit was realized in 1885 in Glasgow by a company known as G. and J. Weir. Early desalination technologies were thermal based methods due to the low cost of fossil fuel at the time. However, as fossil fuel prices increased, research and development shifted to developing cost effective and efficient desalination technologies, resulting in membrane-based desalination. The first membrane desalination method was realized in 1959 and the first experimental plant with a capacity of 19,000 L/day was installed in 1965. Since then, the membrane-based desalination method has adapted to include energy recovery systems to reduce the energy required for the process and increase the lifespan of the membranes. To date, the most popular method of desalination is the reverse osmosis (RO) membrane method.[14]

Types of Desalination Technologies

Desalination removes salts and other impurities from seawater, brackish-water, or wastewater to produce freshwater for human consumption. At present, the desalination process is categorized into two main parts: 1.) membrane-based desalination methods, or 2.) thermal-based desalination methods. Membrane-based desalination technologies can be further divided into either RO or electrodialysis.[14]

RO involves the concept of hydraulic pressure to drive the water through a semipermeable membrane to remove the impurities from either source of water. The electrodialysis method uses an electric potential difference to transport the salt ions through a permeable membrane to dissolve the minerals.[15]

Thermal-based desalination was the first desalination technology to be developed and is hence considered the "traditional method". This method uses evaporation and condensation principles to desalinate water.[15] Thermal based desalination methods include:[15]

1. Multi-stage flash distillation (MSF)
2. Multiple-effect distillation (MED)
3. Vapor compression distillation (VCD)
4. Membrane distillation

Combining the appropriate WEC system with the desalination technology has the potential to provide clean water to rural communities and provide clean water during disaster relief applications in a much more sustainable manner.

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[14] IRENA, Water Desalination Using Renewable Energy, 2012
[15] World Bank, The Role of Desalination in an Increasingly Water-Scarce World: Chapter 3, 2019

Wave energy: Challenges

Within the wave energy desalination systems, the challenges mostly lie within the wave energy resource and the integration of it with desalination technologies including RO systems with varying pressure inputs. Here, we focus on the main challenges of wave energy including:[6]

1. **Less mature compared to wind or solar power** - The cost of wave energy systems is drastically higher than that of wind or solar energy resulting in hindered uptake.
2. **Environmental impacts may not be easily evaluated** - Since there are no systems in operation for a considerable period of time yet.
3. **High variability** - Variable wave/sea state is high leading to fluctuating output energy across short time periods (although more predictable over longer periods of time and compared to wind and solar[16]).
4. **O&M is challenging**- Especially with the offshore systems- offshore location systems maintenance is difficult compared to that of onshore or nearshore systems.

Wave energy: Opportunities

Although wave energy has its challenges there are many opportunities within the sector as well.

1. **Can increase and diversify the renewable energy mix in the global energy generation -** Wave energy can expand the global renewable energy generation share through generating clean electricity and by complementing other renewable sources of energy.[7] Relative to solar, it can provide continuous power day and night, can be reliably used in post-hurricane or cloudy settings, and can be compact for deployment in disaster contexts.
2. **Range of suitable end users** - Wave energy can be used in a wide range of applications from electricity to providing clean water for rural communities and also providing clean water for disaster relief applications.
3. **Collaboration between academia and industry –** Challenges identified by academia & industry can be reduced through organizing innovative competitions to promote wave energy tech (e.g. Waves to Water Prize)
4. **Wave energy promotion** - Promoting wave energy systems to a wider audience through competitions such as the W2W prize.
5. **Job creation** - By promoting wave energy there is potential for generating jobs within the rural coastal communities thereby enriching their livelihoods.

Integrating wave energy to power up desalination technologies can be a potential solution to solve the global water scarcity issue in a sustainable manner. This can enrich the livelihoods of the rural communities across the globe simultaneously ensuring environmental sustainability by using low carbon energy technologies.

Waves to Water Prize

The Waves to Water Prize is one of several prizes in the American-Made challenges series created by the Water Power Technologies Office (WPTO) at the United States Department of Energy.[17] This competition, administered

[16] Reikard, G., Robertson, B., & Bidlot, J. R. (2015). Combining wave energy with wind and solar: Short-term forecasting. *Renewable Energy*, *81*, 442-456

[17] American-Made Challenges, American-Made Waves to Water Prize

by the National Renewable Energy Laboratory (NREL), aims to accelerate innovation in wave energy-powered systems to desalinate water. The goal is to advance technology in this sector to meet global needs for access to safe and affordable water, with a focus on disaster relief scenarios and remote coastal or island communities.[18] To produce viable wave energy-powered systems, the prize focuses on tackling the aforementioned challenges in the wave energy sector, particularly the scalability of wave energy systems, competitive pricing, and reduction of environmental impact. Additionally, the prize emphasizes on the future potential of these systems for different contexts, such as disaster relief, and for the widespread promotion and adoption of novel renewable energy systems. Hence, the winner of this prize is expected to create a desalination system powered by renewable wave energy small enough to fit into a standard shipping container, modular to allow for scalability, and cost-competitive. More specifically, the winning wave-powered desalination system must be[19]:

- **Adaptable to varying wave conditions** - the system should be able to survive harsh wave conditions in different areas without major tuning
- **Easily deployed** - the system should be able to be installed and functioning quick and easily, within 48 hours, for disaster relief scenarios
- **Shipped in standard shipping container** - the system must fit within the dimensions of a predefined shipping container (41 x 44 x 35 inches) to allow easy shipping in constrained disaster relief situations
- **Operable without environmental degradation** - any brine discharge from water desalination must be managed to avoid any environmental issues
- **Produce minimum water quality** - the maximum allowable total dissolved solids (TDS) is 1,000 mg/L

To create a system that effectively meets the above goals, the competition has five distinct stages with a total cash prize of $3.3 million USD. Spanning over three years, each of the five stages focus on a different aspect of the design, paving the pathway for innovators from the initial conceptual design stage to a fully functional prototype.

Stage I - CONCEPT

June 13, 2019 - September 11, 2019

In this initial stage, competitors submitted proposals of their solution which described the functionality of their wave energy and desalination technologies, as well as any potential risks and associated risk mitigation strategies. This stage lasted 90 days and 20 winners with innovative designs were chosen, each receiving a $10,000 USD cash prize from a $200,000 USD prize pool to continue the development of their proposed concept.[20]

Stage II - DESIGN

November 14, 2019 - March 13, 2020

The DESIGN stage tasked competitors with the development and analysis of technical plans, consisting of detailed designs of their system, models of system performance, and prototyping plans. Seventeen winners demonstrated the necessary technical capability and were each awarded $47,000 USD from an $800,000 USD prize pool to develop their design.[21]

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18 Energy, DOE Announces Prize Competition for Wave Energy Water Desalination, 2019
19 HeroX, Waves to Water: Wave-powered Desalination Challenge
20 American-Made Challenges, American-Made Waves to Water Prize: CONCEPT Stage
21 American-Made Challenges, American-Made Waves to Water Prize: DESIGN Stage

Stage III - ADAPT
June 8, 2020- November 30, 2020

Building on their plans from the DESIGN stage, competitors were given 180 days to design and develop a system specifically for testing at Jennette's Pier in Nags Head, North Carolina, that was scalable for similar environments. The system development included plans for building the technology, engineering analyses, and detailed design drawings. Ten teams were chosen to build a functional prototype of their design, with a cash prize of $80,000 USD each from a prize pool of $800,000 USD.[22]

Stage IV- CREATE
February 2021 - August 2021

Winners of the ADAPT stage were given 180 days to prove the viability of their system through the physical building and testing of system or subsystem components. Each of the five teams chosen to move onto the DRINK stage was awarded a $100,000 USD prize from a prize pool of $500,000 USD.[23]

Stage V - DRINK
September 2021- April 2022 (anticipated)

In this final stage, winners of the previous stage are given 180 days to build their system, ship it to Jennette's Pier, and test them in the open ocean for 5 days. The systems will be tested for efficiency, system integration, and performance against defined metrics. The grand prize winner of this stage, with the overall best score, will be awarded a cash prize of $500,000 for the continued development of their product. Other competitors of this stage will also receive prizes from a $500,000 cash pool based on individual metrics.[24]

Through participation in the Waves to Water Prize competition, teams are provided a novel, structured pathway to design and develop their systems for a niche market. Traditional wave energy and desalination systems are implemented at large scales, rendering them unusable for disaster relief scenarios where small, cost-effective systems are needed to be easily shipped in standard shipping containers. The prize provides a unique opportunity for innovators to develop wave energy desalination units that are modular, scalable, and affordable.

Waves to Water and Engineering for Change (E4C) Partnership

Over the four years of the competition, teams were supported in various ways to develop their system from initial conceptual design to a fully functional prototype. One of the ways competitors were supported was through a partnership with Engineering for Change (E4C). E4C's mission is to improve the quality of life of underserved communities by providing resources and platforms to accelerate the development of impactful solutions, such as the systems developed through the Waves to Water Prize.[25] E4C's extensive experience in providing engineering support services to entrepreneurs and innovators of hardware solutions participating in prize competitions, such as ASME's ISHOW Innovation Showcase and the Siemens Design Challenge, provided a strong pillar of support for teams. Additionally, E4C combined their large network of experts in various sectors

[22] American-Made Challenges, American-Made Waves to Water Prize: ADAPT Stage
[23] American-Made Challenges, American-Made Waves to Water Prize: CREATE Stage
[24] American-Made Challenges, American-Made Waves to Water Prize: DRINK Stage
[25] Engineering for Change, Who We Are

with their expertise in the humanitarian engineering sector to aid competitors with both developing their technologies and implementing them.

Working with competitors in the CREATE stage of the Waves to Water Prize, E4C assessed the needs of each team and identified experts within their network to support those innovators. Using E4C's hardware innovation benchmarking framework, E4C evaluated each team's design for inclusion in the Solutions Library - a living database of over 1000 products that are affordable and accessible for those in resource-constrained environments. The data for each product in the Solutions Library is normalized across all products to allow for side by side comparison of various technologies.[26] The technologies of each team in the Prize competition were included in the Solutions Library to increase the exposure of wave energy desalination technologies and for easy comparison, highlighting the strengths and weaknesses of each product along with market trends.

Documenting trends in the wave energy and desalination sector allows competitors to understand the market, their direct competitors, and how to best develop their product to be competitive in the current market. This also enables them to choose a marketing and commercialization strategy that best fits their target market. Hence, E4C's partnership was helpful for teams to understand their position in the market and what steps must be taken to ensure ongoing success.

Sector Observations

Based on the state of the wave energy and desalination sector, as well as Engineering for Change's involvement with the Waves to Water Prize, we have observed the need for the following:

- Increased funding opportunities for individuals and groups working on these technologies
- Collaboration with academia, industry, nonprofits, and government entities for a holistic approach in developing these technologies for widespread adoption
- Collaboration with diverse organizations representing end-user needs for wave-powered desalination design
- A robust procurement pathway for products with growth of the innovation ecosystem attracting diverse entrepreneurs via platforms such as prizes (ex. Waves to Water Prize) to facilitate funding and networking

The fulfillment of the above needs will ensure further advancement of the wave energy and desalination sector while reducing challenges in cost, scalability, environmental impact, system output variability and maintenance. Prizes advancing innovation in this sector, such as the Waves to Water Prize, allow for the promotion of these technologies to a wider audience, increasing public adoption and subsequent job creation from implemented systems generating electricity and water. Additionally, increased public interest around renewable energy systems will garner the support of industry partners and academic researchers for innovators, further spurring collaborations between academia, industry and technology innovators. Hence, prizes such as the Waves to Water Prize play an integral role in advancing the wave energy and desalination sector.

[26] Engineering for Change, Solutions Library

E4C was founded by ASME as part of the Society's mission to advance engineering for the benefit of humanity. Engineering for Change (E4C) is powered by the American Society of Mechanical Engineers (ASME).

E4C's mission is to prepare, educate and activate the international engineering workforce to improve the quality of life of underserved communities around the world. We are a Knowledge organization with global community of 1,000,000+ that believes engineering can change the world. Founded in 2009 by ASME, IEEE and EWB-USA.

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