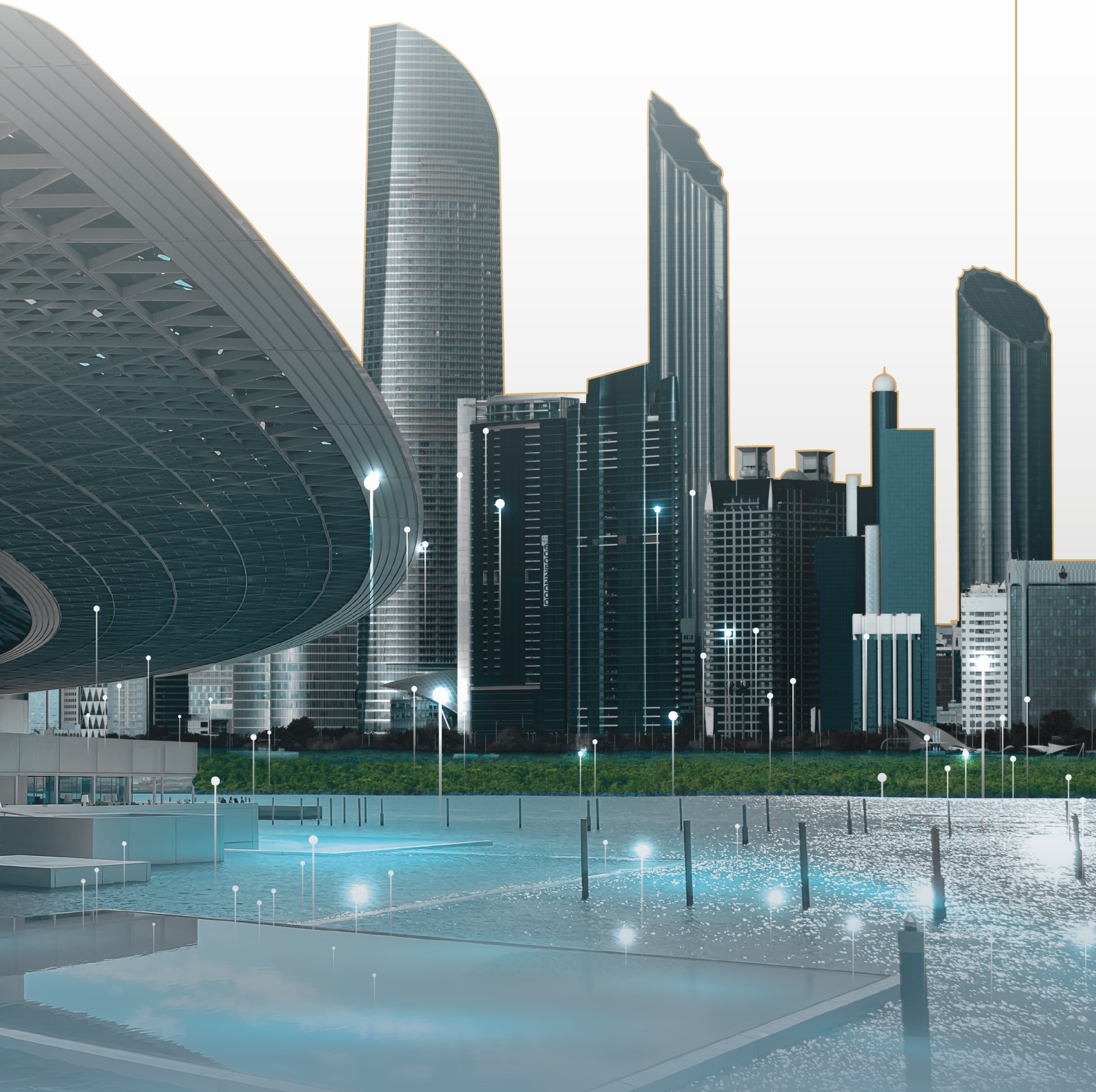




2024 DOE Future Foresight Reports

# The Future Of Enhanced Water Sustainability Through The Graphene Revolution



# Executive Summary

The Abu Dhabi Department of Energy (DOE) is committed to proactively navigating the evolving landscape of the energy sector through a series of Future Foresight Reports. These reports published by DOE are designed to align with DOE's corporate strategy as well as influence it by anticipating future trends, scenarios and implications. By incorporating future foresight practices, DOE is positioning itself to anticipate challenges, leverage emerging technologies, and lead the way in sustainable energy development. The primary purpose of these reports is to systematically analyze potential future scenarios, technological advancements, policy shifts, and market dynamics that could impact the energy sector. By understanding and leveraging this future intelligence, DOE can make informed decisions that drive innovation, efficiency, and sustainability. The report series serves as a strategic tool to guide DOE in achieving its long-term goals, mitigating risks, and capitalizing on new opportunities.

The Abu Dhabi Department of Energy's Series of Future Foresight Reports exemplifies DoE's commitment to strategic planning, anticipating future opportunities and driving innovation. By leveraging foresight practices, DOE are not only preparing for the future but actively shaping it in alignment with our corporate strategy goals. These reports will serve as a cornerstone for decision-making, ensuring that the DOE remains at the forefront of the global energy transition, driving sustainable growth and securing a prosperous energy future for all.

This report titled 'The Future of Enhanced Water Sustainability Through the Graphene Revolution,' explores the future potential of graphene-based technologies in various water-related applications, including desalination & water purification and treatment, and increased efficiencies.

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# Overview

This Future Foresight Trend Report provides a comprehensive analysis of the future potential for graphene in enhancing water sustainability for the UAE. The report identifies the critical challenges of water scarcity, influenced by climate change, population growth, and other drivers of change affecting water sustainability and security in terms of the quantity and quality of water in Abu Dhabi. The study explores the future potential of graphene-based technologies in various water-related applications, including desalination & water purification and treatment, and increased efficiencies.

The document is structured into sections that cover the current state and challenges discovered in the environment scanning conducted for this study, the relevance to the UAE, and Abu Dhabi in particular, with a focus on graphene technologies. It also includes an analysis of the drivers of change, key uncertainties, and the implications of adopting graphene technologies in the water sector according to the defined scenarios.

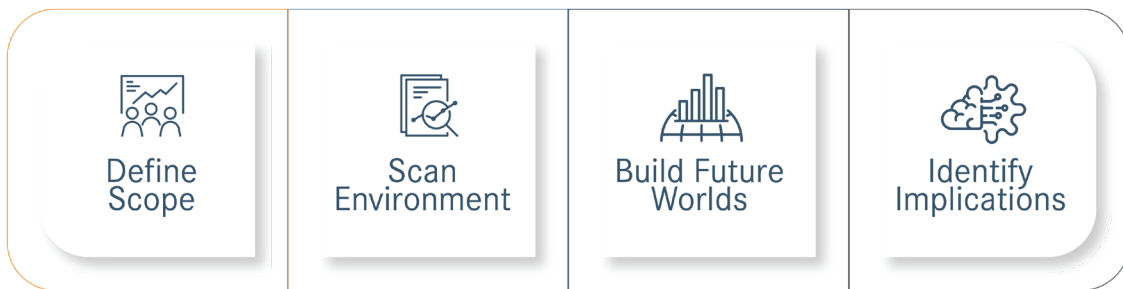
The Defined Scope for this Future Foresight study is “The Future of Enhanced Water Sustainability through the Graphene Revolution”, with emphasis on relevance to the Emirate of Abu Dhabi. The study offers an insightful exploration of the potential of graphene technology in water management. Scenarios are analyzed for their implications, and the future vision for graphene-based future water applications, as a pivotal response to the defined scope. The Future Worlds (scenarios) analysis is focused on the Key Uncertainties of Technological Feasibility and Economic Viability for graphene utilization in water management.

The findings from this report call for greater research & development, innovation, policy and regulations development, and wide-scale partnerships and global cooperation to help harness graphene’s capabilities effectively. The report underscores the importance of strategic foresight, planning, and collaborative efforts to mitigate the region’s water scarcity and ensure long-term sustainability and water supply security by 2036.

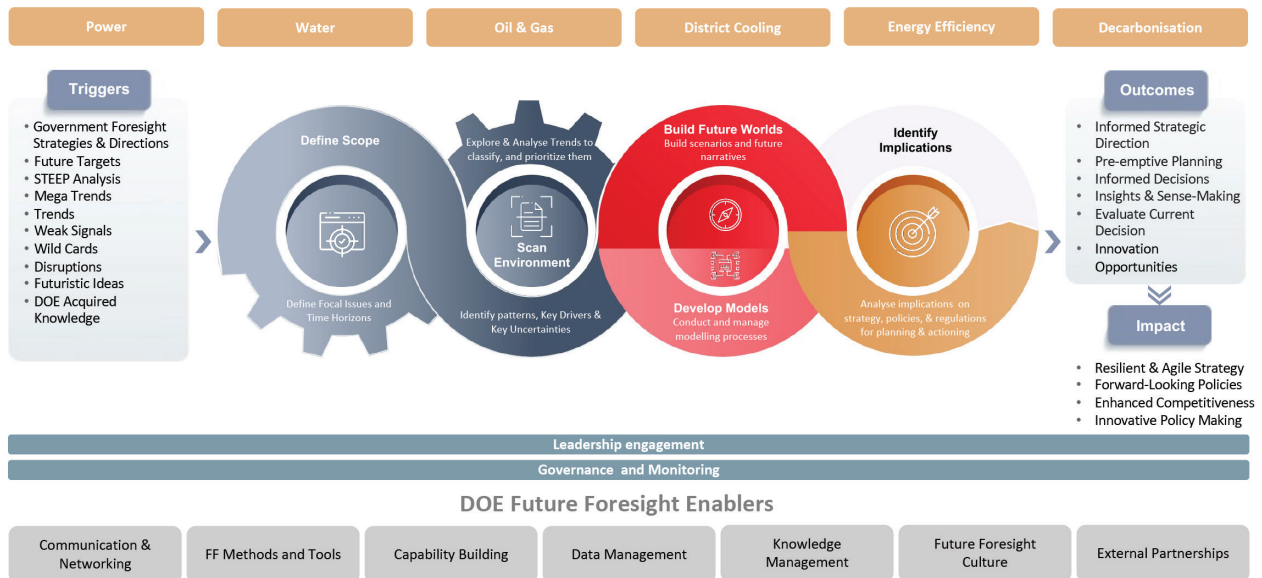
# Approach

A Future Foresight Framework aims to address UAE leadership and government’s farsighted visions and aspirations for the energy transition and water sustainability and security. The model provides for determining future perspectives and directions for enhancing water sustainability and identifying the implications and related possible actions.

**The core operating model of the Future Foresight Framework is comprised of four key phases, which are:**



**The DOE Future Foresight Framework is illustrated below:**



The framework is initiated by a set of triggers, from external and internal factors, such as government directions, strategies, and targets, as well as drivers of change (trends, megatrends, weak signals, and wild cards), knowledge from internal business intelligence and ideas, and disruptions affecting the sustainability of Water in the Abu Dhabi Emirate.

Along with the implementation of the framework model, DOE develops and acquires knowledge about the future that helps to achieve impact through the development of more resilient and agile strategies in plausible futures, and developing innovative and forward-looking energy policies and regulatory frameworks that support the Energy sector in the energy generation and usage optimization, while enhancing competitiveness.

The DOE Future Foresight model is supported by seven enablers that act as catalysts for the effective implementation, which are considered an integral and important part of the framework execution. Key findings along the model's implementation are aligned with the DOE leadership to ensure the outcomes of the model contribute to improved decision-making, strategic planning, providing insights, and recognizing opportunities and threats. The framework, when implemented effectively, aims to lead to a positive impact for DOE in innovative policy-making, developing forward-looking policies and regulations, resilient and agile strategies, and improving competitiveness.

# Current State

Water scarcity is one of the most formidable challenges facing the world in the future. As climate change takes effect and temperature rises, natural water sources will become even more scarce. The challenges of water scarcity are exacerbated by expedited urbanization, population growth, and economic development placing greater pressure on water systems fueling water scarcity, according to the Economist Intelligence Unit (2021). This in addition to human consumption habits, water extraction rates, and other factors contributed to less potable water, more widespread salinity, and increased contamination, as well as desertification and drought conditions. Water is the most critical resource for human survival and the well-being of communities. It is essential to manage this finite resource sustainably due to its significant implications on people's lives, the environment, the economy, and the livelihood of future generations. It becomes critical to manage water sustainably and ensure water security in the face of the growing challenges of Water Scarcity.

As part of the Water-Energy-Food Nexus, water has a strong affinity and interdependencies with energy and food. Generating more water in principle requires more energy, and potentially more emissions and climate impact. Likewise, energy production utilizes water resources. Without water sustainability, it will be very challenging to ensure food security for the population.

According to the UN, current and future drivers of water scarcity such as population growth and inefficient water management can further exuberate the challenges and result in a scenario in which by 2025 over 1.8 billion people are living in countries or regions with absolute water scarcity, with less than 500 m<sup>3</sup> per person per year (Measured by the Falkenmark Water Stress Indicator).

## Countries Most Likely To Suffer Water Stress In 2040

The World Resource Institute (WRI), a global organisation that seeks to create conditions of equity and prosperity through the sustainable management of natural resources, used a set of climate models and socio-economic scenarios to rate the water stress - when the demand for water is higher than the amount available - of 167 countries by 2040

**33** countries with extremely high water stress (ranges between 4.00 and 5.00)

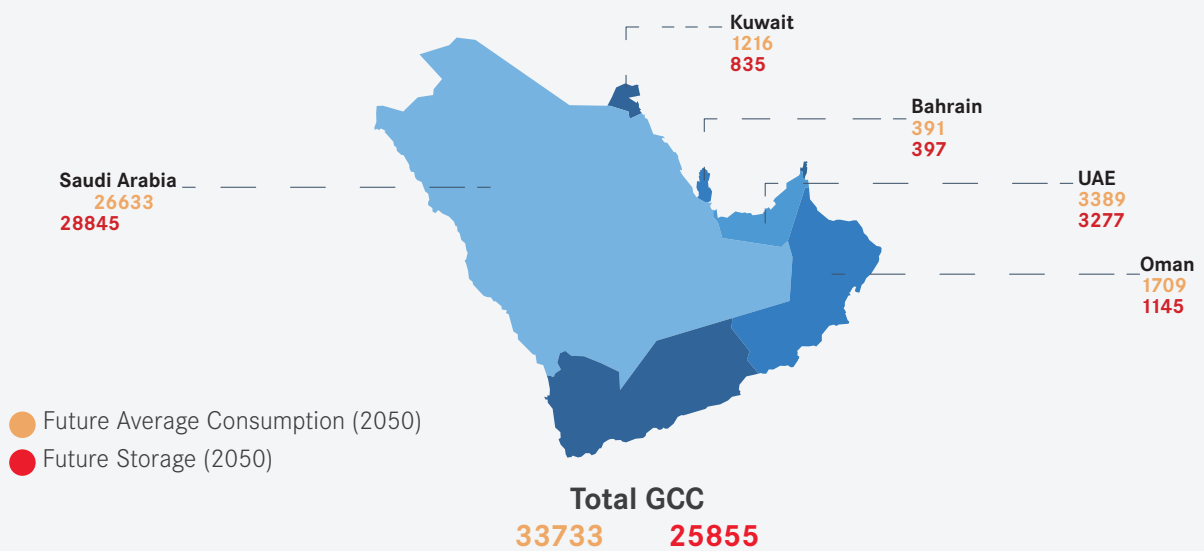
**14** countries of the 33 are located in the Middle East (the region faces exceptional challenges)

01	Bahrian	5.00	12	Kyrgyzstan	4.93	23	Pakistan	4.48
02	Kuwait	5.00	13	Iran	4.91	24	Chile	4.45
03	Qatar	5.00	14	Jordan	4.86	25	Syria	4.44
04	San Marino	5.00	15	Libya	4.77	26	Turkmenistan	4.30
05	Singapore	5.00	16	Yemen	4.74	27	Turkey	4.27
06	United Arab Emirates	5.00	17	Macedonia	4.70	28	Greece	4.23
07	Palestine	5.00	18	Azerbaijan	4.69	29	Uzbekstan	4.19
08	Israel	5.00	19	Morocco	4.68	30	Algeria	4.17
09	Saudi Arabia	4.99	20	Kazakhstan	4.66	31	Afganistan	4.12
10	Oman	4.97	21	Iraq	4.66	32	Spain	4.07
11	Lebanon	4.97	22	Armenia	4.60	33	Tunisia	4.06

**Figure 1** Water Stress in 2040. Source: WRI

By the year 2040, according to the World Institute for Water Resources (WRI), the majority of countries that are expected to suffer from a sharp water crisis are in the Middle East region, including the UAE. This makes the Middle East region the least water-sustainable and secure region in the world.

### GCC'S Potential Freshwater Shortage By 2050 (Million Cubic Meters/year)



**Figure2** GCC Potential Freshwater Shortages. Source: Orient Planet Research

The GCC's water needs are expected to reach 33,733 Million m<sup>3</sup> per year by 2050, but the region's projected future storage is only 25,855 Million m<sup>3</sup> per year, according to a report by Orient Planet Research (2020). The same report established that the region needed to boost its water by 77% to meet the requirements of its population growth within the next 30 years.

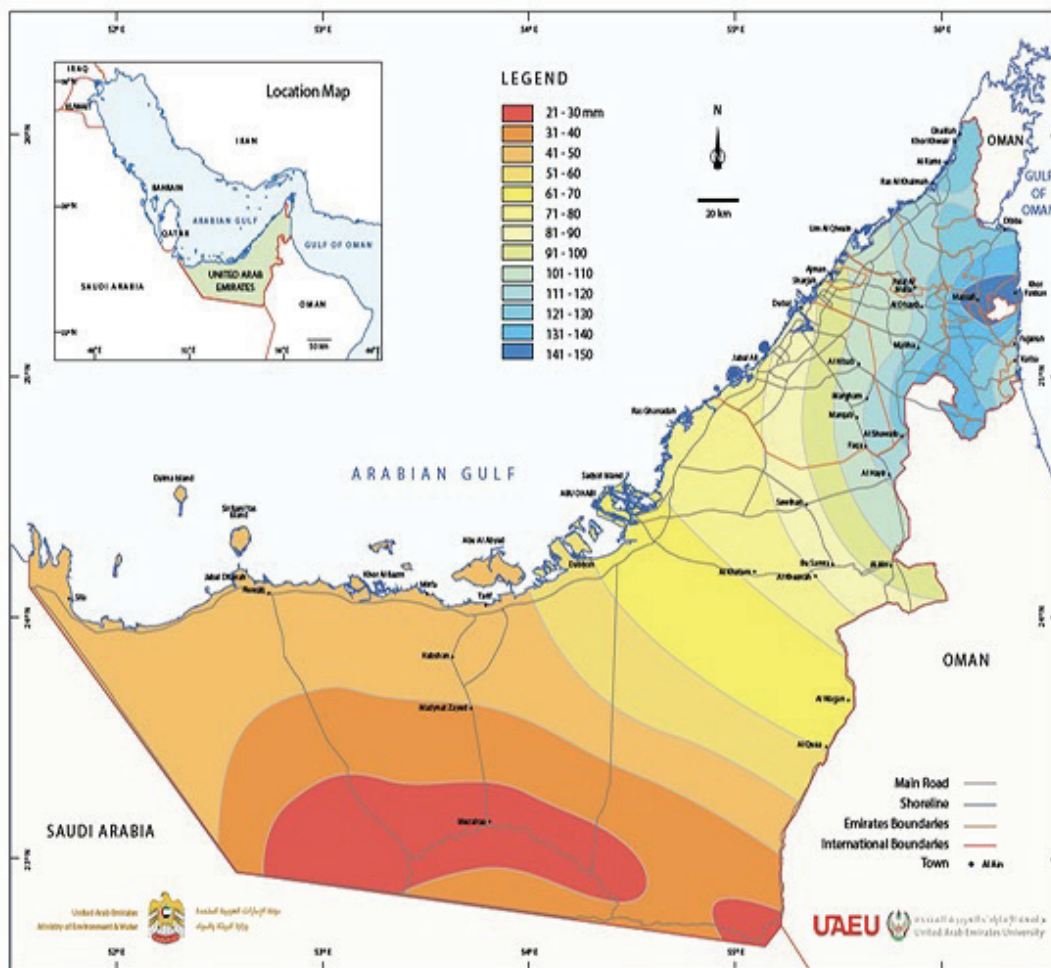


Figure3 Source: UAE University National Water and Energy Center

The UAE is among the highest in water consumption per capita in the world, at approximately 500 liters per day which is 50 percent above the global average. This is largely affected by the UAE’s arid desert landscape and humid climate. The water table in the UAE has dropped by around one meter per year over the last 30 years. Some researchers predict that the UAE will run out of natural freshwater resources within 50 years if the trends continue to take effect.

This is while the UAE and Abu Dhabi Emirate, in particular, have limited rainfall. The UAE has been experimenting with methods such as cloud seeding to promote increased rainfall.

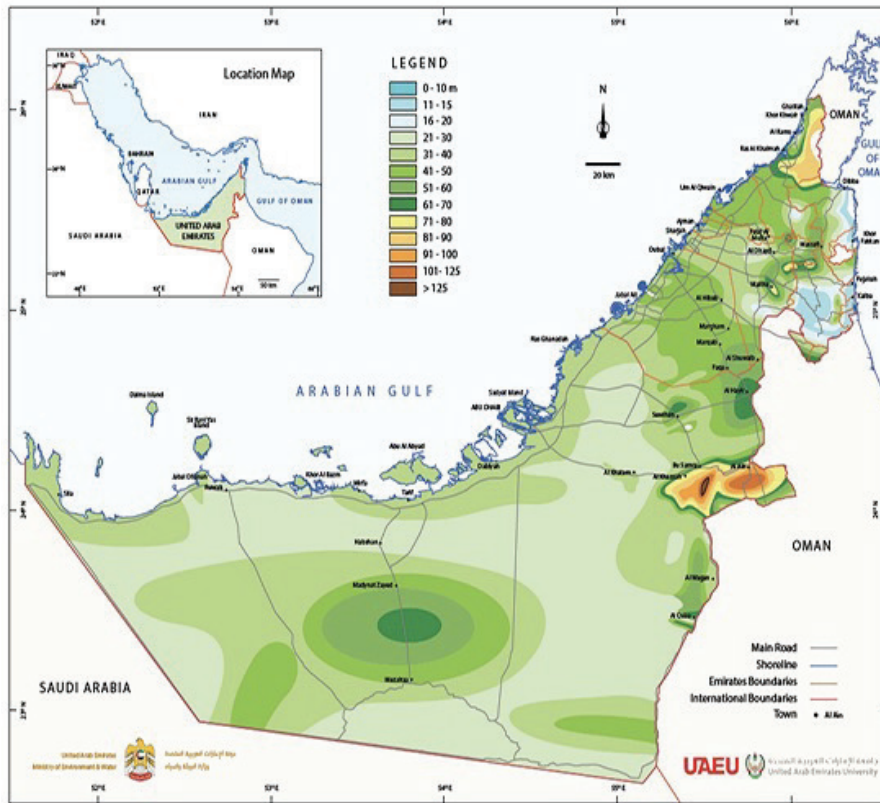


Figure4 Source: UAE University National Water and Energy Center

Water tables depths below the ground surface recorded from monitoring wells. Increase in depths observed in Al Ain, Al Dhayd, and Al Hamaranyah due to over-abstraction depleting saturated thickness.

Our Water Security strategy came out of necessity as we have limited rainfall in the UAE, and we had to look at our resources to ensure access to clean, adequate and affordable water for years to come. For us living in this arid environment, we have to work harder.

His Excellency  
**Suhail Al Mazrouei**  
 Minister of Energy and Infrastructure

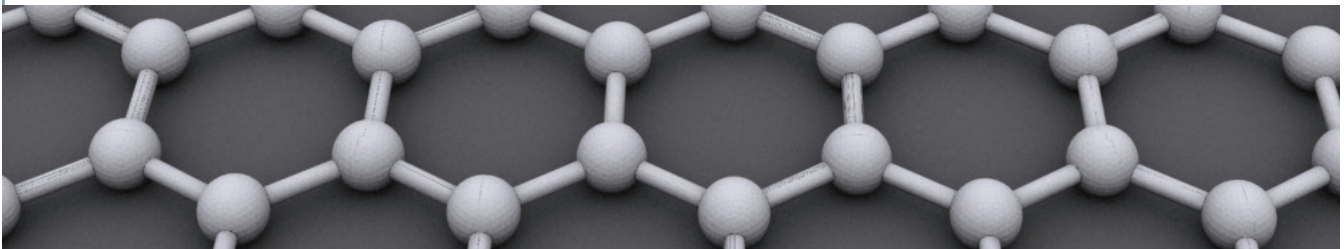


The UAE Government understands the challenges around water scarcity and has launched several strategies, programs, and initiatives in the UAE, and further on the global arena, with leading efforts to promote international cooperation, increasing investments, accelerating the pace of innovation to address global water scarcity and security, and fostering collaboration between the government, private sector, universities, researchers, entrepreneurs, philanthropists, and international NGOs.

Abu Dhabi, and the UAE in general, rely heavily on Desalination Plants to support their long-term strategies for water sustainability and security and have become a pioneer, along with Saudi Arabia, in using Desalination processes, utilizing leading technologies and innovations while optimizing efficiency, energy consumption, and emissions. Desalination is the primary source of all potable water in the UAE. Thermal-based desalination (MSF and MED) has been historically the predominant form of desalination in the emirate. In addition, improved membrane technology, reduced costs, and resulted in a push toward power and water decoupling, Reverse Osmosis (RO) in Desalination are on the rise in Abu Dhabi, along with other examples in the wider region.

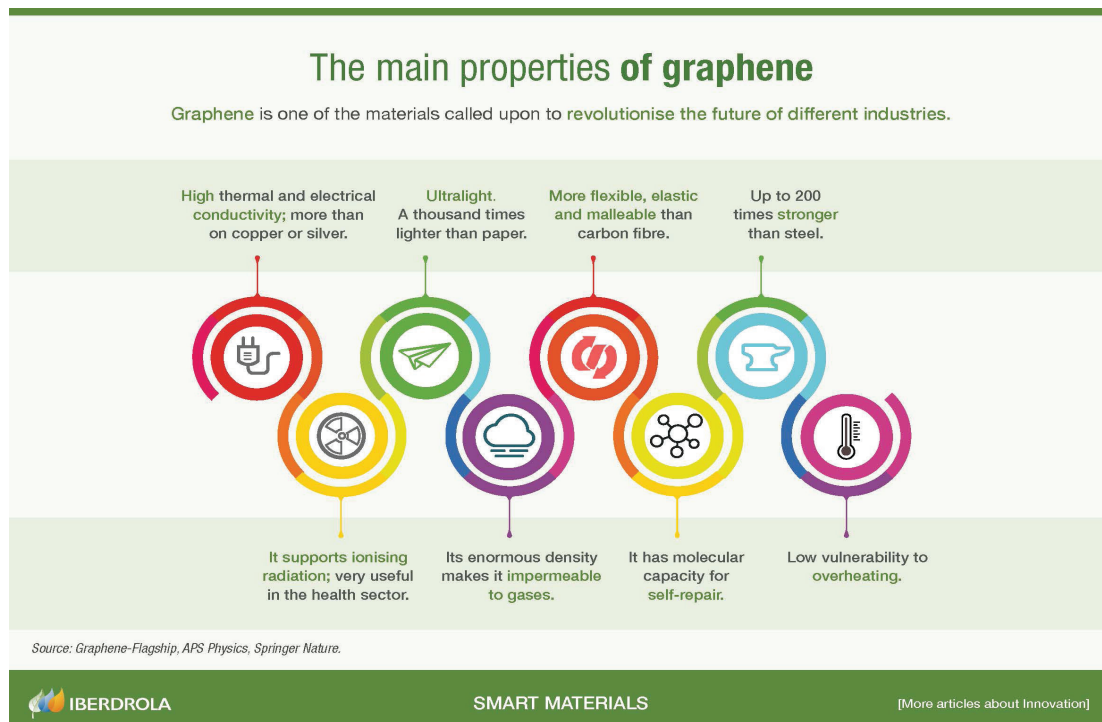
Overall, a business-as-usual scenario in the face of the highlighted formidable challenges could have immensely negative future implications for the world, such as loss of life, food insecurity, economic underdevelopment, humanitarian crises, involuntary migration, and geopolitical instability or conflicts over water. Adequate approaches are required to ensure water sustainability and security and to address the water-related challenges to future-proof from unacceptable scenarios and cascading effects.

### Graphene Revolution



Graphene, a single-atom molecule carbon nanosheets and graphene nanomaterials are demonstrating enormous potential in water management technologies due to their extraordinary properties offering higher efficiency and potentially lower energy requirements. It is often referred to as the wonder material, miracle material, or simply the “Graphene Revolution”.

Graphene has several uses on its own, but it also has great potential in combination with other substances, which further widens its future significance. Graphene is expected to yield greater efficient and innovative solutions, including in electronics, construction, automotive, aviation, food, and medical industries, water production, and water treatment processes, amongst many other potential applications. Graphene was discovered in 2004 at Manchester University, with research on graphene awarded the Nobel Prize in Physics in 2010. Research & Development on graphene have been growing since then, and it is believed that graphene can revolutionize the performance of current materials, components, and machines, and forms the groundwork for many innovations. More than 50,000 graphene-related patents were filed worldwide only between 2004 and 2017.



**Figure4 Source:** IBERDROLA, Graphene Flagship

The unique properties of graphene, from its high thermal and electrical conductivity, mechanical strength, tunable optical properties, and large surface area present many applications for graphene in water management applications, including membrane technologies, water desalination, adsorption, atmospheric water harvesting, and environmental monitoring, and other applications.

Desalination and other water treatment and purification methods are in the process of transformation through the Graphene Revolution. Graphene can provide significant performance enhancements from traditional Desalination techniques, such as Reverse Osmosis and thermal-based Desalination process, that continue to face challenges of high energy consumption, costs, and the need for extensive pretreatment of water. A multi-layer membrane made from Graphene Oxide can filter out the sodium chloride in seawater more rapidly and cleanly than existing techniques, in addition, it helps with the remediation of chemicals and water contamination like heavy metals, synthetic dyes, and microorganisms in wastewater, and compounds such as pesticides.

Researchers at Khalifa University Research & Innovation Center for Graphene and 2D Materials (RIC2D), established in 2022 in Abu Dhabi based on the directions of H.H. Mohammad Bin Zayed, have been working on applications of graphene in water management including graphene-enhanced membrane that could help make the Desalination process more efficient and cheaper in the production of potable water. RIC2D works as well on other graphene applications, however, graphene in water has been defined by UAE leadership as a top priority. RIC2D is collaborating with the University of Manchester to develop Graphene membranes for testing in a local Desalination Plant.

This report further explores the enormous potential to leverage the Graphene Revolution for water sustainability by enhancing both water quantity and quality. More information on the unique qualities and properties of graphene is provided in the Scan Environment section below.

# Topic Relevance

Government and organizational strategies rely on natural resources that are ever-changing. Changes in the availability of water resources affect operations and continuity, create challenges in securing water with the needed quality or quantity, and can affect the efficiency of production, with a potential for competition for water resources among countries, communities, industries, and agriculture.

Water-related risks and uncertainties apply to all sectors of the economy, according to the EPA- USA, at the same time, every sector depends on water, directly or indirectly. Water is essential in manufacturing and for virtually all products, making almost all entities affected by water scarcity risks and uncertainties. Water scarcity could cost some regions and governments up to 6% of their GDP over the next 30 years according to the World Bank. It could also drive migration, increase food prices, and is likely to increase the risk of water conflicts.

Governments can respond to the current and future water challenges in many ways. In arid regions, such as in the Emirate of Abu Dhabi, the government will need to develop further far-reaching strategies, policies, and regulations, and explore different scenarios and their implications to prepare for and mitigate these uncertainties and address them in different ways, including promoting innovation in water-related technologies, encouraging efficient use of water, allocating water to high value uses, facilitating more efficient production practices, or preventing inefficient water usage. Accordingly addressing the risks of water scarcity and further boost its water security and sustainability.

In 2023 the UAE hosted COP28 which bolstered its leading role in promoting international cooperation for protecting the environment, its natural resources, water security, and climate impact into the future. The UAE has established a partnership with Brazil to assist Parties to incorporate water and food into national climate strategies. Historically water scarcity was not on the COP agenda before COP28, but concrete discussions started in COP27. The COP28 cover decision, with resulting unprecedented agreements between global parties driven by UAE values, leadership, and supporting policies, also urged parties to “accelerate swift action at scale and all levels, from local to global” to significantly reduce climate-related water scarcity, enhance resilience to water-related hazards, and realize climate-resilient water supply.

DOE, as the regulating arm of the Abu Dhabi Government for Energy and Water, has made significant efforts since its formation only a few years ago to ensure water sustainability and efficiency of water utilization with various regulations and policies, such as maximizing the use of the valuable recycled water to support national efforts in preserving water resources. For example, Abu Dhabi used nearly 195 million m<sup>3</sup> of recycled water in 2021 for irrigation, which helps in water sustainability and the optimization of all water sources in the emirate. There are also several projects underway in Abu Dhabi to enhance the utilization of rainwater and groundwater for agricultural activities and other uses.

DOE is continuing to address water challenges in its mandate through strategies, policies, and regulations to further enhance Abu Dhabi's water and energy sustainability. As such, DOE is always on the lookout for future trends, technologies, and methods to further boost future readiness and promote innovations to continuously enhance water sustainability into the future. This includes new approaches for filtration and extracting moisture from the air to alleviate the looming water scarcity crisis in arid regions.

Abu Dhabi boosts four main Desalination Plants using RO technologies, providing around 24 percent of the emirate's total water production capacity. Production from Reverse Osmosis is expected to rise to nearly 43 percent by 2025. The RO Desalination Plant Al Taweelah is set to produce nearly 909,000 m<sup>3</sup> of desalinated water per day when fully operational, making it the largest Reverse Osmosis Water Desalination Plant in the world, with plans for two additional stations: Al Mirfa M2 and Shuweihat S4.

Graphene demonstrates great potential in Desalination Plants and Desalination processes. With its many unique properties, from high permeability to high selectivity, Graphene can reduce energy usage and operating costs of desalination, extending a membrane's life by preventing fouling (When bacteria accumulate on the filter and degrade its quality).

DoE has launched the Abu Dhabi Demand Side Management and Energy Rationalization Strategy 2030, which aims to reduce electricity consumption by 22% and water consumption by 32% by 2030. There has been a growing focus in the past few years on increasing efficiency and cost rationalization, the realization of the importance of demand side management, considering large subsidies and static rates for most customers. DOE, at the time of this report, has 10 ongoing projects to boost demand-side efficiency.

The Water Management in District Cooling Plant's policy was introduced by DOE in 2023 to promote district cooling systems, decrease energy consumption, and regulate the mechanisms for identifying potential sources of water that can be used by District Cooling Plants, such as recycled water, desalinated water, and seawater.

Although graphene is a very promising technology, there are still many challenges that need to be resolved before the Graphene Revolution moves from laboratories to significant industrial uses. Some of the key challenges are the high costs of its production and the mass production capabilities without compromising on the material quality or any of its desired qualities, supply chain challenges, heating limitations of 30-70 degrees, as well as awareness and acceptance by the water industry. Another challenge is the high levels of cost-efficiencies already achieved in the UAE for desalination, such as Dubai reaching 36 cents per cubic meter cost for desalination, the lowest in the world, making it very hard to match.

In 2020, researchers at MIT found a new way to produce large amounts of graphene while maintaining its electrical conductivity and properties. The new method, which involves placing graphene sheets in a roll-to-roll process, could be key to unlocking graphene's various potentials. One example amongst many, where it could make it possible to place transparent solar cells on mobile devices. The prevailing production method involves removing a single layer of Graphene from Graphite. Graphene can also be produced from oil and gas industry waste, or petroleum products like car tires. Another production method uses plasma chemistry to extract carbon from gases such as methane. Producing Graphene from green gases by-products of the oil and gas industry can contribute to Net Zero by 2050 in different ways, such as using graphene to store hydrogen in stronger pressure vessels, or the extraction of hydrogen from these gases to be used as a sustainable fuel source.

With its apparent enormous potential applications, Graphene R&D has taken many different directions. One key challenge is that research has been limited in key applications for water sustainability, with only a few research papers describing the use of graphene in water treatment by adsorption, filtration, and photodegradation methods. Additionally, compared to other traditional adsorbents and materials, graphene is considered more environmentally friendly. It can be synthesized from renewable sources, and its use in purification and treatment aligns with the growing emphasis on sustainable technologies. Graphene, with its high surface area, mechanical strength, and water intercalation efficiency, has also been recognized as a potential candidate in atmospheric water and fog harvesting. Its high photo-to-thermal conversion efficiency, combined with hydrophobicity enables the facile release of the collected water.

Further analysis and research are provided in the following sections, with a focus on how graphene can enhance water sustainability in the future due to its identified potential impact on UAE water sustainability.

# Report Analysis

## Define Scope:

In the Abu Dhabi Emirate, water is seen as a major priority in ensuring the emirate's sustainability efforts, providing reliable water services, enhancing water quality, and securing water supply for the future. Also, it was evident from the previous analysis that enhancing water sustainability is critical to addressing water scarcity and ensuring water security and sustainability.

In identifying the Focal Issue and Time Horizon for this trend report, DOE aims to ensure alignment with the government's future direction and long-term strategies. Accordingly, the identified Time Horizon is impacted by the UAE Water Security Strategy 2036 and the Integrated Water Resources Management Plan 2030 in the medium and long term horizon, therefore indicating a target Time Horizon of 2036.

With the enormous potential of Graphene in improving water management, and enhancing water sustainability, in addition to other applications and benefits such as improved energy efficiency and storage, the focal issue that has been identified as "The Future of Enhanced Water Sustainability through the Graphene Revolution".

Accordingly, the title of this report per the Defined Scope is: "The Future of Enhanced Water Sustainability through the Graphene Revolution - 2036".

“The Integrated Water Resources Management Plan represents the common vision between the various sectors to adopt the approach of integration and cooperation in managing and developing water resources sustainably. It considers many important issues such as economic efficiency, social development, and environmental sustainability.

His Excellency

**Awaidha Murshed Ali Al Marar**

Chairman of the Department of Energy



## Scan Environment:

In scanning the environment, a multi-pronged approach is followed for the defined scope, where more targeted research was conducted on the core topic of graphene technology to better understand its capabilities and potential benefits, identifying signals, trends, drivers of change, and uncertainties. Additionally, a STEEP analysis is conducted and summarized below for the larger topic of water sustainability that graphene can contribute to.

Graphene consists of a single layer of carbon atoms arranged in a two-dimensional hexagonal lattice nanostructure, with several unique properties including high electrical and thermal conductivity. Graphene is up to 200 times stronger than steel, a thousand times thinner than human hair, and flexible to be bent without breaking. Such exceptional properties provide promise for a wide range of applications across different industries and applications.

Other variations of Graphene have emerged for this new technology, such as Graphene Oxide, and Reduced Graphene Oxide. Other variations are still emerging, like Graphyne, a material synthesized by scientists in 2022, which is similar to Graphene with a two-dimensional structure of carbon. However, Graphyne contains double and triple bonds, and its atoms are not necessarily in a hexagonal arrangement, which allows very different types of supermaterial capabilities. While graphene allows super-fast two-way conduction of electrons, Graphyne allows it in only one direction, which for example can help design faster transistors and other electronic components that process super-fast one-way currents.

Membrane Distillation (MD) has garnered significant global interest as a thermally operated membrane technique, particularly for its ability to process high-salinity solutions such as seawater and various industrial wastewaters. Despite its potential, the widespread implementation of MD on a large scale remains limited. The development of superior MD membranes is crucial, with the membranes possessing enhanced qualities, including hydrophobicity, elevated permeation rates, minimal fouling susceptibility, robust mechanical integrity, reduced thermal conductivity, and a high Liquid Entry Pressure (LEP). Graphene's role can be vital for optimizing the effectiveness and applicability of MD technology.

Graphene has been recognized as a key material for sensors, due to its high surface area, excellent conductivity, and sensitivity to the environment. The development of Graphene-based sensors is showing a lot of promise and is on a fast track to be developed and commercialized for practical applications in the near term. Graphene-based sensors have great potential to be used to detect concentrations of contaminants, monitor water quality parameters, and provide real-time data on factors such as PH, heavy metals, or specific pollutants in water networks.

Water treatment and purification also stand to benefit greatly from the varied applications of graphene in water-related industries, most importantly from its filtration capacity and properties. Graphene enhances the performance of filtration by allowing water to flow through the perforated membrane with less friction, resulting in increased speed, and thereby less energy consumption than traditional membranes with graphene's high water permeability, at least twice as much as the traditional polymer filters.

Graphene can bring significant improvements in operational efficiency, allowing Desalination plants to run more efficiently for longer times, with less maintenance and additional labor costs for the cleaning of the filters due to its self-cleaning properties, and avoiding damage from fluoride cleaning of filters that wear the polymer filters, while Graphene Oxide filters are chemically resistant to fluorides. This also leads to greater durability, with less need for the replacement of the polymer membranes. Graphene membranes can also improve salt removal efficiency for removing sodium and chloride ions from saline water with their high-salt rejection rates.

Graphene has a long-term potential to reduce the need for large capital investment and large plant construction, which can also lead to faster water production time. The integration of effective graphene solutions has the potential to promote decentralized applications and solutions, with the capability to serve smaller or targeted communities, and helps in reducing the complexities of Desalination plant operations to produce potable water.

## PESTEL Analysis

To understand the DOE external environment in water sustainability, the following is a summary of the STEEP (Social, Technological, Economic, Environmental, Political) analysis related to enhancing water sustainability in water management, with its related technologies:

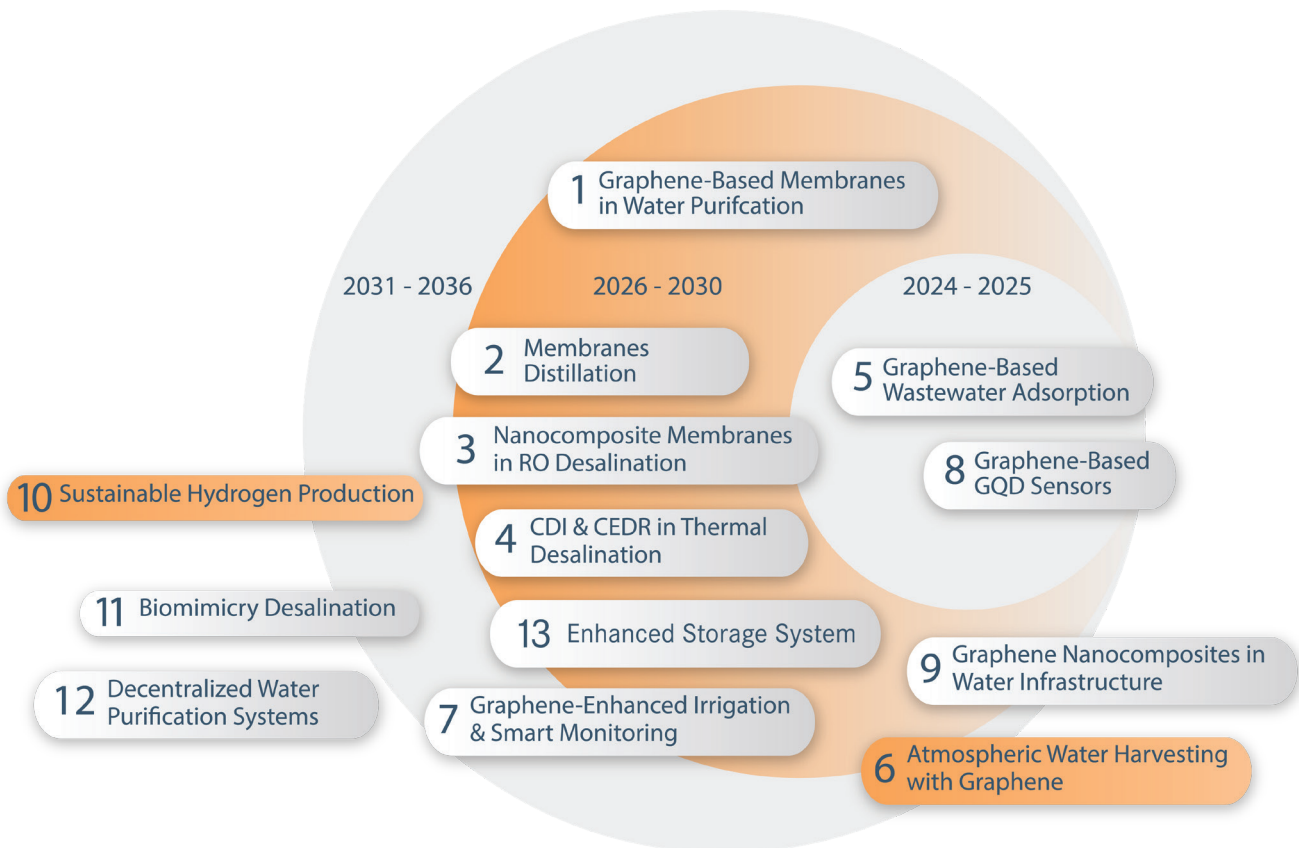
Table 1	STEEP Analysis
<b>Social</b>	<ul style="list-style-type: none"> <li>▶ Water-stressed Communities: The Middle East, GCC, Rural and regional communities, are impacted by water scarcity, and changes in water sustainability as water-stressed countries.</li> <li>▶ Public Health: Improved water quality and quantity has a positive impact on public health and well-being with better access to clean Water.</li> <li>▶ Public Awareness and Cultural aspects: Society Consumption Habits, and Regulations are important to be addressed as they affect consumption patterns, utilization, and water sustainability.</li> <li>▶ Population Growth: Population growth and Human demographics changes, Urbanization, Mobility, Migration, Refugees, and Animal demographics are all affected by or affect the sustainability of water.</li> </ul>
<b>Economic</b>	<ul style="list-style-type: none"> <li>▶ Globalization and Global Economic growth, recession, and volatilities impact the utilization of water resources, particularly in industries.</li> <li>▶ Circular economy: Water sustainability and circular water are directly linked with the circular economy and sustainable industry practices.</li> <li>▶ Agricultural Economics: As the highest usage of water locally, the link between water and food production can have an impact from unsustainable agricultural and irrigation practices and Reduced potable water resources, which can impact unregulated water usage and the consumption patterns of water-intensive foods.</li> <li>▶ Financing in the Water Sector: Financing mechanisms, and underfinancing in the water sector, greatly impacts the capabilities to implement graphene to gain from its many potential benefits.</li> <li>▶ Human capital: Availability of skills and knowledge in addition to the Intellectual Capital can impact capabilities to implement graphene.</li> <li>▶ Industrial Factors: Industrial demand for water, Infrastructure, Industrial production, and Products impact water sustainability through production capacity as well as from consumption of production and products that rely on water.</li> </ul>

**Table 1** **STEEP Analysis**

<b>Environmental</b>	<ul style="list-style-type: none"> <li>▶ <b>Water scarcity:</b> The availability and sustainability of water affect water security, as well as renewable water resources, drought conditions, Surface water, Groundwater, and water storage levels.</li> <li>▶ <b>Water quality:</b> Graphene Nanomaterials and filtration affect potable water, and the quality of water, which also includes salinization levels. <b>Waste Water:</b> The conditions of brackish water and other water types for water treatment, emerging contaminants, biotoxins, parasites, microplastics, and other contaminants are directly impacted by graphene filtration capabilities to treat contaminants.</li> <li>▶ <b>Climate Change:</b> Global warming, Decarbonization, Chemical and Biological cycles, Climate variations (precipitation, temperature, humidity, wind), and Carbon emissions are linked with the sustainability of water requiring Adaptation and mitigation strategies, especially impacting Vulnerable eco-systems, Natural disasters, Ecological disasters, and other elements of Climate Change</li> <li>▶ <b>Renewable Energy:</b> Eco-friendly energy sources contribute to environmental sustainability with the use of renewable energy sources as water production can be energy intensive.</li> </ul>
<b>Technological</b>	<ul style="list-style-type: none"> <li>▶ <b>Graphene Technologies:</b> The technology development and graphene discoveries lead to multi-faceted applications of graphene in different water industries and scope of applications.</li> <li>▶ <b>Emerging Digital Technologies:</b> The emergence of digital technologies, Data Science, the increased role of AI, and the integration of graphene in sensors, for example in IoT for Smart Water and Irrigation Systems, coupled with technology integration and convergence, can lead to a new range of impactful industry solutions.</li> <li>▶ <b>Innovation:</b> R&amp;D efforts in Graphene can lead to breakthrough technologies, and result in an increasing number of IP and Patents.</li> <li>▶ <b>Experimentation:</b> Proving the feasibility of graphene in industrial applications through piloting has a significant impact on graphene utilization for enhancing water sustainability.</li> <li>▶ <b>Advanced Science:</b> Biomimicry, Nanotechnology, Nanomaterials, Advanced production systems, etc.</li> </ul>
<b>Political</b>	<ul style="list-style-type: none"> <li>▶ <b>Geopolitics:</b> As a strategic resource, water sustainability can be impacted by political stability and political conflicts, and the implications of regional restrictions and sanctions that can also affect access to intellectual property and patents of graphene technologies.</li> <li>▶ <b>Cross-boundaries water disputes:</b> With the increased scarcity of water resources, evidence of several water-related conflicts can impact water sustainability.</li> <li>▶ <b>Policies &amp; Regulations:</b> Policies on fossil fuels, biofuels, environment, and health can impact the level of water sustainability, in addition to water policies and regulations. At the same time, changes in subsidies and tax policies can also impact the level of water sustainability, for example, from increased taxes, or water rates from the reduction of subsidies.</li> </ul>

## The Future Radar

The Future Radar is used to identify and track emerging trends, technologies, drivers, and regulatory changes that are likely to shape the future of enhanced water sustainability from graphene-based technologies. Through a systematic approach, individuals and organizations can gain a better understanding and anticipation of future trends and developments related to Graphene. It allows for insights into how the landscape of Graphene is likely to evolve.



**Figure 5** Future Radar with long-term (2031-2036), medium-term (2026-2031), & short-term (2024-2025) periods.

### Trends

Manifestation of a direction of change, that usually represent a gradual change, generally long-term, in the factors that will define the future of an organization, business sector or country

### Wildcards

Discontinuities on the usual course of things. They are sudden events with low probability to happen, and high impact on the Focal issue.

\* Note: Trends time horizons are approximate and based on estimates from current research progress and anticipated challenges in development and commercialization. Ascertaining more accurate Time Horizons is dependent on many factors, and varied according to sources, and interpretation from region to region. Trends time horizon is provided as indicative estimates and may vary greatly over time with R&D progress.

The following are the key trends identified in the environment scanning for the defined scope. Since the core topic is emerging technology, mostly in R&D and laboratory stages, the trends revolve around Graphene-technology trends for enhancing water sustainability. Non-graphene technology-related trends and key factors are addressed in the following sections and the Drivers of Change analysis.

Table 2		Trends analysis	
01	<b>Graphene-Based Membranes for Water Purification</b>	<b>Trends</b>	<ul style="list-style-type: none"> <li>Graphene-based membranes are providing a key technology that will help enable ultrafast water purification and removal of contaminants such as heavy metals and pollutants from water, and cater to the advancement of several new desalination methods. There are three key Graphene-based water desalination membranes categories: Nanoporous graphene (NPG), GO-based frameworks (GOF), and GO-doped polymer membranes. Laboratory research indicates promising advancements, with commercialization prospects as scalability, cost-effectiveness, and other key challenges are addressed.</li> </ul>
02	<b>Efficient Membranes Distillation</b>	<b>Trends</b>	<ul style="list-style-type: none"> <li>Membrane Distillation (MD) is demonstrating effective desalination of high concentrations of saline water. Graphene-based membranes provide superior permeability and selectivity for the removable of salts and impurities from water, providing for energy-efficient seawater desalination in Desalination Plants. MD can provide a cost-effective process based on the vapor pressure gradient induced by the temperature gradient. Graphene can be used in MD processes in Abu Dhabi, such as for recreational farms and improving TDS levels. However, suitable low-cost hydrophobic membranes are a major obstacle to the commercialization of the MD process for separation applications in water desalination.</li> </ul>
03	<b>Nanocomposite Membranes in RO Desalination</b>	<b>Trends</b>	<ul style="list-style-type: none"> <li>Graphene Oxide is demonstrating uses in nanofiltration, ultrafiltration, and more recently Reverse Osmosis (RO). The synthesis of nanocomposite graphene caters to the host polymeric membrane to withstand twice or much higher operating pressure than unmodified membranes. This provides for graphene-based membrane applications even in ultra high-pressure RO (100-120 bar), contributing to higher recovery of product water from high salinity brines, which has been a major limitation for conventional RO Desalination technologies, with the potential to enhance energy utilization and Decarbonization.</li> </ul>
04	<b>CDI &amp; CEDR in Thermal Desalination</b>	<b>Trends</b>	<ul style="list-style-type: none"> <li>Graphene demonstrates the potential to be used in Capacitive Deionization (CDI) and Capacitive Electrodialysis Reversal (CEDR) for the absorption of ions on the graphene electrodes, which are cleaned easily by electrode polarity reversal, resulting in a very small volume of concentrated brine. These new technologies are not dependent on applied pressure. This can result in a third of the energy input requirements in comparison to RO. While CDI has seen some limited commercialization, CEDR requires extensive pilot testing and optimization, which suggests a longer adoption timeline.</li> </ul>

**Table 2 Trends analysis**

05	<b>Graphene-based Wastewater Adsorption</b>	<b>Trends</b>	<ul style="list-style-type: none"> <li>▶ Graphene-based materials are demonstrating great potential for enhanced wastewater adsorption capacity for various pollutants including heavy metals, organic dyes, and other contaminants. The incorporation of graphene in transition metal oxides, metal ions, polymers, etc. can greatly boost the photocatalytic efficiency against the elimination of organic dyes in wastewater by increasing the adsorption capacity of organic pollutants. The surface of graphene can be modified for selective adsorption properties, allowing the targeting of specific pollutants in wastewater, and providing for a tailored and efficient treatment approach. Also, adsorption capabilities can be catered for targeted removal of emerging water pollutants, therefore addressing challenges posed by substances such as nano plastics, pharmaceuticals, PFAS, and other emerging contaminants.</li> </ul>
06	<b>Atmospheric Water Harvesting with Graphene</b>	<b>Wild Cards</b>	<ul style="list-style-type: none"> <li>▶ Research on scalable and cost-effective materials for decentralized water production is evolving with techniques to collect very low-salt water from the air, without creating concentrated waste streams. The high surface area and hydrophobicity of graphene allow for effective condensation of water vapor from the atmosphere. Graphene-based materials have demonstrated outstanding water collection capacity by acting as an effective nucleation site. Scalable and low-cost materials for atmospheric water and fog harvesting can potentially be created utilizing graphene. A promising technology to integrate thermoelectric technology with solar thermal energy conversion and atmospheric water harvesting, utilizing Graphene Oxide and natural sunlight to produce electricity and fresh water simultaneously. Practical applications of graphene in atmospheric water and fog harvesting, in addition to rainwater harvesting, could prevail within several years, however, the scalability, water product volumes, and cost-effectiveness are dependent on many factors.</li> </ul>
07	<b>Graphene-Enhanced Irrigation &amp; Smart Monitoring</b>	<b>Trends</b>	<ul style="list-style-type: none"> <li>▶ Graphene-based sensors are demonstrating great potential to optimize water utilization in landscape irrigation, as well as improving yields in precision agriculture. The sensors can optimize water utilization by monitoring and providing real-time data on soil moisture, TDS levels, detecting leaks for timely repair, and minimizing water wastage, or can also be embedded in soil to help monitor water content and salinity levels. The integration of Graphene-based sensors with IoT, AI, and Data Science provides a realm of factors that can impact the potential for this trend, and the scope of its impact, and timeline.</li> </ul>

**Table 2 Trends analysis**

08	<b>Graphene-based GQD Sensors</b>	<b>Trends</b>	<ul style="list-style-type: none"> <li>▶ Graphene-based sensors integration into water systems and water distribution grids through Graphene Quantum Dots (GQDs) is demonstrating capabilities in enabling smart monitoring and management, optimizing water flow, and minimizing wastage, and other benefits. This can improve capabilities in monitoring water quality, detecting contaminants, and triggering automated responses for purification or remediation. Graphene-based sensors are enabling more efficient water continuous monitoring and control of water systems and infrastructure, including saline feedwater sources in Desalination Plants, inlets, hubs, outlets, etc. GQDs have outstanding photoluminescence, good water solubility, and biocompatibility, therefore have applications in optical sensing platforms and bioimaging of water networks. Graphene Quantum Dots in Water Quality Sensors are rapidly evolving and could see notable adoption in the short-term.</li> </ul>
09	<b>Graphene Nanocomposites in Water Infrastructure</b>	<b>Trends</b>	<ul style="list-style-type: none"> <li>▶ Graphene nanocomposite development will enhance the durability and resistance to corrosion and other benefits from its mechanical strength. Therefore, improving the lifespan of water infrastructure of pipes, networks, storage tanks, sealants, desalination water pumps, joints, etc. Also, with Graphene's antibacterial properties, Graphene coating can reduce the need for harsh chemicals and biofilms, through its self-cleaning antibacterial surfaces.</li> </ul>
10	<b>Sustainable Hydrogen Production</b>	<b>Wild Cards</b>	<ul style="list-style-type: none"> <li>▶ Graphene-based photocatalysts process in combination with Solar Renewable Energy Sources (RES) is demonstrating the potential to be used in Water Splitting of water molecules to produce hydrogen fuel. This provides a great promise and potential for providing sustainable energy production from sunlight in a sustainable manner.</li> </ul>
11	<b>Bio-mimicry Desalination</b>	<b>Trends</b>	<ul style="list-style-type: none"> <li>▶ Using graphene-based channels and pores to mimic natural desalination processes to help achieve energy-efficient and sustainable water purification is a promising application. If this can be scaled in, it can provide great potential in desalination technologies in a sustainable manner.</li> </ul>
12	<b>Decentralized Water Purification Systems</b>	<b>Trends</b>	<ul style="list-style-type: none"> <li>▶ Portable, smaller-scale graphene-based filters could provide clean drinking water in remote areas, reducing reliance on centralized infrastructure and minimizing water supply disruptions. Graphene Portable Graphene-Based Water Purifiers are already demonstrating commercialization Potential, although on a small scale. The Graphene Revolution is expediting the trend and wide range of possibilities for smaller, decentralized water purification and desalination systems.</li> </ul>

**Table 2** Trends analysis

13	Enhanced Energy Storage	Trends	
			<ul style="list-style-type: none"> <li>▶ A fast-evolving trend for graphene among the many applications is for energy storage. This trend can potentially help water systems in different ways, including the integration of RES in water systems in addition to a wide range of applications. Some of the promising applications for graphene are in Lithium-ion battery enhancements, with a growing significant R&amp;D interest in graphene in Sodium-ion batteries as a potential alternative to traditional lithium-ion batteries. Ongoing R&amp;D on graphene-enhanced batteries for further optimization, potentially leading to commercial applications in the next few years. Graphene-Based Supercapacitors are another trend impacting energy storage supercapacitors providing high power density and rapid charging/discharging capabilities when compared to conventional capacitors, with the ability to deliver high power in short bursts. Since Graphene is an ideal material for supercapacitor electrodes, Graphene-based supercapacitors can store and release electrical energy efficiently. Graphene's properties make it a valuable material in the development of hybrid capacitors from enhanced energy density and an extended lifecycle.</li> </ul>

### Drivers of Change Analysis

The Drivers of Change analysis helps to gain valuable insights into the overall analysis of enhancing water sustainability through the Graphene Revolution, by analyzing the key forces that are driving the trends and related changes. Below are the key identified drivers that impact the development and implementation of Graphene for enhancing water sustainability.

**Table 3** Drivers of Change Analysis

Name	Description	Implications	Options
<b>Advancement of Technology</b>	<ul style="list-style-type: none"> <li>▶ Improved graphene production from advancements in graphene synthesis and mass production methods.</li> <li>▶ Enhanced Material Properties for water management solutions.</li> <li>▶ Graphene-based Membranes and Filters development with selective permeability for more efficient desalination and filtration processes.</li> </ul>	<ul style="list-style-type: none"> <li>▶ Increased availability of cost-effective graphene for water treatment solutions, resulting in greater adoption.</li> <li>▶ Graphene's exceptional properties lead to more efficient water purification, desalination, and pollutant removal, leading to greater efficiency.</li> <li>▶ Development of selective graphene-based membranes and filters revolutionizing water treatment with more precise filtration and desalination, reducing energy consumption</li> </ul>	<ul style="list-style-type: none"> <li>▶ Incentive for technological companies to develop the market</li> <li>▶ Investing in R&amp;D, collaborating with research institutions, universities, and providers to adopt new techniques on a global scale.</li> <li>▶ UAE leading innovation in graphene for selected water management approaches.</li> <li>▶ Technological leadership of the UAE on a global scale.</li> </ul>

Source: Sia Partners Analysis

**Table 3 Drivers of Change Analysis**

Name	Description	Implications	Options
<b>Environmental Concerns</b>	<ul style="list-style-type: none"> <li>▶ Water Scarcity requires innovative solutions like graphene-based desalination and water treatment. Water Pollution challenges in removing contaminants from water sources for more effective wastewater treatment and improved quality.</li> <li>▶ Water Pollution challenges in removing contaminants from water sources for more effective wastewater treatment and improved quality.</li> <li>▶ Climate change impacts on water quantity and quality emphasizing the urgency of sustainable water management, where graphene revolution can play a key role.</li> </ul>	<ul style="list-style-type: none"> <li>▶ Adoption of graphene-based technologies to help alleviate water scarcity, ensuring a more sustainable and reliable water supply.</li> <li>▶ Graphene's adsorption capabilities will aid in removing a range of contaminants from water sources, improving water quality and reducing environmental pollution.</li> <li>▶ Sustainable graphene-based water solutions to mitigate the impact of climate change on water resources, providing resilience in the face of changing conditions.</li> </ul>	<ul style="list-style-type: none"> <li>▶ Increased demand for sustainable and efficient materials like graphene in water treatment.</li> <li>▶ Standardizing graphene-based solutions as eco-friendly, and compliant with environmental regulations.</li> <li>▶ Expediting graphene integration from demand urgency for graphene-based water solutions.</li> <li>▶ Targeting arid regions with severe water scarcity.</li> <li>▶ Collaborating with international organizations, and tailoring solutions to specific local needs and UAE particularities.</li> </ul>
<b>Economic Viability</b>	<ul style="list-style-type: none"> <li>▶ Economies of scale in graphene production leading to competitive pricing, making graphene-based solutions more economically viable.</li> <li>▶ ROI and cost savings in water treatment processes attract private sector and semi-government investments in graphene applications,</li> <li>▶ Growth of a graphene-based water management industry can create job opportunities.</li> <li>▶ Portable and smaller-scale solutions as economic solutions for individuals, smaller communities, or even events.</li> </ul>	<ul style="list-style-type: none"> <li>▶ Government support accelerating R&amp;D in graphene applications, leading to implementing graphene faster.</li> <li>▶ Globally Partnerships &amp; Collaboration can create a global framework for graphene standards and best practices for consistent and efficient adoption.</li> <li>▶ Strict compliance with safety and quality standards will ensure the responsible use and production of graphene materials, and minimize potential risks.</li> </ul>	<ul style="list-style-type: none"> <li>▶ Feasibility Studies and Cost-benefit analysis.</li> <li>▶ Government subsidies or incentives.</li> <li>▶ Developing scalable production methods to reduce costs.</li> <li>▶ Regulatory framework changes to foster innovation and promote implementation and piloting.</li> <li>▶ Implementation of graphene on a smaller scale or targeted viable applications.</li> </ul>
<b>Regulatory and Policy Support</b>	<ul style="list-style-type: none"> <li>▶ Government Incentives and funding for graphene research.</li> <li>▶ Regulations, codes, and standards that encourage the adoption of graphene in water applications.</li> <li>▶ International collaboration to share best practices and standard setting for graphene applications to promote adoption.</li> <li>▶ Industry Compliance in HSE and quality standards, and responsible disposal and recycling practices in graphene use.</li> </ul>	<ul style="list-style-type: none"> <li>▶ More funding and incentives on graphene R&amp;D.</li> <li>▶ Incentives for the use of graphene in water treatment and desalination solutions</li> <li>▶ Establishing partnerships and collaboration with global regulators to define standards</li> <li>▶ Regulatory framework changes encouraging the adoption of graphene</li> <li>▶ Align environment policies and regulations with graphene practical applications.</li> <li>▶ Defining Code for graphene use in the water industry.</li> </ul>	<ul style="list-style-type: none"> <li>▶ Help in ensuring compliance with regulatory standards</li> <li>▶ Establish funds for graphene-related initiatives</li> <li>▶ Define Standards and best practices for graphene use in the UAE</li> <li>▶ Establish policies and regulations that encourage graphene</li> </ul>

Source: Sia Partners Analysis

**Table 3 Drivers of Change Analysis**

Name	Description	Implications	Options
<b>Research &amp; Development</b>	<ul style="list-style-type: none"> <li>▶ Partnerships and collaborations between academia, government, and industry in interdisciplinary research to drive innovation in graphene-based water solutions.</li> <li>▶ Development and protection of intellectual property related to graphene.</li> <li>▶ Piloting and Validation with rigorous testing and real-world pilot projects to validate the effectiveness of graphene-based technologies.</li> <li>▶ Knowledge Sharing &amp; the dissemination of scientific findings through publications and information sharing accelerates graphene adoption.</li> </ul>	<ul style="list-style-type: none"> <li>▶ Agile innovation and collaboration can result in the development of cutting-edge graphene-based water solutions and solving complex water challenges.</li> <li>▶ Ensuring a competitive edge and fostering continuous innovation in graphene applications.</li> <li>▶ Rigorous testing and validation will build confidence in the effectiveness of graphene-based solutions.</li> <li>▶ Knowledge Sharing and scientific publications will facilitate knowledge transfer and enable researchers and industry to stay updated on the latest developments.</li> </ul>	<ul style="list-style-type: none"> <li>▶ Developing partnerships with Academia</li> <li>▶ Creating joint ventures and industry partnerships</li> <li>▶ Support piloting and validation in desalination and water treatment.</li> <li>▶ Participating in industry events and global collaboration.</li> <li>▶ Focusing on R&amp;D, patenting graphene innovations &amp; IP</li> <li>▶ Staying updated on emerging tech in the field.</li> <li>▶ Finding synergies in the nexus of energy-food-water</li> <li>▶ Support for interdisciplinary research.</li> </ul>
<b>Acceptance of new technology and material</b>	<ul style="list-style-type: none"> <li>▶ Communicating the benefits of graphene and addressing concerns and misconceptions is essential for acceptance.</li> <li>▶ Involving water industry communities in water projects can foster trust and support for graphene applications in their industries.</li> </ul>	<ul style="list-style-type: none"> <li>▶ Analyse changes in demand for Graphene-based applications.</li> <li>▶ Effective communication about graphene's benefits and safety measures will increase acceptance and trust in graphene-based water solution</li> <li>▶ Engaging wider segments of the community in water projects will promote and support graphene applications, fostering shared responsibility for water sustainability.</li> </ul>	<ul style="list-style-type: none"> <li>▶ Incentive for providers to develop the market</li> <li>▶ Marketing campaign of efficiency and benefits</li> <li>▶ Provide the public with necessary information about the benefits of graphene</li> <li>▶ Awareness campaigns, and educational programs on the benefits and limitations of graphene.</li> </ul>
<b>Scalable Production</b>	<ul style="list-style-type: none"> <li>▶ Addressing the challenges in scaling up graphene production</li> <li>▶ Maintaining quality and cost-effectiveness.</li> <li>▶ Partnerships with manufacturers of graphene products.</li> </ul>	<ul style="list-style-type: none"> <li>▶ Scalability issues can greatly limit the adequate adoption of graphene in water mgt.</li> <li>▶ Explore novel solutions that integrate other technologies. Ensure graphene products meet evolving standards and regulations.</li> <li>▶ Develop industry partnerships</li> </ul>	<ul style="list-style-type: none"> <li>▶ Support investing in scalable production technologies, process optimization, and quality control mechanisms</li> <li>▶ Develop new partnerships and collaborations.</li> <li>▶ Support the testing of emerging products that show potential for scalability.</li> </ul>

Source: Sia Partners Analysis

Note: Identification of Drivers and their analysis is provided without defining the years for the potential impact of an emerging technology that is still in R&D with limited commercialization.

## Key Uncertainties Analysis

The development of graphene-based technologies for enhancing water sustainability in Abu Dhabi is influenced by several uncertainties. These uncertainties can be identified and evaluated, allowing decision-makers to prioritize and address the most significant uncertainties.

This can help to make data-driven decisions and develop appropriate strategies to overcome potential challenges and advance the successful implementation of Graphene for enhancing water sustainability in Abu Dhabi and the UAE in the future.

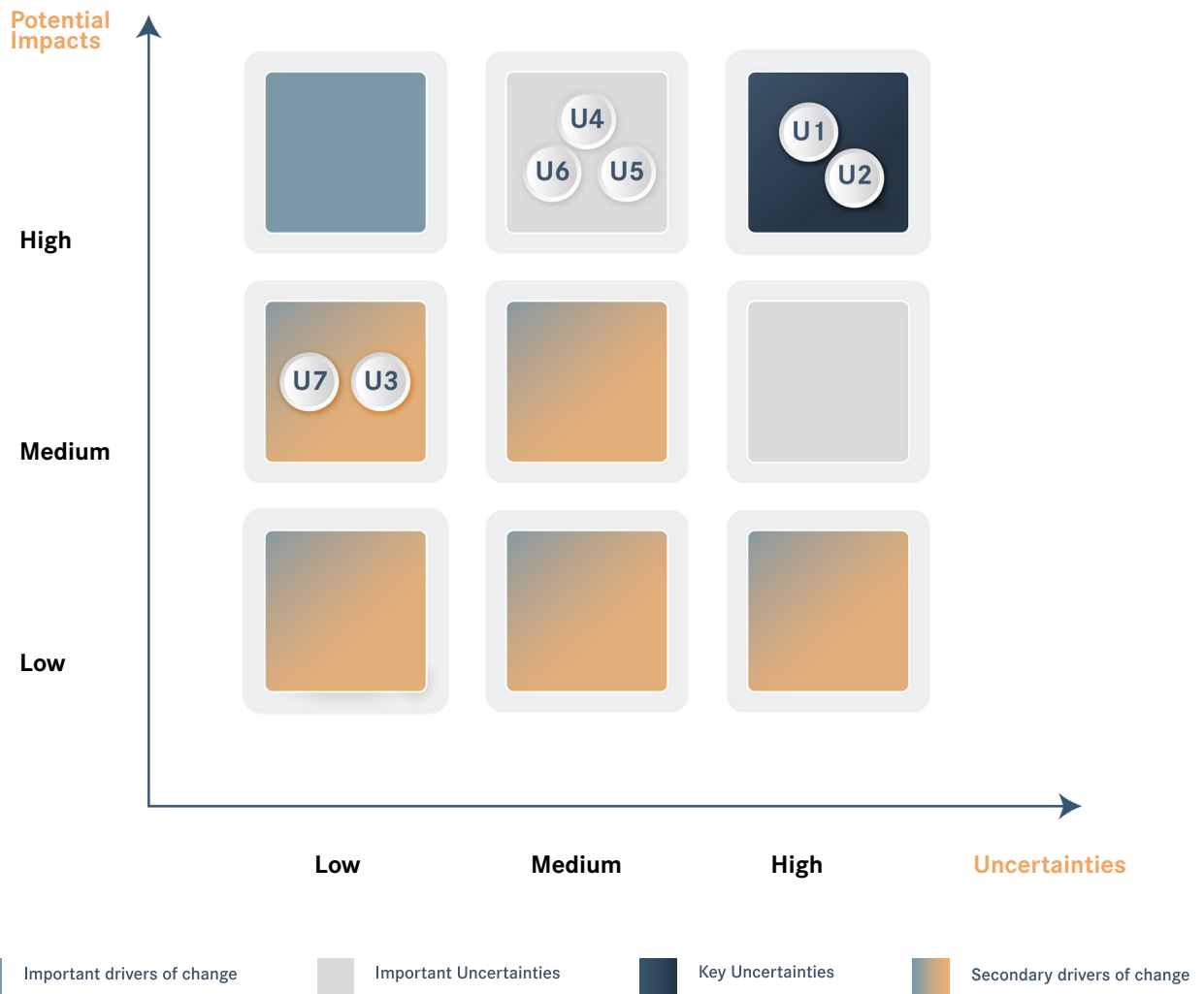
No.	Uncertainties	Description	Degree of Potential Impact (L, M, H)	Degree of Uncertainty Impact (L, M, H)
01	<b>Technological Feasibility</b>	Uncertainty in the technological advancement for high scalability and practical application of graphene in water management, as graphene technological development and innovation can revolutionize current desalination, water purification, and treatment methods. The rapid advancements in nanotechnology and other key technologies suggest promising feasibility, however, mass production remains immature and practical application in research and piloting.	High	High
02	<b>Cost and Economic Viability</b>	Uncertainty regarding the cost-effectiveness of production at a large scale, and the cost impact for scaled graphene applications. Cost is a critical factor for the effective adoption of graphene-based solutions. Current production methods are expensive, with uncertainty on how quickly costs can be viable for cost-efficient implementation in different applications including desalination, water treatment, atmosphere harvesting, and other promising applications of graphene for water.	High	High

Source: Sia Partners Analysis

**Table 4** Key Uncertainties Analysis

No.	Uncertainties	Description	Degree of Potential Impact (L, M, H)	Degree of Uncertainty Impact (L, M, H)
03	<b>Regulatory and Policy Changes</b>	Options and changes in policies and regulations have the potential to impact graphene use. Regulatory framework changes can either facilitate or hinder the adoption of graphene-based technologies. While policy trends favor encouraging innovation and ensuring water and environmental sustainability, the specifics of future regulations and how they are affected by other policies and regulations are unpredictable to a certain degree.	Medium	Low
04	<b>Environmental Impact and Sustainability</b>	Uncertainties regarding the long-term environmental impact of graphene production, usage, and disposal. Negative environmental impacts could limit the acceptance and adoption of graphene in water applications. While graphene is being promoted as environmentally friendly, comprehensive studies on its environmental footprint and impact are limited at present, resulting in uncertainties on how this can impact the adoption of graphene in different applications.	High	Medium
05	<b>Market Adoption and Acceptance</b>	Uncertainty on how quickly and widely graphene-based water solutions will be accepted by the different water industry players and the market is crucial for the sustained adoption of graphene technologies and depends on several factors such as cost and effectiveness.	High	Medium
06	<b>Research and Development Pace</b>	The pace at which Research and Development in graphene technology will progress can significantly enhance adoption, while slow R&D progress and delays could hinder it. R&D progress depends on several factors such as funding, interest in academia and the scientific community, market interests, and breakthrough discoveries and innovations related to graphene, or other emerging materials and technologies.	High	Medium
07	<b>Intellectual Property and Patents</b>	Uncertainty regarding the development of intellectual property and potential patent disputes in graphene technology and related implementation. IP issues can affect the commercialization and collaboration opportunities in this field. With many patents and IP already registered, the evolving nature of graphene technology makes the IP landscape dynamic and somewhat unpredictable.	Medium	Low

Source: Sia Partners Analysis



**Figure 5 Source:** Key Uncertainties Matrix

Based on the results of the key uncertainties analysis, a matrix was constructed above from the uncertainties in the Key Uncertainties Analysis, along the axis of Potential Impact and degree of Uncertainty. As a result, the key uncertainties identified Technology Feasibility and Economic Viability to have the greatest level of uncertainty and impact on the subject area. The Scenarios will be developed along these key uncertainties in the following section.

**Build Future Worlds**

The environment scanning and analysis indicate the promising applications of graphene to significantly improve the potable water quantity, quality, and treatment, with a high potential for ensuring water sustainability and security for Abu Dhabi, and the UAE by 2036. Thereby transforming water management and the UAE’s ability to alleviate water scarcity.

Based on the analysis from the previous section, two Key Uncertainties were identified and used for building Future Worlds in terms of future narratives and scenarios that foresee optimistic and pessimistic alternative future scenario extremes for the development of graphene-based technologies to enhance water sustainability. The optimistic and pessimistic options for these uncertainties are as follows:

● Economic Viability:

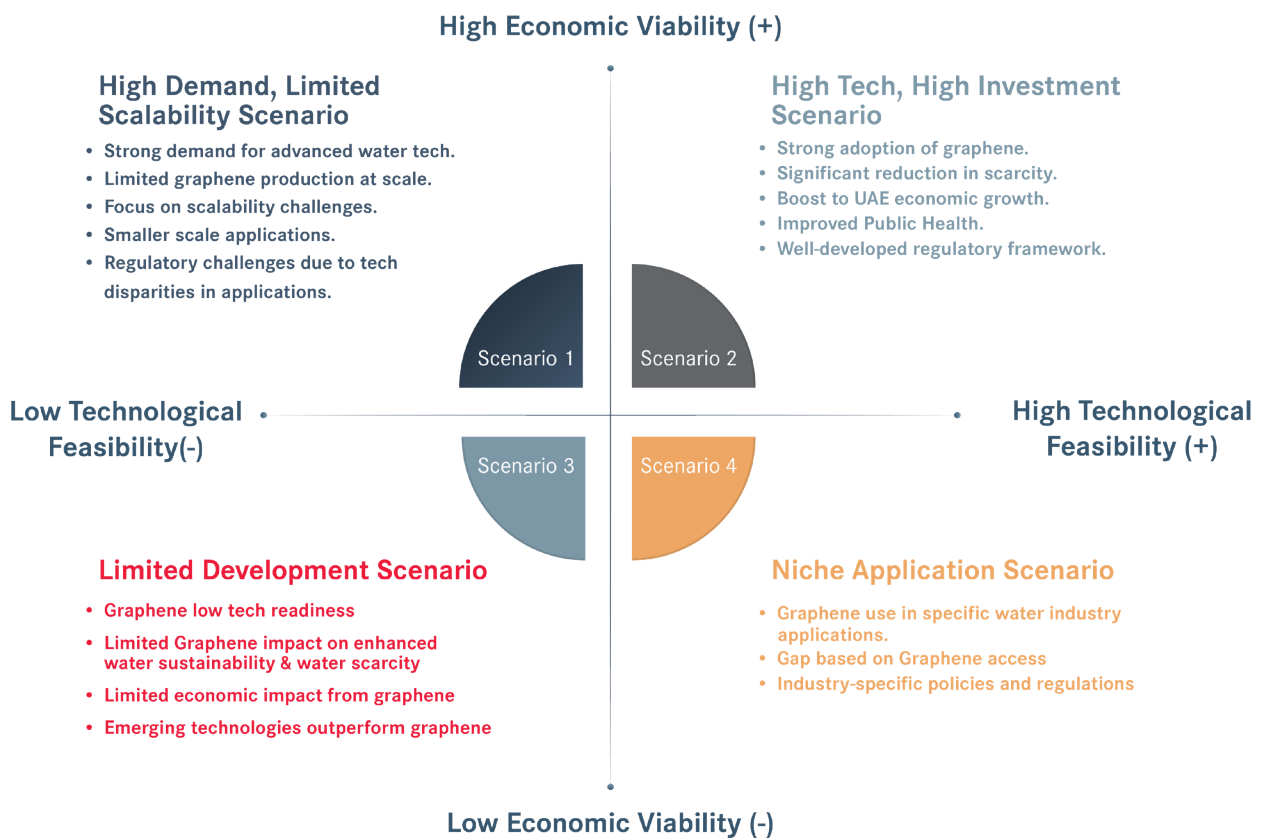
Low Economic Viability (-)

High Economic Viability (+)

● Technological Feasibility:

Low Technological Feasibility (-)

High Technological Feasibility (+)



**Figure 5 Source:** Future scenario matrix

Source: Sia Partners Analysis

The Key Uncertainties are mapped in the Scenarios Matrix that helped to identify the following four Future Worlds (scenarios):

- 1 High Demand, Limited Scalability Scenario
- 2 High Tech, High Investment Scenario
- 3 Limited Development Scenario
- 4 Niche Applications Scenario

In developing the Future Worlds for the identified scenarios above, Future Narratives are developed for each scenario to express the future state for the time horizon of these Future Worlds:

**Table 5 Future Narratives**

01	<p><b>Graphene Oasis: Small-Scale Solutions in a Thirsty World</b></p> <p><b>A Future World with High Demand and Limited Scalability of Graphene</b></p>	<ul style="list-style-type: none"> <li>▶ By 2036, the UAE’s thirst for advanced water technologies to meet the increasing demand has soared. Graphene, with its superior filtration properties, is in high demand for various applications (including desalination and water treatment and purification). However, there are still challenges with scaling up graphene production due to technological challenges that prevent mass production and scalability in key applications for desalination and water treatment plants, leading to a focus on smaller-scale applications that can be widespread due to the high demand, such as home and portable filters, or localized graphene-based water applications.</li> </ul>
02	<p><b>Blue Revolution: Rewriting the Water Sustainability Narrative in the Water World</b></p> <p><b>A Future World with High Tech and High Investment in Graphene</b></p>	<ul style="list-style-type: none"> <li>▶ By 2036, the UAE will be positioned as a world leader in water sustainability and security in arid regions, thanks to fully embracing graphene-based technology in desalination, water treatment, and purification on a large scale. The shift to graphene-based membranes has drastically reduced water scarcity and is propelling economic growth, especially from industries linked with high water usage and other economic opportunities. With water sustainability and security, public health, and well-being are further improved.</li> </ul>

Table 5

## Future Narratives

03

**Graphene Mirage: The Unfulfilled Promise of Water Sustainability**

**A Future World with Limited Development of Graphene**

- ▶ While Graphene has shown promise in the early stages of R&D, graphene's impact in ensuring the UAE's water sustainability and security by 2036 has been limited due to cost-effectiveness challenges, low technology readiness, enhanced performance by emerging technologies from the development of polymer membranes or other emerging material and technologies that have kept graphene in the background as a key revolutionizing material in water management. Other factors can contribute to its limited development, such as emerging evidence of environmental impact on environmental sustainability and public health from Graphene and Graphite use, production, or disposal.

04

**Graphene Gems: Unearthing Niche Water Innovations**

**A Future World with Niche Applications for Graphene**

- ▶ Graphene is found to be effective in specific water industry applications, such as enhancing the efficiency of Desalination Plants, or providing value in Water Treatment and Purifications, even while Graphene-based material is still expensive. However, graphene applications are not widespread as the most-effective material due to the high costs of implementation on a larger scale, or limitation on the cost-effectiveness of its varied applications and potential compared with other technologies.

## Identify Implications

The following are the initial implications identified based on the identified Future Worlds. This can help in driving further analysis and identifying the implications of these scenarios.

### Graphene Oasis: High Demand, Limited Scalability Scenario

#### Key Challenges:

In this scenario, the key challenge is that graphene is implemented in different water applications, at different scales. This would require the development of regulatory frameworks and codes for the different water applications to develop and adapt to managing inconsistent graphene technology utilization for different purposes. This will add complexities and challenges in developing regulatory frameworks for DOE.

Scalability issues remain a challenge to overcome. This would require an increasing investment in graphene R&D. And with the high demand for cost-effective and efficient graphene-based solutions, there will be a greater push for the need to find innovative solutions and effective production methods.

#### Key Opportunities:

In this scenario, there will be more focus on smaller-scale, impactful innovative applications of graphene technologies that address the specific use cases and provide value through innovative solutions for the needs of individuals and local communities. Graphene-based solutions can also cater to specific locations or events. There will also be a potential for high-value industries to utilize graphene-based solutions. However, the benefits will be different between the various industries and applications.

Graphene technology will be tailored to meet specific local water challenges, especially in arid regions, or for specific use cases, such as implementing Graphene at the outlet of treated water to improve water quality for farms or homes in Abu Dhabi Emirate. With the growing demand, this phenomenon will push for, and lead to a more decentralized model of potable water production and graphene applications in water management.

## Key Challenges

### Blue Revolution: High Tech, High Investment Scenario

In this scenario, there will be high levels of adoption of graphene-based water solutions across the different water industries, with increased competition. As technology advances further, DOE can be faced with the challenge of developing well-defined regulatory frameworks that are effective in covering the different and growing applications of graphene in water management.

With the uncertainties on the environmental and health impact of graphene, based on the current state of research lacking sufficient evidence, there can be potential for growing environmental and health risks that would need to be addressed through environmental or other policies and regulations to address the growing impact of graphene-based technologies in water applications.

### Key Opportunities

In this scenario, the UAE's advanced utilization of graphene in water management and the implementation of related best practices will position the UAE as a Case and benchmark globally in the effective utilization of graphene for water sustainability in water-challenged regions. The UAE plays a leadership role in setting global standards, and industry norms, in addition to developing policies and regulations for the effective utilization of Graphene-based technologies in water management. Also, the UAE has become a global Center of Excellence (CoE) for Desalination using Graphene-based innovations.

The UAE has increased global competitiveness and is experiencing further significant economic growth in many different industries driven by better water access and graphene technology advancements and innovation, attracting global investment and talents in advanced water technologies.

Additionally, public health and well-being are improved as a result of better water quality, the removal of contaminants, and the UAE's advanced purification infrastructure.

## Graphene Mirage: Limited Development Scenario

### Key Challenges:

In this scenario, graphene's utilization in water management has been limited due to the challenges of cost-effectiveness, low technology readiness, or enhanced performance by emerging technologies. This is leading to shifting the focus to alternative and emerging water management technologies and methods including ceramic membranes. The UAE is experiencing limited economic impact from graphene-specific investments.

For water sector regulators such as DOE, the development of policies, regulations, codes, and standards pivot towards other more promising technologies and innovations for ensuring water sustainability and security. This can be due to emerging evidence of environmental impact on environmental sustainability and public health from graphene and Graphite use, production, or disposal.

### Key Opportunities:

Graphene is creating value in the Energy sector, or other industries with promising applications, shifting focus to other graphene technologies applications and innovations.

Graphene is finding useful applications, however in a supplementary role to other solutions. It could be used in other composite material applications, or its integration in other water management materials and technologies, and with the advent of digital 5th industrial revolution technologies.

Graphene's promising potential is promoting innovations for water sustainability, and results in increased exploration and experimentation of novel solutions, leading to the diversification of the innovation portfolio in the water sector.

## Graphene Gems: Niche Applications Scenario

### Key Challenges:

The high costs of implementation of graphene technologies are proving to be a key challenge for mass adoption or implementation on a larger scale, due to the cost-effectiveness of graphene applications and potential in the various methodologies and solutions, or the high costs of graphene production. Economic benefits in graphene-utilizing industries will be concentrated on specific efficiency increases and benefits.

The implementation of graphene-based solutions would require conducting a cost-benefit analysis of each graphene-based niche application to ensure value creation and contributions to water sustainability.

### Key Opportunities:

Graphene is found to be effective in specific water industry applications, including enhancing the efficiency of Desalination Plants and Water Treatment Plants, such as its use in heat exchange processes, even while Graphene-based material is expensive, from the enhanced efficiency of Desalination plants benefiting from the advancements of using graphene-material and specialized graphene oxide membranes.

Graphene is finding other niche applications such as water treatment membranes for fine bubble aeration, or its integration in IoT technologies using Graphene-based sensors to enhance and develop smart irrigation systems, detecting soil moisture levels and pollutants, reducing waste and leakages, and other values created from Graphene use, including other niche applications such as improving Water Treatment processes, or graphene-enhanced water retention materials to reduce water losses in arid and hot climates like Abu Dhabi emirate.

Abu Dhabi is leveraging the potential of graphene to come up with innovative solutions utilizing graphene to solve specific challenges, through small-scale, portable desalination units for coastal communities in the emirate, or through Graphene-based atmospheric water harvesting.

The implementation of graphene for specific applications would require the DOE to develop policies and regulations that adequately govern, regulate, and promote innovations for the specialized graphene niche applications.

# Future Vision

Water stress, operational challenges, and climate change in recent years have highlighted the importance of enhancing water sustainability at a far-sighted strategic level. Ensuring access to sufficient supplies of potable and treated water will be essential for water sustainability, and will become increasingly strategic for the UAE and regulators in the coming years.

Based on the analysis of the 4 scenarios, there are several key considerations that DOE can take for the enhancement of water sustainability through the Graphene Revolution. The following can be applied to a different degree in the four presented scenarios:

## 01 Support R&D for Graphene applications in Water:

The promising potential of graphene applications for water sustainability, and considering the challenges of water-stress, give priority to research and development in graphene-based technologies for Desalination, water treatment, purification, and key applications.

DOE should consider the investment in graphene R&D programs and initiatives to help materialize the implementation of Graphene for the targeted applications while supporting R&D efforts through different programs and initiatives that could include partnerships, collaborations, and support for researchers and startups working on developing, experimenting, and piloting Graphene-based water management solutions, with monitoring and governance to provide support for the related R&D.

DOE can allocate sufficient funding to dedicated graphene research centers and universities, including launching grant programs specifically targeting innovations in graphene for water treatment. Additionally, the government offering incentives to organizations that invest in graphene R&D related to water sustainability can stimulate private sector engagement and innovation.

## 02 Policy Development:

DOE should develop and establish effective policies and regulations that encourage further innovations in water management and facilitate the adoption of graphene technologies for improved water sustainability. This would require identifying the specific needs and requirements that need to be addressed in the regulatory frameworks to ensure that the policies and regulations are encouraging and promoting graphene-based innovations, and not hindering it.

The government should formulate regulations that support the effective and safe deployment of graphene-based water technologies. A regulatory framework by DOE that incentivizes the adoption of graphene technologies will help accelerate its integration into existing water management systems.

## 03 Public-Private Partnerships:

Developing partnerships between the government, academia, and industry is key for the development and implementation of graphene technology. This can be achieved by facilitating knowledge sharing and communications, holding meetings and forums for interaction with and between the partners.

DOE can establish joint funding schemes and programs for graphene research & piloting projects and create Innovation Hubs, similar to or inspired by innovation hubs in Hydrogen, where partners can collaborate to drive forward the development of practical graphene-based solutions on the ground.

## 04 Sustainability Focus:

Ensuring that graphene applications are aligned with other sustainability policies and regulations, and environmental and sustainability goals. This includes integrating sustainability assessments and monitoring in all graphene-related water projects, including its carbon footprint, lifecycle analysis, impact studies, and contributions to Decarbonization efforts.

The government can develop certification or standards compliance programs for graphene technologies to ensure they meet environmental standards.

Communicating and promoting the use of graphene in water systems should be part of the broader sustainability strategies and campaigns to highlight graphene's benefits to ensuring water sustainability.

## 05 Technology Scaling:

Addressing the challenges in scaling up graphene production for water management needs is critical. The government should support the development and adoption of large-scale graphene production facilities, and funding for research into more cost-effective and efficient sourcing and production methods.

Encouraging industry involvement, and support for graphene-related partnerships to address and overcome scalability challenges will be instrumental in making graphene a viable option for the adoption and utilization to help ensure water sustainability.

## 06 Cost-Effectiveness Analysis:

Conducting feasibility studies to assess the economic viability of graphene-based solutions is essential, particularly with the key uncertainty of its economic viability.

The government should commission studies comparing the cost and benefits of graphene-based solutions with traditional methods and processes of desalination, water treatment, and purification. The government can also develop models, methods, tools, or frameworks, for the cost-benefit analysis for the specific types of applications. This can involve collaborating with financial institutions or experts to help provide a clearer understanding of the economic aspects and cost-effectiveness of graphene technologies, including their impact on energy consumption.

## 07 Pilot Projects:

The government can provide initiatives and support pilot projects to test and validate the effectiveness of graphene in real-world water management scenarios, with prioritization for Desalination and Water Treatment technologies, Farms, and Agriculture to detect salinity, infiltration, measuring intrusion from groundwater, reduce TDS levels, and Graphene in water infrastructure (Coating of Pipes, Tanks, etc.) for corrosion, and using graphene in sealants. Other valuable initiatives can be in pilot projects for the integration of graphene-based sensors for IoT, Sensors, and other smart irrigation applications, or initiatives for enhancement of irrigation and agricultural utilization in specific use cases and challenges such as Graphene based solutions at the output or distribution points of the Water or TSE, and recreational and producing farms for sustainable agriculture.

The government initiatives for the pilot projects can include pilot projects to be set up graphene-based solutions in diverse geographic and demographic regions, such as in Abu Dhabi city and islands, along the Abu Dhabi-Alain Road Farms, and Al-Dhafra region, to test the versatility and effectiveness of graphene-based solutions for the specific regions or use cases, with defined criteria to measure the success of the pilot outcomes.

The government can fund and support these pilot projects, especially in collaboration between government entities, industry key players, and other key stakeholders, which will provide valuable feedback, and learning opportunities, and foster collaboration, partnerships, and engagement.

## 08 Awareness Campaigns:

The government plays a key role in increasing the awareness of industry key players, the public, and key stakeholders through effective communication strategies for the awareness and developing knowledge of the potential benefits and limitations of graphene-based technologies for water sustainability.

This can be achieved through launching informational campaigns, holding workshops and seminars designed to educate the key stakeholders including water industry key players, other government entities, partners, and the public at large.

The government can also develop educational materials and infographics specifically designed for universities and the academic sector, to help foster a new generation that is knowledgeable about graphene technology and its potential, to enable the UAE to develop local talents and its drive for innovation and international competitiveness.

The government can consider in the future developing case studies that demonstrate the UAE's thought leadership in the space of enhancing water sustainability through graphene-based applications, or in other applications of graphene in energy.

## 09 Standardization:

DOE should actively engage in the development of standards, and best practices for the utilization of graphene in Desalination, water treatment, and purification. This will ensure improved consistency, safety, and quality of water.

DOE can collaborate with international bodies and programs, such as the EU Graphene Flagship, in the development of graphene-related standards. Also, collaborating with experts and establishing working groups to formulate these standards, and contribute to assessing the impact on public health and safety.

DOE can establish compliance and certification processes for graphene-based water treatment products and technologies to ensure the quality and efficacy of Graphene-based membranes and other graphene-based products, as well as for other graphene applications in the energy sector.

## 10 Global Collaboration:

DOE should engage in international cooperation to share knowledge, standards, and best practices in graphene-based applications for water sustainability, and security and contribute to the UAE government's directions and strategies. This can include engaging in regional collaborations with other water-stressed countries affected by water scarcity and further developing partnerships for increased collaboration.

DOE can also develop initiatives for collaboration in international R&D programs and develop partnerships with academia, research centers, and industry thought leaders.

DOE should ensure its active participation in global forums and conferences related to graphene. Furthermore, Abu Dhabi can establish a conference event for graphene that provides a platform to facilitate knowledge sharing, learning, and promoting related knowledge production and innovations. Thereby, fermenting Abu Dhabi's leadership position on the global stage.

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# Glossary

- **Future Foresight**

Future Foresight is a structured, analytical, interactive, and systematic future-oriented process that aims to better prepare and motivate for change and enhance decision-making, both medium and long-term.

- **Triggers**

Events, signals, or actions that indicate a change or a condition that instigates the need to activate the Future Foresight model.

- **Environment Scanning**

A continuous process of monitoring signals, collecting ideas and insights, organizing information, collecting data on past and current trends, and researching on sources of change to relate information about triggers and their relationships internally and in the external environments helping to determine the drivers of change.

- **Focal Issue**

The focal issue is the topic or question that will guide the Future Foresight exercise. The focal issue should be defined as precisely as possible. During the entire foresight project, it will act as an anchor for regaining focus and re-centering discussions.

- **Time Horizon**

The time horizon is the period, usually defined in years, considered in the Future Foresight project. This period is always long-term, although the year defining the long-term may change. Close time horizons are more detailed and rigorous compared with distant time horizons which are more diffuse and general. The ideal Time Horizon for a foresight study is the horizon of ruptures.

- **Future Worlds**

The process of imagining and building alternative futures, including scenarios, future narratives, and generated images and representations of the future.

- **Scenarios**

Scenarios are narratives of alternative environments in which today's decisions may be played out. Scenarios are very powerful communication tools. They knit together multiple facets of the foresight analysis and illustrate the whole through a narrative that can be very effectively recounted, visualized, and discussed.

- **Models**

Models are qualitative or quantitative descriptions of key components of a system and relationships between those components, used to forecast or simulate scenarios and options with the support of historical data. (Part: <https://www.ipbes.net/scenarios-models/what>)

- **Trends**

A trend is a manifestation of the direction of change. It is usually a gradual and long-term change in the drivers that shape the future of an organization, business sector, or country.

- **Megatrends**

Megatrends are long-term processes of transformation with a broad scope and a dramatic impact. Based on the available evidence, they can be considered powerful factors that will shape the future.

- **Weak Signals**

Weak signals are external or internal warnings that are too incomplete to allow an accurate estimation of their impact and/or to determine what a suitable response should be.

- **Wild Cards**

Wild card is an event with a relatively low probability of occurrence, but an inordinately high impact in the conduct of businesses, catching most people by surprise.

- **Pre- Determined Elements**

Predetermined elements are events where change is largely predictable (or has already occurred), but whose consequences have not yet unfolded. In other words, it is what we know that we know, such as demographic changes, accelerating technology, and increasing health concerns.

- **Key Uncertainties**

Key uncertainties are variables that are essential for understanding the future dynamics of the change. They must have a strong potential impact on the focal issue, a high level of uncertainty, and a high degree of independence. This concept stems from the concept of structural uncertainty; an event that is unique enough not to provide us with an indication of its likelihood, such as the COVID confinement period, prices of a commodity, and international competition.

- **Graphene**

Graphene is a single layer of carbon atoms arranged in a two-dimensional honeycomb lattice. Made from Graphite, it is renowned for its exceptional strength, flexibility, electrical and thermal conductivity, and is considered one of the thinnest, yet strongest materials known. Graphene's unique properties make it a promising material for a wide range of applications.

- **Water Scarcity**

The mismatch between the availability and supply of water, and its demand in a particular region.

- **Water-Energy-Food Nexus**

An integrated management and policy approach that recognizes the complex interdependencies between water, energy, and food systems. It aims to ensure sustainable resource use, enhance efficiency, and achieve security in all three segments.



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