The Economist Group
WORLD OCEAN
INITIATIVE

Accelerating Energy Innovation for the Blue Economy

Commissioned by Pacific Northwest National Laboratory

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Acronyms and abbreviations:

APED	Act to Promote Energy Diversity
AUV	Autonomous underwater vehicle
Btu	British Thermal Unit
CLCPA	Climate Leadership and Community Protection Act
CO2	Carbon dioxide
DOE	US Department of Energy
EIA	Energy Information Administration
EV	Electric vehicle
GDP	Gross domestic product
GW	Gigawatt
IEA	International Energy Agency
IMO	International Marine Organisation
IRENA	International Renewable Energy Agency
LCOE	Localised cost of energy
MW	Megawatts
MWh	Megawatt hour
NOAA	National Oceanic and Atmospheric Administration
OECD	Organisation for Economic Cooperation and Development
OTEC	Ocean thermal energy conversion
SIDS	Small island developing states
TRL	Technology readiness level
UUV	Unmanned underwater vehicle
VC	Venture capital

About this report

This report aims to foster better understanding of energy innovation for the blue economy and prospects for investment in marine renewable energy. The Economist Intelligence Unit conducted an in-depth literature review and interviewed 30 blue economy, energy innovation and marine energy experts to produce this report.

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Executive summary

What is the demand for energy within the blue economy? What enablers have driven past innovations, and what were the impacts? What is the current state of marine energy innovation?

As the blue economy continues to grow, energy needs will continue to rise. At the same time, as new energy innovations emerge the potential of the blue economy to create both sustainable value and jobs can be realised through the expansion and transformation of existing markets as well as the creation of new ones.

In this report The Economist Intelligence Unit examines the past, present and future of energy innovation within the blue economy. We look at the energy needs of different ocean economy sectors to see where demand exists and may be growing. We assess groundbreaking energy innovations to date—the sail-to-steam transition, improved energy storage mechanisms and the development of offshore wind—to better understand their initial and ongoing effects on blue economy markets. We use insights gleaned from these case studies alongside in-depth interviews with blue economy, energy innovation and marine energy experts to determine the central elements needed to create an enabling environment for innovation within the ocean economy.

This report provides valuable insights for all stakeholders working to develop new, clean solutions to serve the growing energy needs of the blue economy, particularly marine energy technologies. The report sheds light on enabling factors that can accelerate energy innovation for the blue economy and unlock the promise of marine energy.

Through improvement of the enabling environment marine energy technologies can be driven forward, transforming and expanding the blue economy in the process.

The report is divided into the following five chapters:

In **chapter one**, we briefly outline the central sectors of the blue economy—both emerging and established—and identify the main energy consumers. The ocean economy is an important part of both the US and global economy: maritime transport is the largest consumer of energy in the blue economy and a large contributor to global CO2 emissions. As such, the sector is now pushing towards cleaner energy usage. Maritime tourism is the largest ocean-based industry in terms of GDP contribution and employment in the US and is a major consumer of energy. Ship and boat building and the offshore oil and gas industries are also major consumers of energy within the US. Within all of these sectors, including fishing and aquaculture and ocean observation and navigation, marine energy presents opportunities for renewable, in-situ or local power generation that could help pave the way towards the blue economy of the future.

> **"The blue economy differs from the market economy. It's not going to be the same; it cannot be the same. We have been dependent on the oceans to protect us from climate change and we cannot do that anymore. We have to give back."**
>
> Claire Mack, Scottish Renewables

Defining the blue economy:

As the Economist Intelligence Unit has noted in the past, the blue economy remains hard to define. Is the notion of a blue economy only concerned with minimising harm or should its goal be to actively restore the health of the ocean? Is it the same as a sustainable ocean economy?

In this report the following adapted working definition is used: "A sustainable ocean economy emerges when economic activity is in balance with the long-term capacity of ocean ecosystems to support this activity and remain resilient and healthy."

This means harnessing ocean resources for economic growth while protecting ocean health and ensuring social equity. While "blue economy" and "ocean economy" are used interchangeably throughout this report, working towards a blue economy involves not only responsible and sustainable use of the ocean environment but also of terrestrial environments given the important links between global climate change and ocean health. While traditional energy sectors are discussed in this report, establishing a blue economy requires shifting energy production and consumption to clean sources, including marine energy.

In **chapter two**, we examine the sail-to-steam transition. Steamships were central to a revolution in global trade and migration in the late 1800s and early 1900s. Nearly a hundred years passed between the first voyage of a commercial steamship in 1807 and the completion of the transition from sailboats to steamships. Settling on the paddlewheel as a propulsion system facilitated the earliest commercial steamships while subsequent innovations, particularly screw-driven propulsion and the marinisation of the compound engine, drove increasing diffusion. Steamships gained traction through a series of increasingly large pathway markets while policy support, financing and insurance and complementary infrastructure (among other factors we discuss) were integral to the scaling-up and long-term success of steamships. While wind propulsion went out of fashion with the rise of steamships (which were part of a global transition towards fossil fuel energy sources), new methods of harnessing wind for ocean transport are now burgeoning.

Energy storage, especially batteries, is the theme of **chapter three**. New economic and political attention towards alternative energy paradigms drove a wave of battery innovations during the 1970s. The lithium-ion (Li-ion) battery has become the most prominent of these and now serves as the backbone of the electronics, electric vehicle (EV) and utility storage markets. In the blue economy, energy storage—especially the higher energy density offered by Li-ion batteries—powers ocean observation and research. This observation and research produces fundamental knowledge that enables all blue economy sectors to grow. Furthermore, the battery-driven autonomous underwater vehicle (AUV) market is rapidly growing while the electric boat market is poised to expand in the near future. Time, collaboration, pathway markets and marinisation (adapting technology for use in marine environments) were all central to the development of new battery technologies. Yet batteries still have major limitations for blue economy usage that new innovations—like improved in-situ power generation—could help to overcome.

Chapter four examines the rise of offshore wind. Despite being a relatively new source of energy, offshore wind is now one of the fastest-growing renewable energy sources in the world and will expand massively in terms of value and power generation by 2040. This growth has been fuelled by the advancement of all aspects of offshore wind farms, but especially larger, more advanced turbines and improved foundations. The emergence of new materials led to improved turbines while lessons from the oil and gas industry allowed for better foundations and improved siting further offshore and in deeper waters. While the market size has increased, prices for offshore wind power have rapidly declined and the industry is now creating a large number of jobs and becoming a major player in its own right. Offshore wind is one promising option for green hydrogen production which could enable a near carbon-neutral energy system. Though a number of factors drove the development of the offshore wind industry, marinisation of pre-existing onshore wind technology and specific government policy support are two critical elements of its success. Offshore wind shows us that with proper government and societal incentives and an eye towards leveraging existing technologies, other offshore technologies may have a path towards success.

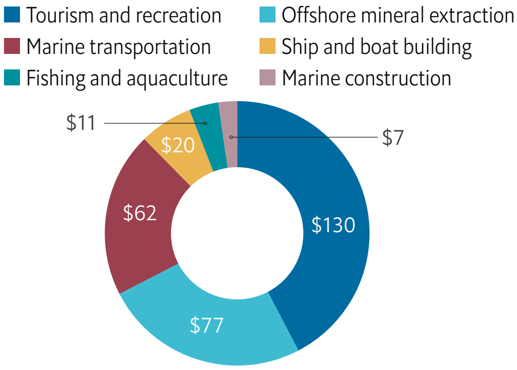
Finally, **chapter five** ties the lessons of the case studies and interviews together to identify resource mobilisation—particularly of time—as key for energy innovation in the blue economy. It then outlines eight elements of the enabling environment that can increase the likelihood of successful innovation and reduce the need for the two key ingredients. The chapter details the state and relevance of each element generally, as well as for marine energy specifically, a set of technologies that hold particular promise for the blue economy. These eight elements, ordered broadly by the technology readiness levels (TRLs) they correspond to, are: 1) marinisation, technology transfer and collaboration; 2) policy support; 3) financing environment; 4) enabling and complementary technologies; 5) public awareness, attitudes, and social acceptance; 6) pathway markets, competition and economies of scale; 7) testing, standards and certification; and 8) complementary infrastructure.

Chapter 1:
Energy consumers in the blue economy

The blue economy covers a wide range of interlinked established and emerging sectors operating in oceans, seas and coasts. Established sectors are those which have made long-term, proven contributions to the economy, such as the shipping industry, while emerging sectors are still nascent but showing potential for future growth.

The blue economy is an important part of the US economy. In 2017 it employed an estimated 3.32m people and contributed US$307bn to the national gross domestic product (GDP). Over the past 15 years, the blue economy has experienced strong growth. From 2005 to 2017 the blue economy grew by 3% per year—more than one-and-a-half times faster than the US economy as a whole.

The blue economy's contribution to US GDP in 2017
($US bn)

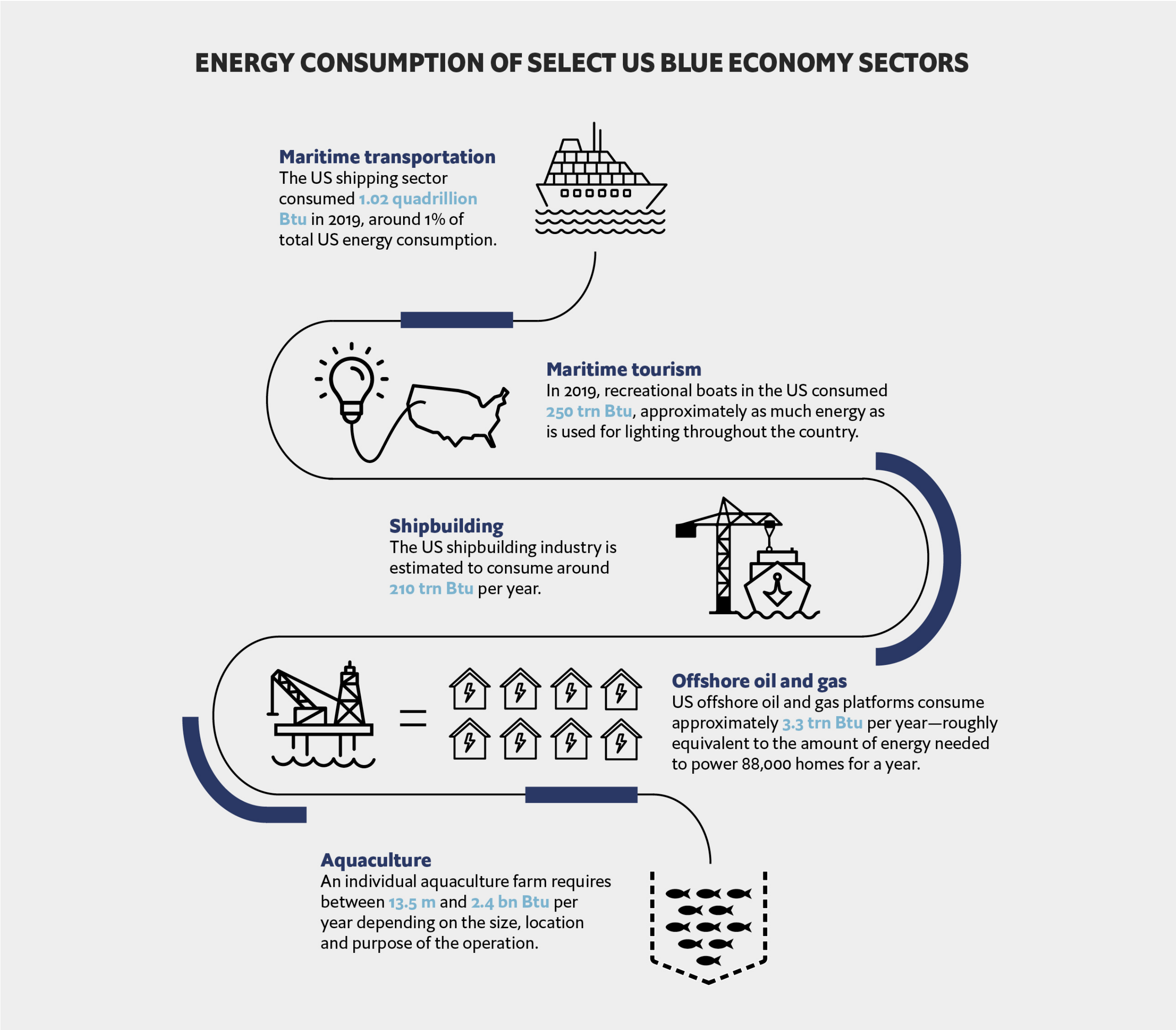


Source: NOAA.

Globally, established sectors—fishing and aquaculture, marine construction, tourism and recreation, marine transportation, ship and boat building and offshore mineral extraction—are the main source of employment and economic activity within the blue economy. In the US, coastal tourism is the largest ocean economy sector both in terms of employment and contribution to the economy, followed by maritime transport, offshore oil and gas and ship and boat building. Fishing and aquaculture and marine construction are relatively smaller industries compared with other established sectors. Still, they jointly employ around 136,000 people.

The emerging sectors of the blue economy include industries such as marine energy, ocean observation and navigation, marine pharmaceuticals, ocean cleanup and marine conservation, marine mining, desalination and submarine cables. Although the majority of these industries in the US are still fledgling, a few are rapidly transforming into established industries. Marine mining, for instance, grew from US$780m in 2014 to an almost US$1bn industry in 2018 while the marine pharmaceutical industry experienced an average annual growth of 6% during the same time period, crossing the US$1bn mark in 2018.

Among the emerging sectors of the blue economy, marine energy serves both terrestrial as well as ocean industries. Marine energy refers to the energy harnessed from oceans and seas, including wave, tidal stream, tidal range, ocean thermal, ocean current, run-of-river and salinity. The harnessed energy can be converted into electricity and other forms of usable energy to power cities, manufacturing industries, electric vessels, ocean observation instruments,



offshore aquaculture farms and autonomous underwater vehicles (AUVs), among many others. The sector is still nascent but holds enormous potential to meet growing energy demand. By the end of 2018 there was just 529 MW of total installed marine energy capacity globally.

However, the output capacity of marine energy could potentially reach 748 GW by 2050.

Insatiable demand for energy

Energy demand is intertwined with economic growth. Similar to terrestrial sectors, blue economy industries need reliable energy sources to power growth and enhance productivity. Currently, fossil fuels are the main source of energy for ocean economy sectors. However, large energy consumers, such as the shipping and offshore oil and gas industries, are actively exploring options to increase the share of renewables in their energy mix, predominantly in response to mounting public and policy pressure to cut carbon emissions and other greenhouse gasses. Some blue economy industries that are moving further offshore, such as aquaculture, or those that operate in the midst of the ocean, such as marine mining and ocean observation and navigation, are constantly challenged by a lack of regular and reliable energy sources. Marine energy is well poised to meet the energy demands of the blue economy industries. In this section, we briefly describe the current and future energy demands of select blue economy sectors and explore the potential of marine energy to meet their energy needs.

Maritime transportation is by far the largest consumer of energy in the blue economy. The US shipping sector consumed 1.02 quadrillion Btu in 2019, which is around 1% of total US energy consumption. As per US Energy Information Administration (EIA) forecasts, the overall energy consumption of the shipping industry will slightly decline over the next five years, reaching 0.96 quadrillion Btu by 2025. The shipping industry—which accounts for 2.5% of global carbon dioxide (CO2) emissions—is under increasing pressure to decrease its carbon footprint as well as other air pollutants such as nitrogen oxides (NOx) and sulfur oxides (SOx). The United Nations International Maritime Organisation (IMO) has set aggressive decarbonisation targets for the shipping sector. It aims to reduce CO2 emission by at least 40% by 2030 and 70% by 2050. In addition, the IMO is pushing the sector to reduce air pollutants. Earlier this year it passed a new regulation limiting the sulfur content of fuel to a maximum of 0.5%. Previously, ships could use fuel with up to 3.5% sulfur content.

The push towards cleaner energy in the shipping industry combined with its increasing energy needs presents a great opportunity to further explore marine energy sources. New visions of a global hydrogen economy with in-situ fuel generation and refuelling for marine transportation offer one way in which marine energy and offshore wind could help bring about the long-term decarbonisation of the shipping industry.

Marine tourism and recreation is the largest ocean-based industry in terms of GDP contribution and employment in the US. It is also a major consumer of energy. According to the EIA, recreational boats consumed 250trn Btu in 2019, which is approximately as much energy as is used for lighting throughout the entire country. Maritime tourism had an average annual growth rate of 3% over the past five years and was on track to continue its expansion. However the covid-19 pandemic has decimated tourism in general, and maritime tourism in particular, across the globe. Despite the sharp decline in 2020, maritime tourism is expected to pick up growth once the pandemic has subsided. As with marine transportation, marine energy has the potential to contribute to maritime tourism's energy demand in the long term. It could be particularly beneficial to islands that are already popular with coastal and maritime tourists. For example, the Caribbean Islands of Bermuda, Aruba and Curacao have established plans to harness wave energy to meet local energy demands. Ocean thermal energy conversion (OTEC), which relies on the temperature difference between the ocean's surface and its depths to generate power, offers great promise for powering and cooling alongside other complementary benefits (like fresh water

> **"The exclusive economic zone and continental shelf under the protection, care and ownership of the Small Island Developing States (SIDS) is estimated to be sixteen times the size of the EU. The ocean is our biggest resource. When we talk about the blue economy, we see ocean energy as the foundation for the SIDS. We like ocean thermal energy conversion (OTEC) technology for the multiplicity of products it provides that reduce the need for or substitute for imports, and as a consistent source of fresh water."**
>
> Al Binger, Small Island Developing States Sustainable Energy and Climate Resilience Organisation (SIDS DOCK)

and nutrient-rich cool water for aquaculture) in low-latitude locations where most of the Small Island Developing States (SIDS) are located.

The US ship and boat building sector includes the construction, maintenance and repair of ships, boats, ferries and vessels. Although relatively small compared with some countries in Asia (eg China, South Korea and Japan) and Europe (eg Germany, Poland and Romania), it still employs 159,000[i] people and generates US$20bn in goods and services. The Economist Intelligence Unit estimates annual energy consumption of the shipbuilding industry to be around 210trn Btu a year.[ii] Large US shipyards are concentrated in a few locations, mainly in Virginia, Washington State, and the gulf of Mexico, while smaller establishments are dispersed around the country. Almost all shipbuilding companies are connected to the grid and have access to terrestrial sources of energy. Until grid-connected marine energy systems become commonplace, the use of marine energy to power the shipbuilding sector is likely to remain limited.

The offshore oil and gas industry is not only a major producer but also a massive consumer of energy. In 2019, the US offshore oil industry extracted 1,897 thousand barrels of crude oil per day. However, oil companies use around 5% of oil and gas wellhead production to power offshore platforms. The Economist Intelligence Unit estimates that the US offshore oil platforms consume around 3.3trn Btu per year—roughly equivalent to the amount of energy needed to power 88,000 homes annually. Similar to maritime tourism, the oil industry has also been negatively impacted by covid-19. Offshore crude oil production declined from 1.9m barrels a day in January 2020 to 1.6m a day in May. Still, offshore oil production is forecast to increase as oil demand recovers from the coronavirus crisis.

As pressure to act on climate change builds, oil and gas companies are increasingly being compelled to decarbonise their operations by replacing onboard fossil-fuel burning electrical generating systems with zero-emission alternatives. One option is to transport shore-based generated energy to offshore oil and gas platforms through subsea cables. This solution, however, requires heavy initial investment. Another option is to use renewable energy to power offshore rigs. Due to co-location advantages, marine energy is particularly well suited to meet the energy demands of offshore oil exploration and production activities.

There are early indications that some actors in the industry are exploring options to

[i] 2017 figures
[ii] The estimation has been calculated based on the relative size of shipbuilding to the broader manufacturing sector as EIA does not provide disaggregated energy consumption data for the ship and boat building sector.

deprioritize the extraction of fossil fuels to focus on renewables. Equinor and Shell, for example, are expanding their portfolio of offshore wind. BP has committed to offsetting carbon emissions to net zero by 2050, and is ramping up investments in offshore wind and other clean energy technologies as well. Oil and gas companies can leverage their offshore supply chains and ocean engineering skills to develop technologies for harnessing marine energy and reaching the zero-emission target.

Fishing and aquaculture is a growing industry in the US. In 2018 the value of domestic production of processed fishery products was US$11.6bn. According to the United Nations Food and Agriculture Organisation, half of the world's seafood comes from aquaculture. In the US, however, aquaculture accounts for only 21% of the value of domestic fisheries landings. Within the aquaculture industry, the share of marine aquaculture (cultivation of finfish, shellfish, crustaceans and seaweeds) is particularly limited. Out of total US aquaculture production, marine products account for only 13% by volume and 26% by value. As a result marine species, such as shrimp and salmon, are among the main import items in the US. In 2018, imported shrimp was valued at US$6.2bn, roughly 28% of the value of total seafood imports.

While marine aquaculture has great growth potential in the US, its development has been hampered by a lack of clear regulatory policies around permitting processes. Except for the Catalina Sea Ranch—located in federal waters six miles off the coast of Huntington Beach in California [iii] —all aquaculture farms are located near shore in state waters. However, regulations may soon change in favour of establishing offshore mariculture farms. On March 7th 2020, US President Donald Trump issued an executive order allowing commercial offshore marine aquaculture in federal waters. Although environmental advocacy groups have challenged the executive order in the courts, the US government is determined to remove regulatory barriers to boost the offshore aquaculture industry.

Aquaculture farms require energy to freeze harvested products and to power circulation

> **"We need to grow ocean observing by thousands of percent to understand the ocean better and to give decision-makers better understanding of climate change and sea level rise."**
>
> Chris Meinig, NOAA

[iii] The company filed for bankruptcy in February, 2020.

pumps, feeding systems and monitoring equipment. Larger farms also need energy for crew support such as lighting, heating and cooking. The energy needs of an individual farm can range from 13.5m to 2.4bn Btu per year depending on size, location and purpose of operation. Marine energy is well suited to fulfil the energy demands of the offshore mariculture industry given its notable advantage of co-location.

Ocean observation and navigation services enhance our understanding of the ocean. Various instruments are used for data collection, such as buoys, surface and subsurface autonomous vehicles and floats. Scientific researchers, the US Department of Defense and ocean economy industries (such as commercial shipping, fisheries and aquaculture, oil and gas production and ports) are the main users of the data collected through ocean observations.

Ocean observation and research serve as an enabler for the entire blue economy. US research organisations alone spent around US$2.9bn on ocean research in 2018. The findings of the National Oceanic and Atmospheric Administration (NOAA) 2016 Ocean Enterprise Survey show that providers of ocean observing infrastructure and intermediaries that use ocean data make approximately US$7bn in annual revenue. While there is a strong demand for ocean data, a lack of reliable energy sources to power equipment is still a challenge. A recent survey of ocean observation experts using data for a range of scientific, commercial and security purposes shows that the majority of respondents consider power and batteries as a limitation to current ocean observing activities. For example, operators of buoy networks mentioned that access to additional energy would enable continuous operation throughout the year, especially in winter months and high latitudes. According to many industry observers, marine energy is well positioned to provide regular and reliable power to ocean observation and navigation systems.

Chapter 2: The sail-to-steam transition and lessons for energy innovation

The sail-to-steam transition transformed pre-first world war global maritime transportation

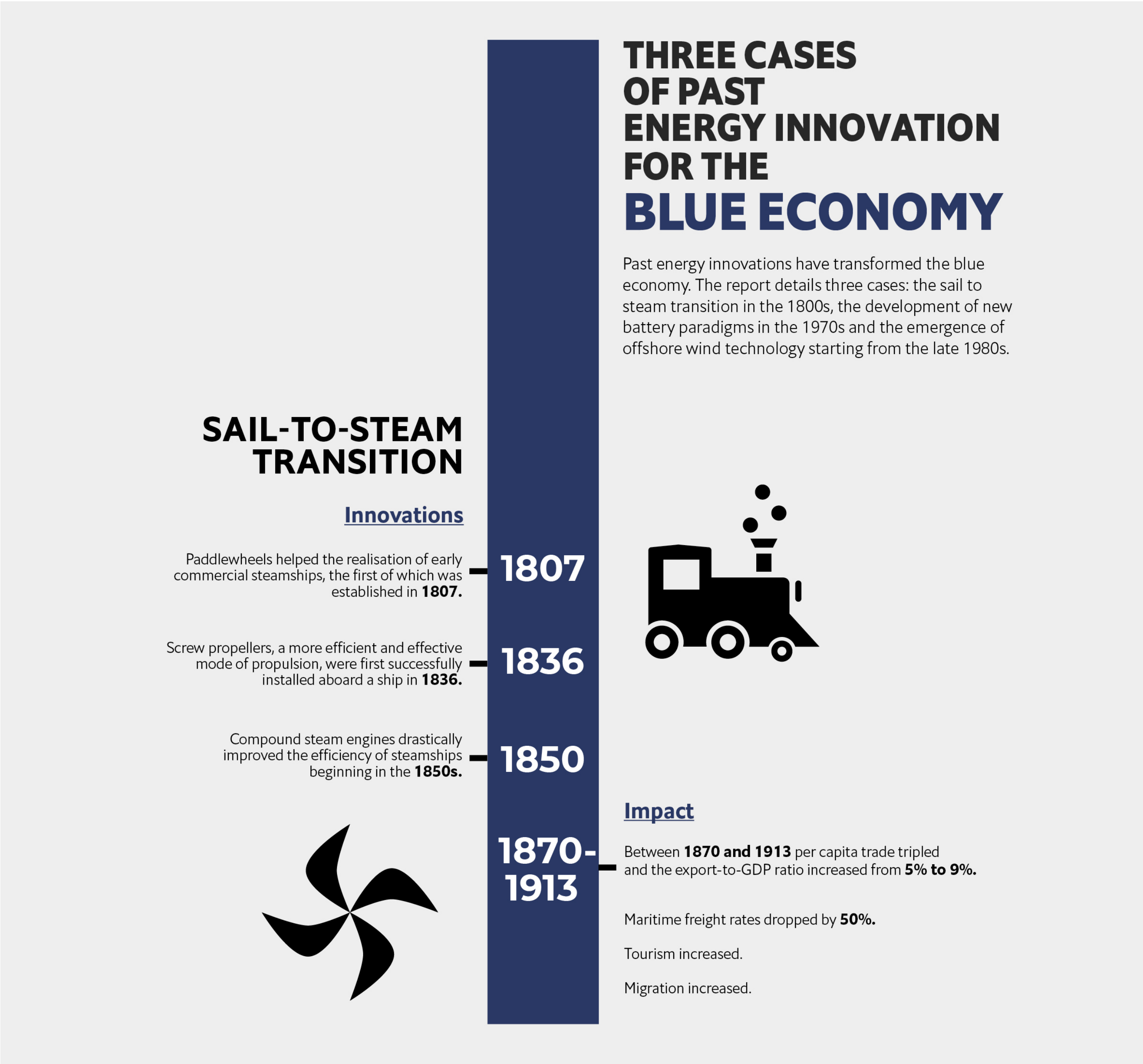
Among past energy innovations within the ocean economy, the transition from sail to steam looms large. New innovations of the mid-1800s facilitated a boom in global interconnectivity and trade, including the railroad and the telegraph. The steamship in particular was pivotal to the rapid rise in global transportation. Between 1870 and 1913, global trade increased by 400%. Migration out of Europe averaged around 300,000 people per year up until the 1870s, but, bound by steamships, around 1.4m migrants left Europe each year before the first world war. What did it take for the steamship to overtake the sailing vessel, and what lessons about energy innovation can the transition from sail to steam teach us about energy innovation for the blue economy?

Technical advances drove efficiencies, opening the world for steamships

It took nearly a century of progressive improvements, and the major advancements of the screw propeller and the compound engine, to drive the steamship from niche markets to become the primary mode of global maritime transportation. The earliest versions of the modern steam engine itself were developed at the end of the 1600s to assist with the draining of mines. British entrepreneurs continued to enhance steam engines throughout the 18th century and quickly saw the potential value of these engines for powering ships.

The first experiments using steam to power ships occurred no later than 1705 when the French inventor Denis Papin created an early paddle boat experiment. Entrepreneurs worked to establish a reliable mode of propulsion and demonstrate the technical and commercial viability of putting a steam engine on a ship by experimenting with early jet propulsion, paddle arrangements and complex rowing mechanisms in the late 1700s. Thereafter, attempts to develop and commercialise steamships took place periodically in Europe, the UK and the US throughout the early 1800s. The paddlewheel, which had earlier been dismissed by notable inventors like Thomas Jefferson, eventually became the propulsion of choice for early steamships.

Following the first commercialisation of steamships in 1807, progressive improvements—for instance in ship design, the incorporation of new materials (iron, then steel) and anti-biofouling paints—contributed to the advancement of steamships. However issues with inefficiency persisted, particularly relating to paddlewheels and existing steam engine capabilities. So did difficulties with fouling, which was more of an issue for steamships because they were much more likely to use iron hulls than sailboats in order to prevent over-vibration. These limitations hampered the competitiveness of steamships for longer shipping routes.[1] The more inefficient the ship, the more coal it had to carry, leaving less room for cargo. It took a series of step changes in steamship technology before they began supplanting sailing vessels as the prominent mode of maritime transportation from the 1870s onward.[2]

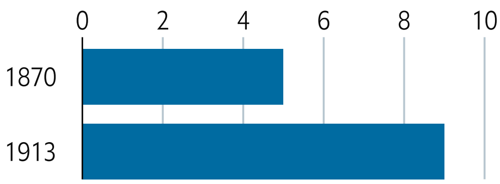


One vital innovation that allowed steamships to overtake sail boats was the development of screw propellers. Screw propellers, which were much more effective than paddlewheels, were first successfully installed aboard a ship in 1836. Another breakthrough was the successful marinisation of compound steam engines—which use steam twice—in the 1850s and later the triple-expansion engine in 1884 which drastically increased power output. Before the compound engine, steamships used 30 to 40 imperial tons of coal per day to carry 1,400 tons of cargo for a long trip. After the compound engine, they could use 14 imperial tons of coal per day to carry 2,000 tons of cargo. Steamships also offered much larger average tonnage than sail boats after the mid-19th century. Size was roughly equivalent during the 1830s and 1840s, but the average steamship was two times larger than the average sailing ship by the 1870s.

Paired with advances in power efficiency, the size of steamships drove economies of scale in shipping that reduced shipping prices and allowed steam to overtake sail.

Massive global expansion in trade during the late 1800s

(global export-to-GDP ratio; %)



Source: Pascali (2017).

The long-term impacts of the sail-to-steam transition

The steamship facilitated a sea change in global interconnectedness. Between 1870 and 1913—until the start of the first world war—there was a revolution in global trade. Per capita trade tripled. In just over four decades, the global export-to-GDP ratio jumped from 5% to 9%, meaning that not only did the volume of global trade increase rapidly, but trade also became a much more important component of the global economy. Over the same period there was a rise in tourism from countries like the US, due in large part to steamship development. Maritime freight rates dropped by 50% and global prices converged, particularly between British and colonial markets.[3] The difference in price for rice between London and Rangoon (Yangon) declined from 93% to 26% during this period, for instance.

As the transition from wind- to steam-based transportation was underway, sail remained the predominant mode of transit along many routes and the steamship and sailing ship overlapped and competed for markets. During periods of economic depression when global trade contracted, construction and operation of sailing ships (cheaper technology) gained an edge while the opposite was true during boom times.[4] Sailing vessels also benefited from technological advances and policy changes during the period of transition.[5] Fast and mobile American clippers were enlarged and improved throughout the early and mid-1800s. A series of policy changes between 1836 and 1855 in the UK changed tax incentives on cargo ships and enabled innovation in sailing ship design. Sailing ships were also able to benefit from iron hulls, refined throughout the mid-1800s, which could be lighter and stronger than wood, though most sailing vessels were still built with wood during that period. Steamship tugs even promoted larger and more efficient sailing vessels as they could be towed in and out of harbour. Steamship and sailboat development took place concurrently, but once steam-based global transport became predominant, demand for fuel created new markets for sailing vessels to serve the international coal transportation network—itself a new business.[6]

By the start of the first world war, steamships were undeniably the preferred mode of global transportation. The extent to which the steamship drove the rise in global shipping is a matter of ongoing debate.[7] The rise of steamships may be a result of the market imperative of economies worldwide growing and global income convergence—meaning more people in more places having money to pay for more things. The extent to which the expansion of global trade during this time period was a global force for poverty reduction is also uncertain, though evidence suggests that gains were context-dependent. What is unassailable is that the steamship rose to meet the needs of the time. The energy transition from wind to steam facilitated a new era of interconnected global trade and brought the world closer together.

An enabling environment fostered long-term steamship development

It took trial and error, international collaboration and a number of failed attempts to demonstrate the worth of steamships before they came to market. The first UK patent for a steamboat came in 1736 and was assigned to a tug that could not operate in storms or large surf. Its inventor was ridiculed and was never able to commercialise the idea. Attempts to determine the best method of propulsion and commercialise steamships occurred in fits and starts. There were demonstrations in both the UK and the US, even one involving passenger transport between Pennsylvania and New Jersey in 1787.[8] These experiments and cross-Atlantic collaboration between Robert Fulton in the US and Henry Bell in the UK eventually led to the first commercially successful steamships. Fulton established the first on the Hudson river in 1807 for passenger service, with Bell following suit in the UK in 1812. Even in the case of steamships which seem in hindsight to be a clear example of a superior technology overtaking an inferior one, it took decades before technical issues could be solved and the commercial value of the early systems demonstrated.

Before they transformed the world, steamships gained traction through a series of pathway markets, particularly on canals and as tugboats on rivers and in harbours followed by mail service and short distance passenger transport.[9] In these pathway markets, steamships took hold rapidly between 1815 and 1840 due to their speed and regularity. In 1815, there were 15 steam vessels belonging to ports of the UK. Fifteen years later there were 342. The first regular service across the English channel was established in 1821 and by the mid-1830s "services extended to all navigable rivers, most coastal trades and further short-sea routes" including cities across Europe.[10] Steamships were operating on routes in the Mediterranean and on to India[11] and were essential for pre-rail mass transit in the UK. Gravesend, on the Thames, saw an increase from 292,000 steamship travellers in 1830-1831 to more than 1.1m by 1841-1842. While total tonnage of constructed steamships in the UK lagged far behind sailboats up to the mid-1800s,[12] the number of steamships in use rapidly increased.

In these niche markets, steamships were faster and more regular than existing transportation methods as they did not have to depend on wind conditions to dictate travel patterns.[13] With energy innovations, new technologies are almost always imperfect and expensive but able to deliver performance improvements in markets where the high cost is worth it. Technological refinement in these early markets eventually leads to industrialisation, mass production and standardisation that drive costs down.[14] Especially prior to 1830, steam engines in general were not very cost effective. Early steam engines typically cost over US$10,000/kW in modern terms.[15] Early adopters were looking at the future potential rather than just short-term energy cost savings. Each early use case spurred further improvements to ship and component design, thus widening the range of purposes for which steamships were used.

Before steamships supplanted sailing vessels for trade, the transport of people served as the major intermediary market. On average steamships were twice as fast to most destinations. The steamship reduced the time from Europe to America from five or six weeks down to less than two. They were also more comfortable, largely due to their bigger size which offered roomier and more pleasant lodgings compared with sailing vessels. While the market for passenger transport began with upper-income passengers, by the end of the 1960s steamships dominated for lower-income passengers as well.[16] Steamships then took over short-haul and coastal routes before they became competitive with sailing ships on long-haul routes: cost was generally the primary concern as steamships had to carry too much fuel relative to storage capacity. It wasn't until after 1880 that steamships became the dominant mover of long-haul goods thanks to improved efficiency and larger ship sizes.[17] In Norway, for instance, steamships accounted for 10-20% of investment into shipping in 1870, 40-50% by 1880 and then 80-90% from 1895 onwards.

Throughout this time there was stiff competition between various steamship operators and entrepreneurs as well as sailboat builders. Even once the market viability of steamships had been proven, progress was not a simple march forward. For companies applying new technologies that would later become standard, like screw propellers, early innovators still often failed in their ventures.[18] Entrepreneurs failed both when they entered markets too early before there was any demand and when they entered markets too late without a clear strategy for competing against incumbent firms. There were at least forty-three steamship companies advertising in the UK between 1844 and 1845, a large proportion of which went under. Competition advanced steamship technology and drove new markets, though the strong shipping cartels that later formed had the opposite effect.

Policy support was critical for steamship development—though changes during this era not only helped steamship but also sailing ships, the competing technology.[19] The UK took the lead on policy initiatives though they were put in place after the steamship had already demonstrated value in a number of markets. These initiatives included mail subsidies introduced in 1838 to provide support for steamships used for postal operations. The US followed in the late 1840s. The Pacific Mail Steamship company, for example, transported mail along the West Coast of the US down to the isthmus of Panama, financed by New York-based investors with government subsidies and a government contract.[20] Other nations later utilised active policy support measures as well, such as China in the 1870s.[21]

In addition to policy support, investment and insurance were critical to steamship development. The early steamship industry in the UK took advantage of a new insurance and investment environment around shipbuilding and shipping that had been developed in the late 1700s and made it easier to build private enterprises within shipping.[22] Given their potential dangers, the establishment of legal and normative standards for steam boilers that raised safety and lowered financial risk was also critical to the industry's success. Throughout the 1800s policymakers, academic groups and insurers worked to ensure these were put in place. The development of screw-propulsion was significant as it lowered insurance premiums for steamships in the UK in the 1850s. Then, in 1863 the insurance premium on iron ships—which had been significantly higher than premiums on wooden ships—was also lowered, further building steam's advantage against sail.

Complementary infrastructure developments and innovations—often requiring massive investment—such as improved coaling networks and the construction of the Suez Canal, helped to facilitate the transition from pathway markets in local transport and mail through to transporting people globally and finally to transporting goods globally.[23] These aspects of the enabling environment paired with ongoing technology improvements eventually led to virtuous cycles for steamships. Infrastructure development, investment and coal mining all drove steamship development, which in turn created more demand for infrastructure, investment and coal.[24]

A new era brings wind energy back to the fore, a renewed understanding of the cost of coal and an eye towards new energy innovations for the blue economy

While the era of the steamship as the dominant force in global shipping is long past, evidence of this period remains. For one, there is the legacy of the shift to fossil fuels as the world's primary energy source as well as the rise in burning fuel to power ocean transportation and the emissions that came with that rise.[25] There is physical evidence, too. Clinker, a residue of burnt coal that was typically dumped over steamships sides, now comprises more than 50% of the hard material sitting on parts of the ocean floor. It is yet another reminder that our choices around energy use have long term-implications whether we are aware of them at the outset or not.

> **"Shipowners are definitely looking for where savings can be made, and there's increasing interest in green performance metrics. There are some interesting and promising projects with wind rotors being put on ships which can lead to important energy savings, though I don't see the total energy needs of these ships being replaced by wind energy in the immediate future."**
>
> Roel Hoenders, IMO

As one of the subsequent cases discusses, wind energy is making a comeback off coasts worldwide. Though this is primarily in the form of turbines rather than sails, there is once again a growing interest in harnessing wind for global shipping.[26] As we consider future energy innovations within the blue economy—including the potential of marine energy, the focus of this report—the lessons of the sail-to-steam transition serve as a useful reference. First, the case serves as a reminder that energy innovations can have true global impact. Despite the fact that it began 200 years ago this case also demonstrates some significant elements of energy innovation for the blue economy: new technology meeting the needs of markets; pathway markets and competition as a gateway to scale; the importance of marinisation; policy incentives as a central support system and driver of innovation; the long timeline of technology maturation; and the important role of investment (capital and financial) and insurance for undergirding and enabling innovation.

Chapter 3:
Energy storage and the blue economy

Energy storage innovations are changing the world and enabling us to gain a deeper understanding of our oceans

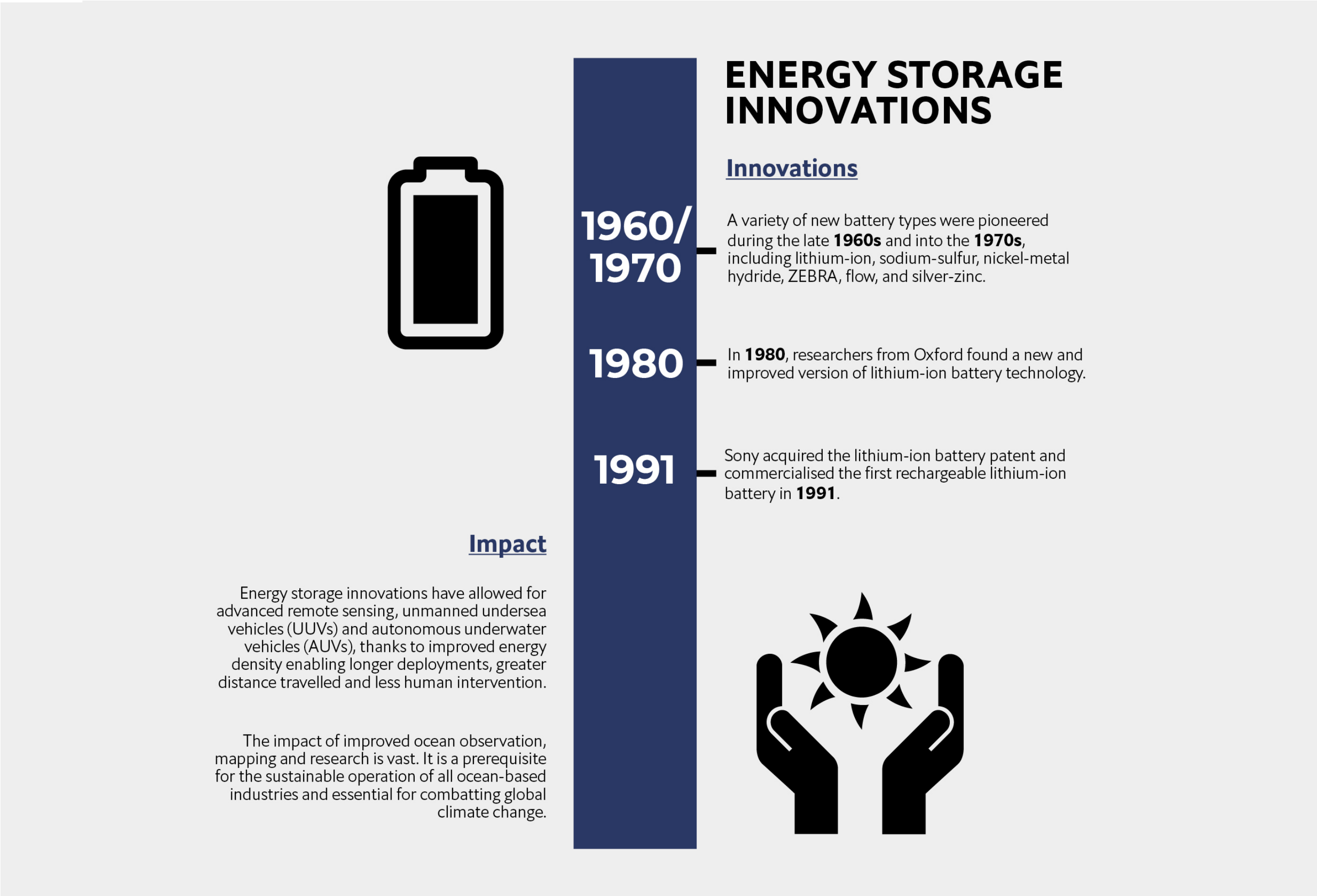
Since the 1970s the development of high-quality rechargeable batteries has expanded the realm of energy possibility. The lithium-ion (Li-ion) battery in particular has been hailed as the most disruptive technology in human history.[27] Between electronics devices, energy storage and transportation, the Li-ion battery has shaped countless markets. Thanks to their high energy density and reliability, Li-ion batteries have become increasingly ubiquitous.[28] Sales of electric cars, which rely on these batteries, jumped 40% year on year between 2018 and 2019, up to 2.1m.[29] Global energy storage is expected to triple by 2030 and, according to market research analysis, energy storage could create well over to 100,000 jobs in the US in the coming years.[30] The 2019 value of the energy storage market was already US$59bn and could increase nearly tenfold by 2035 even with the precipitous drop in battery storage costs.[31]

These past breakthroughs in energy storage have also transformed the blue economy by enabling a new era of remotely operated and autonomous sensors and vehicles that are propelling us towards a future where we can better understand and utilise our oceans.[32] Advances made in energy storage to date hold great promise for the expansion of the blue economy, but their limitations leave plenty of room for new energy innovations to pave the way forward.

Innovations in energy storage were driven by the oil crisis, but commercialisation took time

There are a variety of ways to store energy ranging from pumping water uphill and compressed air to flywheels and fuel cells. Chemical batteries, though, stand out among the others for their impact on the blue economy. Beginning in the late 1960s and continuing throughout the 1970, there was a surge of research and interest in rechargeable batteries, including a series of breakthroughs that permanently altered the energy storage landscape.

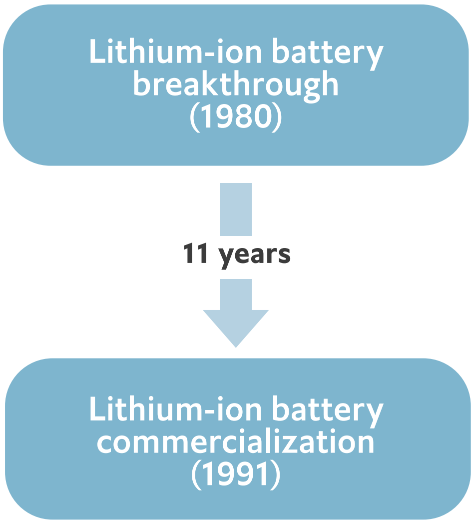
Batteries create electrical energy through stored chemical energy. There are both primary cells (non-rechargeable batteries) and secondary batteries (rechargeable). As with the sail-to-steam transition, the history of battery development spans centuries. The first primitive modern primary battery was developed in 1800 by the Italian physicist Alessandro Volta, with ongoing research, improvements and inventions (like the lead-acid rechargeable batteries found in most modern cars) emerging throughout the mid-20th century.[33]



The Ford Motor Company's early research on sodium-sulfur (NA-s) batteries in 1967 was the first step in a "revolution in solid-state electrochemistry" that took off during the oil crisis of the 1970s. During this time, researchers began to understand the value of intercalation (moving ions into molecules without changing the structure) for energy storage. Leveraging intercalation is one of the major breakthroughs underpinning the development of modern rechargeable batteries, including the Li-ion battery and the nickel-metal hydride battery.[34]

Engineers at multinational oil and gas firm Exxon developed the earliest versions of the Li-ion battery in the 1970s, and in 1980 researchers from Oxford University found a new and improved version of the technology (though other scientists were independently researching similar ideas at the same time).[35]

Hoping to get the batteries to market, John B Goodenough, the lead researcher, signed royalty rights to the UK's Atomic Energy Research Establishment.[36] After internal development, Sony then acquired access to the patent ten years later and in 1991 released the first commercial rechargeable Li-ion battery.[37] The batteries were critical for the improvement of Sony's hand-held video cameras. Soon after, they became vital components of a variety of small electronics at Sony and other firms. Li-ion batteries have now become the standard for a range of products, such as electric vehicles, and the most important battery type globally in terms of market size. While the standard form of Li-ion batteries more than tripled in energy density between 1991 and 2012 and ongoing progress continues—progress that has roughly quartered the cost of battery storage since 2013, no major changes have been made to the basic reaction type of commercialised forms of Li-ion batteries in recent years.



Innovation in other battery categories also took place during this period but did not result in successful widespread commercialisation until much later and comprise much smaller segments of the overall battery market. For example, sodium batteries—which include both the sodium-sulfur batteries pioneered by Ford in the 1960s and the ZEBRA battery (sodium-nickel chloride) developed in its earliest form in the late 1970s—have seen ongoing development and periodic attempts at commercialisation. While these batteries, including Na-S batteries in Japan, have penetrated some markets, limitations due to efficiency and high operating temperatures still remain. Research is still ongoing to overcome these barriers to greater commercial success. In the same vein, flow batteries saw system development under the US National Aeronautics and Space Agency (NASA) during the 1970s and there have been periodic developments since. As flow batteries are not suitable for most mobile applications, commercialisation efforts for utility-scale storage started in around 2001 but costs remain higher than Li-ion batteries.

Batteries have driven the AUV and UVV markets alongside critical advances in ocean observation

Advances in energy storage—especially Li-ion batteries—have been among the most important energy innovations within the blue economy and have contributed significantly to the field of ocean observing. Li-ion batteries, for instance, have a number of advantages compared with other batteries, such as high energy densities, high voltage and no detrimental impacts on storage from partial charge or discharge. Without advances in energy storage stemming from the innovations of the 1970s, we would not have seen the development of advanced remote sensing, unmanned undersea vehicles (UUVs) and autonomous underwater vehicles (AUVs), for instance.[38] Improved energy density enables longer deployments, greater distance travelled and less human intervention, all of which drastically improve capabilities.

Though the markets that rely heavily on energy storage may not be among the largest in the global ocean economy (like tourism or shipping),[39] research and education together formed a US$4.2bn market in the US in 2018. The US$190bn market for marine defence and public administration is already being reshaped by improved energy storage as the US Navy develops more UUVs.[40] The AUV market is expected to grow at a faster rate than the major global ocean economy sectors and is anticipated to cross the US$1.5bn threshold by 2025. Rising demand for Li-ion battery-powered AUVs is driven in part by the oil and gas sector which is increasingly reliant on these devices for maintenance and observation.[41]

While the economic impact of improved energy storage on the ocean economy is hard to precisely quantify, there is no doubt that its facilitation of better ocean observation, mapping and research has been, and will continue to be, invaluable. As the OECD notes, fundamental scientific understanding of the ocean "is a vital prerequisite for the sustainable operation of all ocean-based industries."[42] At the present, though, most of the ocean remains "unmapped, unobserved, and unexplored"[43] and we have higher-resolution maps of Venus and Mars than we do of the ocean floor.[44] Moreover, developing our understanding of the ocean is essential for countering global climate change: the ocean is responsible for 31% of global CO2 absorption and has so far absorbed 90% of the excess heat in the climate system. Thus the monitoring, observation and research enabled by energy storage are critical enabling factors for all blue economy markets.

There are also future impacts on the blue economy thanks to improved batteries. One estimate places the electric boat market at more than US$20bn by 2027. Ferry electrification is one burgeoning application. Washington state, for instance, is implementing a plan to fully hybridise its ferry fleet by 2040 with the first conversions starting in the next few years. More locations, both within the US and beyond, are likely to follow.[45] Batteries may also play a role in the reduction of diesel consumption within the aquaculture market.

Other kinds of energy storage that could impact the blue economy remain in development. Fuel cells have seen sustained application and research for military and space applications, but while efforts have been made towards their commercialisation this is yet to bear fruit beyond niche markets.[46]

As the International Energy Agency (IEA) notes, hydrogen is "light, storable, energy-dense, and produces no direct emissions of pollutants or greenhouse gases" yet remains almost absent in many key sectors of the blue economy, such as transport and power generation. While there have been systems that have leveraged fuel cells, mostly for demonstration,[47] fuel cells and the hydrogen economy remain a vision of the future—as hydrogen has been for some time. However this vision may be approaching rapidly as innovative groups work to speed up the arrival of new, cleaner energy for the blue economy, like in-situ fuel production systems.[48]

What enabled this innovation?

First, as noted above, innovations take time and collaborative effort. The romantic notion of the overnight, world-changing stroke of genius holds great appeal. Yet even in the case of Li-ion batteries where there was a clear inflection point in 1980, the key innovation was built upon more than a decade of prior research. Just as importantly, it took another 11 years before a successful product based on that key insight came to market. Similarly, the sodium-sulfur battery took nearly 40 years of development before commercialisation.[49] Transformational energy innovations require time, accumulated knowledge, research and trials. This may be an unwelcome lesson in an era of global climate change, but it is also a reminder that if we foster global research and innovation networks and actively seek to pair new innovations with markets, accelerated innovation is possible.

In the case of energy storage innovations, these networks involved research contributions from the public and private sectors and academia. NASA, for instance, developed the silver-zinc batteries often historically used in marine applications during the 1960s and 1970s.[50] US government investment in energy storage solutions spiked during the 1970s, providing the means for essential research and development (R&D) programmes and driving subsequent battery advances.[51] Private sector funding and engagement was also essential. One of the earliest innovations in rechargeable batteries came from the Ford motor company.[52] Li-ion battery development required insights from researchers at Exxon, Oxford University and Sony. The takeaway is not simply that both the public and private sectors are important drivers of basic research, but also that when incentives are aligned the private sector can work with the public sector to help drive new innovations. On the flip side, when incentives are unaligned, innovation slows. When the external economic and political incentives changed for Exxon (as well as internal priorities), for example—reducing the firm's urgency to investigate non-hydrocarbon energy systems—their early, pioneering work on rechargeable batteries and hybrid-electric vehicles was halted.[53]

As with the other innovations covered in these cases, pathway markets were therefore key to getting new innovations to market. For the Li-ion battery, the initial pathway markets turned out to be hand-held electronic devices rather than electric vehicles and hybrids as Exxon had predicted. Sony may have seen the general-purpose use of the Li-ion battery, but the company also had a primary interest in addressing a problem with the energy storage needs of its hand-held video cameras. Innovations that can solve specific problems open avenues for future development and diffusion.

Developing innovations within pathway markets is often non-linear and filled with both research and commercial dead ends. The initial anticipated market for the sodium-sulfur battery was also electric vehicles, but utility-scale storage turned out to be the first market for this energy storage type. Sodium-sulfur batteries and ZEBRA batteries saw the thrust of development shift over decades between academic research groups, motor vehicle companies, energy companies and governments across North America, Europe, Japan and Africa.[54] Along this irregular journey came a series of failed attempts to commercialise these batteries at various stages of this process.

Finally, marinisation has been critical to both oceanographic research and indeed the sustainment of the blue economy as a whole.[55] Being able to leverage and adapt terrestrial energy storage innovations, generally designed with the larger terrestrial markets in mind, has enabled the development of remote sensing, UUVs and AUVs, for instance. Active engagement with non-maritime researchers and terrestrial industries can speed up technology transfer to uses that serve the blue economy.

> **"In transforming ocean science and ocean exploration, innovations in battery technologies have had a significant impact. Batteries today are smaller and more capable, but even with these advancements, there are limitations."**
>
> Alan Leonardi, NOAA

Energy storage systems have limitations—marine energy hopes to fill in the gaps

Unfortunately, today's energy storage options—while being deployed rapidly—will neither be enough to meet the needs of a modern, fully clean grid nor the needs of the global ocean observation and research community. For the blue economy, batteries are by definition a temporary energy source: the prospect of running out of battery in the middle of the ocean understandably holds little appeal. Li-ion batteries also carry safety risks that necessitate ongoing care and inspection. The solution will not be to eliminate batteries outright from systems. Rather, modern energy storage technologies coupled with consistent onboard generation could open up completely new opportunities.

Energy innovations that address existing problems would have a tremendous impact both within the blue economy and beyond.

As energy researchers and entrepreneurs look to provide novel energy solutions for the blue economy, the lessons of the battery revolution remain valuable. Innovations take time and sustained investment, but continuing to foster global innovation networks and pairing new innovations with pathway markets can accelerate scale-up. Setting strong incentives for the private sector while encouraging public-private co-operation can bridge the gap between basic R&D and markets. Meanwhile, persistent marinisation of terrestrial technologies will quicken the pace of marine technology development. All of these steps will contribute to a robust innovation environment, helping new energy innovations thrive.

Chapter 4: The offshore wind boom

Humans have been harnessing wind energy since antiquity—to sail ships and boats, grind grain, pump water, produce food and cut woods at sawmills. Even the technology to make electricity from wind is well over a century old. The first known wind turbine for electricity generation was built in 1887. Offshore wind, by comparison, has a much shorter history: the first offshore wind farm was established in Denmark in 1991.

Despite being a relatively new source of energy, offshore wind is now one of the fastest-growing renewable energy sources in the world. Over the last decade, global offshore wind installation capacity has grown at a staggering rate of 28% per year. Since 2010, offshore wind has attracted over US$200bn in investment. According to research organisation BloombergNEF, in the first half of 2020 alone offshore wind financing reached US$35bn, up 319% year on year. According to the International Energy Agency (IEA), offshore wind power capacity will increase by at least fifteenfold worldwide by 2040, becoming a US $1trn business.

In this chapter, we will discuss two specific technological advancements that helped propel the commercialisation of offshore wind: first, increases to the size of rotors and blades, and second, the ability to move farther away from shores. Then, we will briefly present the impact of these innovations on markets. The last section will provide an overview of enabling environment factors that accelerated the rate of technology maturation.

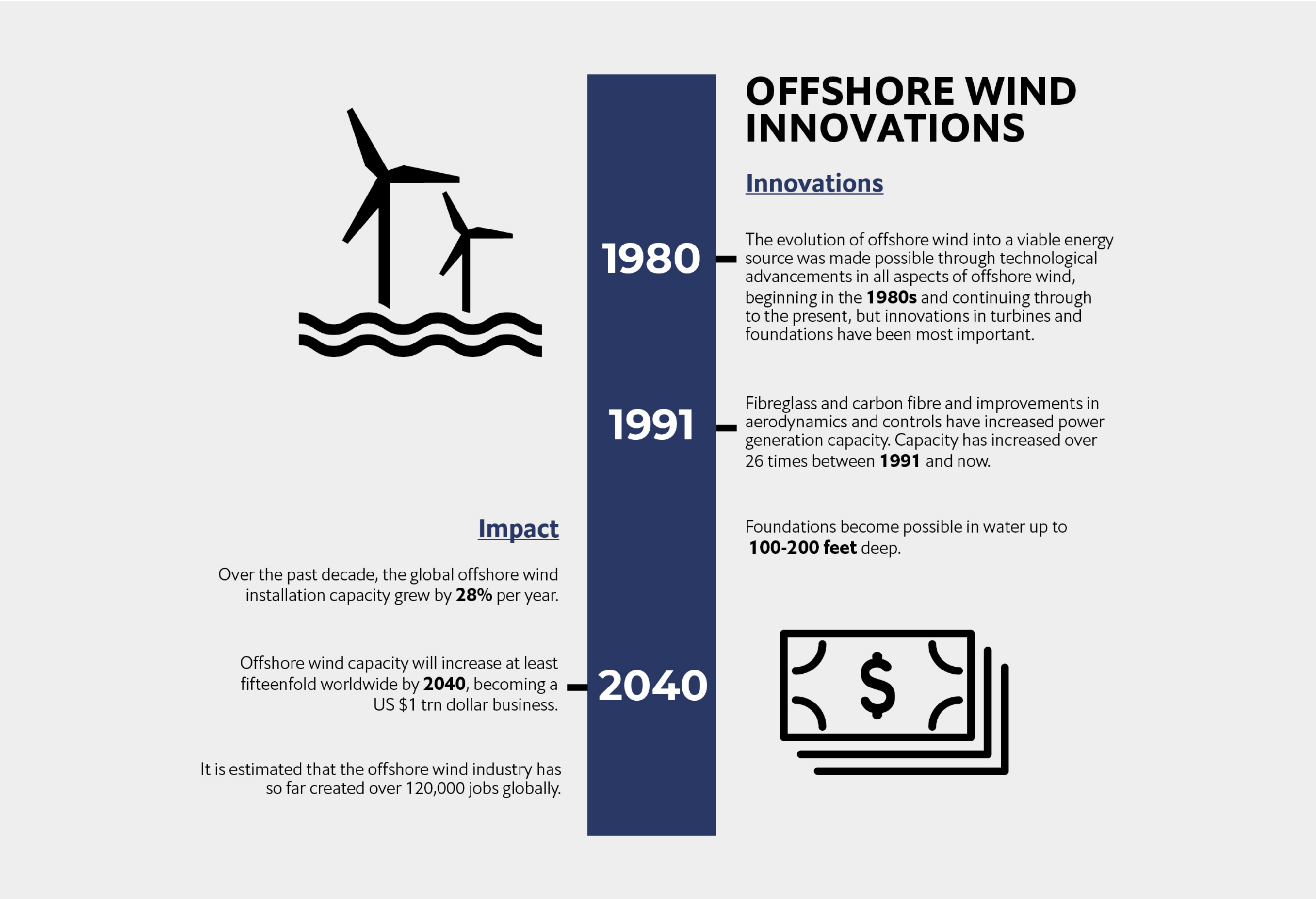
Innovations:

The evolution of offshore wind into a viable energy source was made possible through technological advancements in all aspects of the offshore wind farm—from the wind farm development phase (design and surveys) through to electrical interconnection (array cables, offshore substations and subsea export cables). Innovations related to turbines and foundations, according to many experts, have had the most impact on creating viable offshore wind markets and building new opportunities and businesses.

Innovations in turbine rotor manufacturing have significantly increased the power generation capacity of turbines. For example, while the first offshore wind turbine had a capacity of 450 kW, nowadays the majority of operating turbines have 3-5 MW capacity. General Electronics (GE) is currently testing a turbine, Haliade-X, with a capacity of 12 MW. The industry is already making headway towards introducing next-generation 15-20 MW turbines by 2030.

The increase in output capacity has mainly been achieved by increasing the size of the turbine in terms of tip height and swept area. A larger swept area at higher elevation allows the turbine to harness larger quantities and higher intensities of wind. As a point of comparison, a 3 MW turbine has a swept area of 6,362 square metres and a tip height of around 328 feet. The Haliade-X, on the other hand, harnesses wind from a 38,000 square metre swept-area and reaches 853 feet, approximately one and half times the size of the Washington Monument.

The constant push towards creating bigger turbines has prompted the industry to test different materials—such as epoxy resin, polyester resin, fibreglass, and carbon fibre— for producing rotors and blades. Of these, carbon fibre is the most suitable for



building larger blades. Carbon fibre has great tensile strength and low weight, thus allowing production of larger blades at reduced weight. Carbon fibre's application in the manufacturing sector dates back to the late 1950s, particularly in the transportation and aerospace industries. However, the offshore wind industry has been hesitant to fully embrace carbon fibre due its high cost. There are ongoing research initiatives to find cost-saving ways to make carbon fibre more suitable for offshore wind. At the same time, the industry is also investigating metal-composite hybrid structures for producing blades. No matter which route rotor producers take, it is clear that advances in materials and turbine construction are already facilitating size increases for offshore blades.

Advancements in building foundations have also contributed to the commercialisation of offshore wind. Since the installation of the first turbines, the industry has been working to move foundations further from the shore into deeper waters. Moving further offshore allows for harnessing wind with higher intensity and more consistency. Aside from wind economics calculations, the move is also driven by community pressure. Aversion to projects from homeowners (known as "not in my backyard-ism", or NIMBYism) or pre-existing users of marine environments has been a major obstacle for many offshore projects. Coastal communities often object to the installation of turbines near the shore due to environmental concerns or simply because they want an uninterrupted view of the ocean.

While moving further from shore is desirable, the logistics and mechanics of making it happen are somewhat excruciating. Specifically, the main challenge is to build foundations in deeper waters (more than 100 feet deep) capable of providing stable bases for the world's largest rotating machines. To achieve this, the industry has had to learn, innovate and work with other sectors to find solutions. While technological advancement in building these foundations is still a work in progress, some remarkable achievements have already been made.

The oil and gas industry has been the pioneer of marine foundation technology. Offshore wind developers have adopted a number of structural concepts previously applied to the installation of offshore oil and gas rigs. There are a variety of different types of foundations for offshore wind turbines, including gravity-based structures, monopiles, jackets, tripods and floating foundations. Selecting the type of foundation depends on a number of factors, such as turbine size, water depth and seabed conditions.

Monopile foundations are the preferred option for developers given their much lower cost. Monopiles were once perceived as unsuitable for water of more than 25 metres deep. Given the industry's plans to move further from shore, the depth limitation of monopile structures became a huge constraint. Since then, however, "there has been strong innovation in design, manufacturing processes and installation tooling so that monopiles are now expected to remain cost-competitive with larger turbines in water depths of even more than 35 metres," according to the International Renewable Energy Agency (IRENA). The industry was able to make progress by retrofitting the design of monopiles to make them more appropriate for wind turbines. Initially, the design of foundations was governed by standards for the offshore oil and gas industry, but as more performance data from operating offshore wind turbines became available it emerged that these standards were too conservative and needed revision to become more relevant to offshore wind.

Collaboration with the oil and gas industry has also allowed offshore wind developers to evolve the design of jacket foundations (which use a lattice and multiple points of contact at the ocean floor) to drive down cost and make them suitable for offshore wind in deeper waters. Floating foundations are another design used by oil and gas that the offshore wind industry is adapting for the deployment of wind turbines in even deeper waters farther offshore.

Impacts of offshore wind innovations on markets:

As larger, more powerful turbines have been located in areas with higher wind intensity and greater consistency their output per unit has drastically increased. This means operators need to install fewer of them to generate the same amount of energy. As a result, both development costs and the cost of energy have declined. According to IRENA, the levelised cost of electricity (LCOE) for offshore wind dropped from US$240/MWh in 2001 to $170/MWh in 2015. In the first half of 2020, the LCOE[4] for offshore wind reached $78/MWh.

The offshore wind industry has also created thousands of jobs over the past decade. The workforce needed to develop, run and maintain an offshore wind farm and substation includes scientists, technicians, managers, engineers, surveyors and seafarers, among others. According to IRENA's estimation,

[4] "Levelised cost of electricity represents the average revenue per unit of electricity generated that would be required to recover the costs of building and operating a generating plant during an assumed financial life and duty cycle". EIA

development of a 500 MW offshore wind farm requires 2.1m person-days. It is estimated that the industry has so far created over 120,000 jobs globally. According to the American Wind Energy Association, the revitalisation of offshore wind project development, construction, and operation and maintenance in the US will support 83,000 jobs by 2030 (58,930 project development and construction and 23,582 operations and maintenance jobs).

In addition to economic impacts, offshore wind is making the decarbonisation of other sectors more feasible. A number of projects are working to leverage offshore wind to produce green hydrogen. The electricity generated by offshore wind turbines can be converted to hydrogen via the electrolysis of seawater, which can then be transported onshore using pipelines. Green hydrogen can be used as a fuel for manufacturing, shipping, transportation and heating with almost no carbon footprint. The shipping industry in particular sees hydrogen fuel cells as one promising long-term option for reaching zero-emissions. A hydrogen-powered cruise ship is already under construction in Norway, and the Golden Gate ZERO Emission Marine project is building the first hydrogen fuel-powered ferry in the US. Green hydrogen offers a practical solution for decarbonising the transportation and industrial sectors—both stubborn and difficult sectors within which to achieve zero-emission. Both Germany and the Netherland are in the process of issuing tenders to build offshore wind-generated green hydrogen plants while UK-based gas network operator SGN has launched an offshore wind-powered hydrogen heating project. Developers are also actively exploring hybrid projects to maximise energy output. For example, oil and gas companies Shell and Eneco will develop a novel offshore wind farm off the coast of the Netherland that will also incorporate floating solar, battery storage and hydrogen produced by electrolysis. This joint venture, formally known as CrossWind, is the first of its kind and aims to demonstrate a variety of innovations that can be then rolled out at larger scale.

Enabling Environment

Offshore wind technology has come a long way, particularly over the past ten years. "Offshore wind is really one of the major emerging blue economy sectors," explains Claire Jolly, Head of Unit at the OECD Directorate for Science, Technology and innovation. "Only a few years ago there was almost nothing, and then all of a sudden, boom, you get a sector that's being internationalised more and more." Of course, this transformation from a niche technology to commercial success didn't happen in a vacuum. A number of factors made it possible, notably marinisation and government support.

By the time the first offshore wind farm was established in 1991, wind turbine technology was already well established. In the aftermath of the oil crisis of the 1970s, the US government provided generous funding and incentives for the development of multi-megawatt wind turbine technologies to demonstrate the commercial feasibility of wind energy as an alternative source of power. This government funding led to most of the turbine technologies in use today, including "steel tube towers; variable-speed generators; composite blade materials; partial-span pitch control; and aerodynamic, structural and acoustic engineering design capabilities" according to Boeing. It is worth noting that government support at the time was less focused on rapid testing and innovation than getting turbines in the field and creating room for failure in order to learn quickly. This patience and willingness to learn by trial and error allowed scientists to test bold ideas, take risks and innovate. Through government support, the terrestrial wind industry took off and transformed into a reliable and cost-effective source of renewable energy across the globe. Today, the share of US electricity generation from wind is about 7.3%. As a result of technological advancements in wind turbine technology, the offshore wind industry got a head start. However, the industry has had to adapt onshore technology in order to make it suitable for ocean conditions.

Similar to terrestrial wind energy, government policy intervention has been a key driver of offshore wind commercialisation. First and foremost, policies pertaining to the reduction of carbon emissions have intensified the search for clean sources of energy. In 1990 Denmark was among the first countries to set a target for reducing CO2 emissions. To meet its target the government increased its portfolio of renewable energy, including offshore wind (the first large-scale commercial offshore wind farm was built in Denmark in 2001). Other European countries have followed suit to curtail CO2 emissions while 23 American states plus the District of Columbia have also adopted specific greenhouse gas emission targets. Some states have taken specific legislative action for the procurement of offshore wind energy. For example, Massachusetts enacted the Act to Promote Energy Diversity (APED) in 2016 which allows for the procurement of up to 1,600 MW of offshore wind energy by 2027. New York state also recently enacted the Climate Leadership and Community Protection Act (CLCPA) which requires utilities to rely on renewable energy for 70% of electricity supply by 2030. Policies such as the Denmark energy plan, APED and CLCPA are vital to push the industry to test new ideas, innovate and find practical solutions.

Government financial support has been a major enabling factor leading to the scaling-up of offshore wind technology. Since 2011 the US government has been supporting a large portfolio of offshore wind research, development and demonstration projects. The Department of Energy (DOE) alone has allocated over US$250m for development of offshore wind technology. Such government support schemes have not been limited to provision of grants: in almost all countries governments have actually created the market for offshore wind energy by commissioning the establishment of the farms and then buying the energy produced. Through feed-in tariff policies, countries such as Denmark and the UK incentivised the private sector to invest, develop technology and sell the energy at guaranteed fixed prices to the government.

The transformation of offshore wind from a niche to established source of energy over a short span of time is an illuminating story with clear implications for marine energy. First, the case shows how strong demand for clean sources of power compels investors to move far from shores in pursuit of energy. Second, the case shows how existing terrestrial and marine technologies accelerated the maturation of offshore wind technology. Instead of building processes from scratch, the industry adapted existing technologies to retrofit the requirements of offshore wind. Finally, once all the pieces come together, it doesn't take long for a technology to take off. Back in 2010, the world's installed offshore wind capacity was merely 3 GW. Today, it's well over 28 GW, which represents over 800% growth within ten years. Given the ever-increasing thirst for energy worldwide, the ocean could very well become the next big source.

Chapter 5: Energy Innovation for the Blue Economy

Energy innovations have shaped the ocean economy in the past—as seen in the sail-to-steam, energy storage and offshore wind cases—and new energy innovations hold great potential to transform the blue economy of the future. What will it take to enable this transformation? How can we not only facilitate energy innovation but also ensure that innovations are successfully commercialised? The case studies, expert interviews and literature review combined highlight a series of enabling elements that are critical for energy innovation in the blue economy.

> **"Marine energy is still young, so it's hard to make the business case yet, but I think there could be some technological leaps coming up."**
>
> Claire Jolly, OECD Directorate for Science, Technology and innovation

Readiness of emerging marine energy technologies

Different marine energy technologies are currently at various levels of technology readiness. Tidal stream technologies have moved into the early stages of active community- and utility-scale deployment and a general consensus is emerging around a handful of designs. Wave energy converters (WEC) have seen some small commercial deployments and a variety of companies are testing devices and working to find commercial deployments across a variety of unit scales. However the majority of past wave energy companies have failed commercially and more time is needed to demonstrate the robustness and reliability of existing models. There are several operational ocean thermal energy conversion (OTEC) plants, but technological hurdles remain. Meanwhile, osmotic energy conversion (using the salinity gradient of the ocean to generate power) is still at the basic research and development (R&D) stage.

The precondition for energy innovation, and the foundation upon which the enabling environment is built, is the investment of resources: human, financial and especially time. Time is particularly important (see breakout box) and particularly easy to overlook for those ready to hype up the next best thing. Nascent technologies emerging in laboratories are likely to still be decades away from widespread commercialisation, if history offers any lessons.

The enabling environment involves eight interrelated elements that all contribute to energy innovation for the blue economy. They are: 1) marinisation, technology transfer and collaboration; 2) policy support; 3) financing environment; 4) enabling and complementary technologies; 5) public awareness, attitudes, and social acceptance; 6) pathway markets, competition and economies of scale; 7) testing, standards and certification; and 8) complementary infrastructure. These factors, while not strictly necessary for energy innovation, increase the likelihood of successful innovation and reduce the time or resources needed to bring innovations to market. Their interconnectedness is lived out when advances made in one of the eight areas spurs advances in others, creating virtuous cycles. Given that innovation can comprise the entire technology lifecycle,[56] the enabling environment is important from the nascent stages of R&D right through to market entry, technological maturation and diffusion.

Marinisation, technology transfer and collaboration; the financing environment; and enabling and complementary technologies both accelerate innovation and drive its development. Policy support plays an essential role, for instance by aligning incentives, facilitating market entry and helping to bring technology developers and users together. Public awareness and social acceptance help innovations see the light of day. Building pathway markets—which are critical for creating new opportunities to apply and iterate innovations—demands both innovator push and market pull. These pathway markets then lead to economies of scale that drive further innovation. Deployment and testing sites pair with standards and certifications to prove viability and reliability, opening up new markets and avenues for financing. Finally, when innovations scale up and arrive on the market, complementary infrastructure (whether through private or public actors) can enable and accelerate diffusion and adoption. As stakeholders work to develop and deploy new energy solutions for the blue economy, each element of the enabling environment presents opportunities to accelerate implementation and engender success.

Elements of the enabling environment are generally listed in order by the technology readiness level (TRL) to which they apply,[v] from lower TRLs through to higher TRLs. Each upcoming section in this chapter broadly outlines the overall importance of each for energy innovation in the blue economy. Sections then detail the specific state and relevance of that factor for marine energy, a set of technologies that hold particular promise for the blue economy and have seen ongoing and long-term development.

Time: a key ingredient of energy innovation

Energy innovations require time to reach maturity—typically decades. Many of the enabling environment factors discussed in this chapter relate to the reduction of time required to innovate and bring innovations to scale. The first steamship wasn't built until over 100 years after the invention of the first steam engine. Developing offshore wind took decades. As the International Energy Agency notes, the lithium-ion (Li-ion) battery was among the fastest technologies to be scaled from prototype to mass market,[57] and even that took roughly fifteen years.

Marine energy stakeholders should not expect miracles. It will take time to determine if current tidal energy paradigms can gain a long-term market foothold, though entrepreneurs are cautiously optimistic. It will also take time for wave energy entrepreneurs to continue demonstrating their systems and finding the right market opportunities. Ocean thermal energy conversion (OTEC) and osmotic power solutions both have a long way to go. Even if step-change innovations emerge that hold the potential to reinvent marine energy, it will take years to get them from lab to market, and the refinement process will take longer still.

Once innovations begin to mature, many opportunities will follow, but this maturation requires time and work. For marine energy, firms face a "valley of death" between RDD&D (research, demonstration, development and deployment) and commercially sustainable scale.

[v] The International Energy Agency (IEA) for instance, describes TRLs as a scale that "provides a common framework that can be applied consistently to any technology to assess and compare the maturity of technologies across sectors. The IEA uses an 11 step scale, running from "Initial idea" all the way through to "Proof of stability reached" for mature technologies, including stages for concept, small prototype, large prototype, demonstration, early adoption and maturity in between.

Marine energy holds great promise for remote community power and coastal resilience, for the construction of a carbon-neutral grid and for the expansion and reinvention of the blue economy as a whole—but it will require continued proactive work on the part of marine energy stakeholders and a great deal of patience. However, this process could be sped up through a number of improvements to the enabling environment as outlined in this chapter.

Elements of the marine energy enabling environment

1. Marinisation, technology transfer and collaboration

Relevant TRLs: low to high

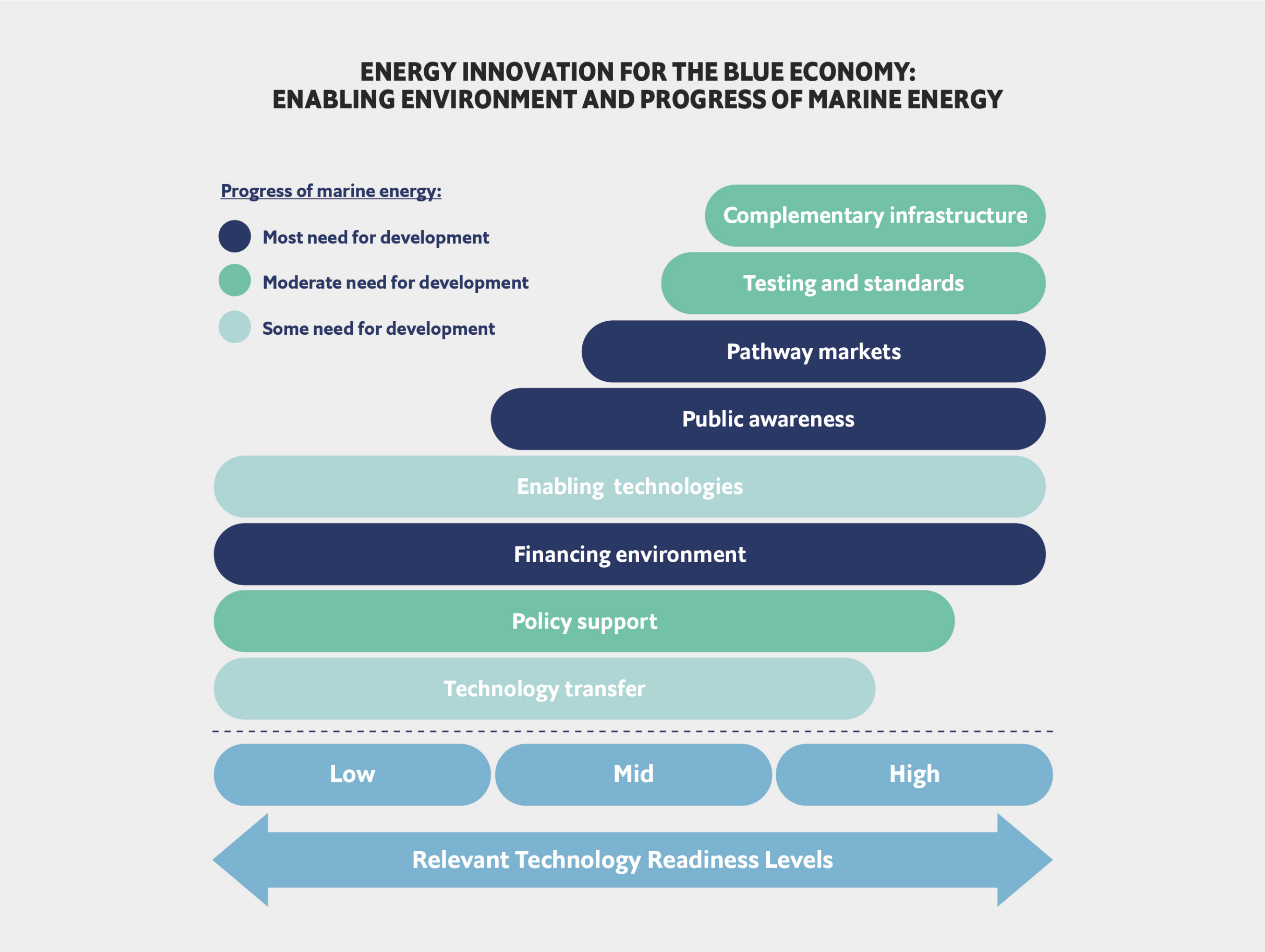
> **"It's about how you more effectively migrate things that are having a great deal of money spent on them in other markets into use in the ocean: you're marinising things that have been developed for broader applications."**
>
> Ralph Rayner, LSE and the Society for Underwater Technology

Technology transfer is essential for energy innovation.[58] The marinisation of technologies originally designed for terrestrial use is especially important. Across all three of our use cases, for instance, the technologies applied and modified were originally developed for terrestrial or general-purpose use: they were marinised. While marinisation is not the only pathway to energy innovation for the blue economy, few energy components or systems are first designed for marine use.

Innovation networks[vi]—particularly those between marine and non-marine experts—ease technology transfer into the blue economy by improving understanding of technologies that might be used for energy innovations. Innovation networks and collaboration in general are a critical method for accelerating energy innovation. Stakeholders like governments, academia and research labs are all important drivers of knowledge and private-sector innovation,[59] and linking these groups together across domains and geographies facilitates knowledge building and technology transfer.

Take the Li-ion battery which was a collaboration largely between corporate and academic research but with public involvement at key moments. Similarly, trans-Atlantic co-operation led to the first commercially successful steamships in the US and the UK. Research is generally disseminated through published materials and in-person meetings (informal or formal) while explicitly fostering connections between different stakeholders can speed up innovation.[60] Public research, for instance, generates ideas that lead to new R&D at companies and can become part of the R&D process itself. International collaboration can also drive improved understanding of the environmental effects of energy innovations within marine ecosystems. According to IRENA, "sustained multi-stakeholder engagement around an achievable, shared vision" is critical for renewable energy policy regimes to be successful.[61] Across non-energy sectors, swift

[vi] Which can be defined as: "a relatively loosely tied group of organisations that may comprise members from government, university and industry continuously collaborating to achieve common innovation goals."



innovation has generally been "characterised by a lively 'innovation ecosystem' that both rapidly incorporates the results of publicly funded research and supports widespread private sector experimentation and rapid entry".[62] Ideally, these ecosystems should be international.[63] Collaboration across organisations tends to drive higher quality innovation while collaboration that also involves a firm's suppliers or customers has a better chance of successful commercialisation.[64]

Technology transfer from outside the marine energy sector, across the blue economy and between marine energy entrepreneurs are all essential for marine energy innovation. There are already robust formal and informal international and regional collaboration efforts around marine energy. These include the IEA Ocean Energy Systems Technology Collaboration Programme, the EU, academic groups and national governments.[65] Interaction

> **"There are a lot of cross-company collaborations in wave power that haven't happened yet. We're actually in a consortium of leading wave developers that have started to collaborate on a specific component. We're on track to follow up shortly to where tidal energy is today."**
>
> Marcus Lehmann, CalWave Power Technologies

between marine energy entrepreneurs also takes place at events, conferences and test sites. Some marine energy engineers are already co-ordinating on the design of key standard components. Continuing to build out networks involving a variety of stakeholders—including marine energy entrepreneurs, researchers, governments, potential end-users, financiers and other marine and non-marine technology experts—could improve awareness of potential solutions, speed up technology transfer and accelerate innovation in the field. Forging links between the public and private sector is particularly important as the public sector tends to focus on new technologies supporting wider policy aims while the private sector (on the whole) tends to support existing paradigms.[66] As such, turning new technologies into new paradigms requires public-private co-operation.

2. Policy support

Relevant TRLs: low to high

> **"Past policy was driving companies to go too big too early. Getting the policy framework right is essential."**
> Deborah Greaves OBE, Plymouth University and Supergen Offshore Renewable Energy Hub

will promote innovation: it is undeniable that governments have played a crucial role in the advancement of energy innovations in the past and will continue to do so in the future.[68] Governments play an important role when it comes to structuring incentives to help enable pathway markets. This was the case at various points in the development of the steamship, the Li-ion battery and offshore wind. Ultimately, these investments can pay off. Take offshore wind: while policy support was costly, the rapid drop in price for offshore wind energy exceeded expectations once the technology scaled up.

> **"Energy transition is about policy decisions. The technology is there: if it's not already mature it's at prototypes and commercial demonstration projects. What gives the business path is a strong commitment to build up capacity. It will happen because we decide it will happen; that's it."**
> Xavier Guillou, EU Directorate-General for Maritime Affairs and Fisheries

Policy interventions generally drive energy innovations. They require a deliberate choice on the part of policymakers regarding the technologies or forms of innovation they wish to support, and these choices also entail costs. Throughout the history of energy innovation, public support has often been vital to the development of new technologies. Not until there is an "expectation of rapidly growing demand" will the private sector generally invest in innovation.[67] Forward-thinking, evidence-based approaches to regulation and policy

Because environmental concerns are typically not included in market pricing, private firms tend to under-invest in clean energy. For this reason, government intervention is critical for incentivising new energy innovations for the blue economy. Stable, long-term policies and stronger interaction between the government and private sector can help drive energy innovation and allow the public sector to complement the private sector.[69] Not all policy is necessarily good policy—not all experts consider patent boxes (where patent revenue is taxed at a lower effective rate) to be useful, for instance—but government support is nonetheless necessary, particularly at the R&D level.[70] IRENA also highlights the importance of "appropriate positioning of a country or region to anticipate and benefit from renewable energy technology flows".[71] This is not only about the promise of supplying low-carbon power domestically but also about the creation of new markets (and therefore jobs and wealth) at both the domestic and international levels.

Policy support will be essential for driving the marine energy industry forward. The types of policy levers, like price support and government investment, that enabled the development of other renewable energy technologies—for instance wind, PV and offshore wind—will be needed to drive marine energy growth. Many arguments for bearing the social costs of policy support for marine energy revolve around the long-term importance of a mixed renewable energy system which could provide the fastest and most reliable path towards carbon reduction. There is hope that marine energy could follow the same trajectory as offshore wind and see a rapid price drop with public policy support. However there is a risk that this will not be possible now that marine energy could be competing with offshore wind in many locations (not only on an investment or cost basis but also for policy support). As an antidote to this, governments could also encourage marine energy innovation within micro- and community-scale use cases where unique competitive advantages can be found, particularly in the near term. Indeed such use cases might then meaningfully contribute to the long-term expansion of the blue economy.

3. Financing environment

Relevant TRLs: low to high

Funding is critical to drive innovation. This was true for steamships where a robust financing environment and declining costs of insurance helped to drive long-term innovation and adoption. This was true of new battery paradigms and wind-energy technologies too, which were spurred by government R&D funding. Funding requirements run the gamut from initial R&D investment to long-term access to capital, including finance for initial testing, scaling up and insurance. Sustained funding and long-term financial commitment are often needed to bring new technologies from conception to market, as was highlighted in each of the case studies.

Many existing sources of funding for energy innovation have both upsides and downsides. Governments, for example, are an essential source of funding, particularly for R&D.[72] Rather than discouraging private investment, public financing of innovations tends to encourage more.[73] Despite these advantages, government funding can be volatile and dependent on politics. When this is the case, it is difficult to plan according to the long-term timelines needed to bring energy innovations to fruition.[74] Venture capital (VC) is one source of finance that has been a central force in the transformation of industries, especially in the US, and holds additional advantages like useful counsel for portfolio companies.[75] On the other hand, VC has often been an unsuccessful model for new energy hardware and processes, due in part to the long period of maturation for clean energy technologies and the boom-bust cycle of the VC industry.[76]

Public-private co-financing is one option that could help minimise the downsides of other financing options for energy innovation.[77] Blended finance, which merges concessional financing (loans offered at below-market terms) or grants with commercial funding is another promising option.[78] Blended finance lowers the risk profile for private investors, can be used to provide loan guarantees and can facilitate the purchase of insurance—though the underlying business proposition must still be strong. Finally, regardless of the investment mechanism, technical experts should ideally have a say in funding decisions.[79] This can help prevent investment into firms without real technical promise, the failure of which can harm overall industry reputation and raise perceived risk.

> **"There have been a lot of failures up to this point. The risk tolerance is low already, and insurance is high. That then requires more money. It's all about risk."**
>
> Tim Mundon, Oscilla Power

Access to finance is a major challenge for marine energy. Even firms with existing commercial deployments are concerned about the "valley of death". Perceived risk is highly significant: risk-adjusted return is viewed as too low for early-stage funders and insurers are unwilling to underwrite marine energy projects, insurance that is required for bank or project financing. Strategic corporate investment and long-term investment from non-VC sources could prove more successful funding models. This is particularly the case if there are ample long-term demonstration and testing facilities which can reduce perceived risk (see below). Standards and certification can also reduce perceived risk. These efforts, in addition to ongoing or new grant or concessionary financing from governments and international financial institutions (such as blended finance), could provide the means for sustainable commercialisation. So could financing from and partnership with large energy companies.

4. Enabling and complementary technologies

Relevant TRLs: low to high

Encouraging the ongoing development of enabling technologies (technologies that allow for leaps in capabilities or performance) can speed up innovation. In offshore wind and the transition from sailboats to steamships, incremental development of key subsystems, materials, and other enabling technologies undergirded the step-changes in efficiency and scale that drove widespread competitive impact. Stakeholders can continue to provide support for the ongoing development and improvement of enabling technologies and tools in order to expedite energy innovation in the future. Because of their more general usability these technologies can promote

> **"We're massively benefitting from the offshore wind boom. Our supply chain costs are coming down. We're winning by having offshore wind be so successful."**
>
> Tim Cornelius, Simec Atlantis Energy

a wide range of energy innovations and therefore play an important part in the energy innovation ecosystem.

Advances in software, robotic, and mapping, for example, have all enabled the modern generation of marine energy systems. These enabling technologies make it easier for engineers to design efficient and sturdy marine energy systems. They also allow for improved deployment, maintenance and recovery. In addition, these technologies facilitate improved site selection and more rapid iteration (for instance through simulation), which can all serve to accelerate the marine innovation process.

Enabling and complementary technologies can also be acquired through technology transfer. For instance, rather than developing components from scratch, some marine energy entrepreneurs are taking advantage of components that have already been developed for general use or for other (marine or non-marine) purposes. This approach can ease production, speed technological iteration and lower costs of systems. Enabling technology development for utility-scale marine energy has been advanced in large part by offshore wind energy which has led to low cost, standardised subsystems (systems within systems) that marine energy entrepreneurs are able to take advantage of.

5. Public awareness, attitudes and social acceptance

Relevant TRLs: mid to high

Even when an energy innovation becomes cost effective for specific uses, that does not mean it will be immediately adopted. One of the major factors behind this lag is public awareness and social acceptance of these new innovations.[80] Potential end-users must first understand a technology and see its benefit over existing technologies—or even anticipated future technologies—before adopting new energy innovations, even if they make sense from a cost perspective. Furthermore, there are other social barriers to be overcome. One is perceptions of how well new technologies will perform, which does not always align with actual performance. This information gap can be overcome through education and exposure—first-hand experiences are especially valuable for changing minds. Another is the "not in my backyard" (NIMBY) factor which is particularly important for navigating innovations that may change the landscape. This has been the case, for instance, with offshore wind. Inclusive and participatory siting decisions that incorporate marine impact assessment can ease acceptance from other stakeholders, including pre-existing users of marine spaces.

Education, for both regulators and the public, can help ease tensions over new technologies. Otherwise, a (justifiably) precautionary approach is likely to prevail. Some understanding of the long-term impacts of new energy innovations may take time to develop, but increasing understanding among stakeholders around what is already known can speed up innovation.

> **"Siting is critical. A lot of ocean users feel left out of the process or brought into the process very late after things can't be changed. Early dialogue is an important step in the process to ensure co-existence of differing ocean uses."**
>
> Candace Nachman, NOAA

Even though many marine energy innovations remain at early TRLs, marine energy entrepreneurs will want to engage with potential end-users early to help them see the value of adopting their systems. Similarly, engagement with all stakeholders from the earliest planning stages can facilitate long-term buy in. Stakeholders often express concerns around potential environmental impacts of marine energy development, so improved knowledge about the true extent and nature of environmental risk will be vital to winning social acceptance.

6. Pathway markets, competition and economies of scale

Relevant TRLs: mid to high

> **"Everyone looks to the grand prize of the utility market, but these pathway markets provide a means to meet that objective, and can be substantial markets in their own right."**
>
> Mark Hemer, the Commonwealth Scientific and Industrial Research Organisation and the Blue Economy Cooperative Research Centre

Opening up niche markets is both a goal for energy entrepreneurs and a catalyst for further innovation. Niche markets can become pathways that help generate economies of scale in terms of both the number and size of systems. Once new technologies are able to get a sustainable foothold in the marketplace, wider use creates a positive feedback loop. Technology developers can more easily work with end-users whose evaluations then lead to greater product refinement. This was true of steamships which started first on canals but improved and expanded into passenger service, tug service and mail transportation across a number of contexts once the initial market was established. Market forces drive competition and new entrants which in turn generates alternative versions of a technology and drives price down. Therefore efforts that support the entrance of energy innovations into niche markets not only help to bring these systems to market in general but also facilitate future innovation.

What is critical is that not all niche markets will become pathways to scale. Many firms fail during development and commercialisation, and there may be fits and starts—as was true in all three case studies. However, this market process advances innovation and can open up further markets as new technologies become cheaper and more refined, leading to a virtuous cycle of innovation. Competition is essential, and beyond the technologies themselves timing is critical. Moreover, these pathway markets are often not those originally intended as was the case with a number of battery storage paradigms. For example, the Li-ion battery, originally conceived for electric vehicles, was first used in hand-held electronic devices.

> **"It's beneficial that several technologies are developed in parallel. There should be competition. There should be interest in establishing the industry and establishing new sites. The more we can do this, the more advanced the technology will be. It's good for all of us."**
>
> Heikki Paakkinen, Wello Oy

Markets may be based on use or they can be geographic: deploying renewable energy systems in low- and middle-income regions, for instance, can promote energy innovation within those countries and lead to an expanded innovation ecosystem.[81] Governments can also create their own markets as the initial buyer (or subsidiser) of energy innovations in some cases, helping to kickstart this virtuous cycle. This was the case for offshore wind, where the government of Denmark served as the key initial market and presented a model that was then followed by other European countries and later China.

Beyond economies of scale in terms of number of systems, as pathway markets for energy innovations expand, demand for systems increases and prices drop, there is often a push towards larger-scale iterations of individual systems. This was the case with steamships and also for offshore wind. For the latter, economies of scale regarding unit numbers have driven further innovation in areas like installation, operations and maintenance.[82] Economies of scale for size have been essential for creating efficiencies in the modern shipping industry by decreasing per-tonne cost and fuel requirements.[83] The industry has also shown that policy choices can help drive and utilise this scale.[84] Yet at the same time the shipping industry demonstrates the limits of scale as complementary infrastructure requirements for bigger ships have created significant costs elsewhere[85] and the majority of efficiencies have in fact been created through improved engines.[86]

In the case of marine energy, entrepreneurs are still working to generate sustained market interest. Marine energy can learn from offshore wind, just as steamships and sail boats learned from one another and different battery technologies have competed for markets and pushed innovation forwards. Some firms are looking to markets like remote communities and providing in-situ power for end-uses including ocean observation, AUVs or aquaculture as a means to scale up their operations. Micro- and community-scale pathway markets hold appeal for expanding the blue economy and advancing marine energy technologies. This is particularly true given the stiff price competition for grid-connected energy, though markets for smaller-scale systems will also require nurturing. These markets can also be end goals in and of themselves before potentially becoming pathways to greater scale and sustained commercial deployment. Others work to deploy utility-scale systems from the outset, seeking markets where ocean energy is abundant, alternative sources are more expensive and policy support can drive a competitive levelised cost of electricity (LCOE).

7. Testing, standards and certification

Relevant TRLs: mid – high

> **"By measuring and demonstrating power, reliability and survivability performance consistently across the sector, I do see the market for marine energy growing in the near term."**
>
> Elaine Buck, European Marine Energy Centre

Testing sites are a key component of energy innovation as they allow for long-term demonstrations in extreme conditions. These demonstrations not only serve as proof of a viable product but also provide evidence of standards adherence and facilitate certificate acquisition, all of which lead to the reduction of risk for investors. [vii] In general, learning by doing is crucial for energy innovation.[87]

Standards and certifications lower information barriers for investors and insurers, barriers that otherwise raise the perceived risk profile of new energy technologies. Without trusted standards and certifications, non-experts must work to evaluate each system on its own merits. This difficult task leaves investors relying only upon their best judgement and past cases. Standards and certifications have been important for offshore wind's development, for instance, particularly in countries that led the way like Denmark, Germany, the UK and China, though more work towards international harmonisation is needed.[88] For steamships, standards were important not only for lowering perceived financial risk but also for reducing the risk of boiler malfunctions which could be extremely dangerous. In order to promote the global spread of energy innovations, history teaches us that the development of internationally recognised standards and certification will no doubt be essential.

Expanding the range of available testing facilities globally could speed up marine energy innovation. In addition, because the cycles of testing are typically longer for marine energy innovations than they are for terrestrial energy innovations—given the complications involved with making devices suitable for harsh marine environments and with physical deployment—exploring ways to speed the process of iteration through testing is one way that marine energy innovation can be fostered.

Given some of the past failures of marine energy systems—particularly wave energy systems—that have made investors wary, standards can provide outside groups with confidence in the survivability and reliability of new marine energy solutions, thereby opening up channels for investment. At present, desk standards—like those from risk management and quality assurance firm DNV GL—and corresponding certification are the norm. International standards which apply across all markets—like those of the International Electrotechnical Commission (IEC) and the corresponding IECRE certification [viii] —could help push the global marine energy market forwards. This would require increases to the number of standards, renewable energy test laboratories and participating firms.

> **"The reduction of perceived risk, and technical risk in general, is absolutely one of the most important things for the marine energy industry. Standards and certification are essential for accomplishing this risk reduction."**
>
> Jonathan Colby, Verdant Power and the International Electrotechnical Commission

[vii] Standards are defined by IRENA as, "a repeatable, harmonised, agreed and documented way of doing something. Standards contain technical specifications or other precise criteria designed to be used consistently as a rule, guideline, or definition." Certification demonstrates adherence to international or third-party criteria (for instance design, build, quality or performance; often standards).
[viii] IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications

8. Complementary infrastructure

Relevant TRLs: mid to high

As larger energy systems are deployed, complementary infrastructure[ix] like transmission and substations, will be needed to take advantage of new energy innovations. This was true of both the sail-to-steam transition and offshore wind. In the case of steamships, development of bunkering networks were required for the technologies to drive towards greater maturity. For offshore wind, new distribution networks have been required. This infrastructure has been one of the major drivers of offshore wind costs, and responsibility for power transmission assets (for instance by the wind farm developer or by the national and regional transmission network) has been a large driver of cost differences between countries.[89] Beyond just cost, the scope of complementary infrastructure development limits the geographic breadth of impact for new energy innovations.

Evidence suggests that when it comes to this complementary energy infrastructure, simultaneous development is the fastest way to speed up the diffusion of new innovations.[90] Complementary infrastructure facilitates the expansion of energy systems while energy systems facilitate the expansion of complementary infrastructure. For energy stakeholders, early consideration of the full innovation cycle—not only energy systems themselves but also the infrastructure needed to enable these systems—will lead to maximum impact. To accelerate innovation, stakeholders from both the energy innovation and complementary infrastructure sides should communicate throughout the entire development cycle. Finding methods to improve the information sharing between these two groups of stakeholders could help speed up the rate of energy innovation diffusion too.

For marine energy, complementary infrastructure will be an increasingly important issue as community- and utility-scale systems become more viable (most likely for tidal stream projects in the near term). Planning for and building out this infrastructure in tandem with the mobilisation of marine energy resources can help ensure that marine energy innovations flourish.

Some sites for offshore grid interconnectivity will already exist in certain locations but may not be the best sites for marine energy from an energy potential perspective.[91] In some cases, marine energy will be able to take advantage of offshore wind's first mover status and reduce overall costs. This would especially be the case for co-located marine and wind energy which can improve predictability and power output, among other potential benefits.[92] In other cases, innovative approaches to project development around electrical interconnectivity and complementary infrastructure could help expand the market potential of marine energy.

For micro-power marine energy solutions, complementary infrastructure will serve as less of a barrier but still remain an important consideration. This is true for projects like remote AUV charging networks.[93] Simultaneous development and installation of remote charging stations alongside the AUVs themselves would require extensive co-ordination but could nonetheless prove to be the best method for rolling out this technology. Ongoing collaboration from all stakeholders—like energy system developers,

[ix] In this case, the infrastructure that enables the successful development, deployment and use of energy systems

AUV manufacturers and regulators in the case of in-situ AUV recharging—could significantly accelerate the development of new energy innovation systems for the blue economy.

> **"There is a need for innovation around the infrastructure required for project development. Many countries have highlighted the importance of electrical interconnections for offshore energy and the need for innovation in this area."**
>
> Francisco Boshell, IRENA

Towards the future of the blue economy

It will take a concerted effort among stakeholders from all corners to drive a new era of energy innovation for the blue economy.

With regard to marine energy specifically, barriers remain—particularly around rapid testing of new technologies (a difficult task for marine technologies in general), policy and financing. There is interest across the blue economy in the promise of marine energy, ranging from micro-scale uses all the way to utility-scale power generation. However, this promise has yet to be delivered upon. Through continued collaboration and improvement of the enabling environment, all stakeholders in the ocean economy can work together to accelerate innovation and drive marine energy technologies forwards—perhaps even paving the way towards a truly "blue" economy in the process.

Annex: Research methodology

A. Interview programme

The Economist Intelligence Unit conducted interviews with 30 blue economy, energy innovation and marine energy experts between June and August 2020. The aim of the interview programme was to work with experts in the field to guide our research, select case studies and establish the central elements of the energy innovation environment for the blue economy.
The interview programme consisted of discussions around the following topics:

- Trends in the blue economy, including major growth and emerging sectors
- Energy usage in the blue economy
- Most important aspects of energy innovation, including the principal enablers of energy innovation within the blue economy
- Key past energy innovations within the blue economy
- Current state of the marine energy field, major drivers of marine energy innovation, barriers to progress for marine energy and the future of marine energy
- Interviewees' specific areas of expertise

B. Method of impact assessment

To support the development of the case studies for this report, The Economist Intelligence Unit developed a conceptual framework that was used to identify the most impactful energy innovations to have taken place within the blue economy. Considerations around market impact,

Method of assesment for impact of energy innovations in the blue economy	
Main Output	**Sub outputs and outcomes**
1) Market impact	Market growth—for instance in value
	Market opening—for instance creation of new market
	Market transformation—for instance the creation of opportunities in existing markets, or the creation of new ways for old markets to reinvent themselves (even if there was not substantial growth)
2) Innovation environment impact	Extent to which an energy innovation enabled the development of other complementary and future innovations
	Extent to which an energy innovation improved the energy innovation ecosystem
3) Expert relevance	Number of experts who mentioned an innovation
	Extent to which experts who mentioned an innovation believed a given innovation was inpactful

innovation environment impact and expert relevance were included:

For case study decision-making, primary weighting was given to expert relevance.

Market impact and innovation environment impact were relied upon in the following ways:

1) Informing the questions asked of expert interviewees—for instance inquiring specifically about innovations that had grown markets, created new markets or transformed existing markets

2) Informing understanding of impact—primarily investigated during the literature review with more research subsequently conducted on each case

3) Informing conceptual framing—for instance by examining the extent to which energy innovations have driven impact in other sectors, clarifying how energy impacts can shape markets and exploring how markets themselves can then inform and drive energy innovation (based on the literature review)

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