Innovation in the Blue Economy:

Opportunities in Shipping, Aquaculture, and Offshore Wind for Climate Change Mitigation

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Executive Summary

As the world's population continues to grow, increasing pressure will be placed on the ocean's valuable resources. It is predicted that by 2030, nearly two-thirds of the fish on our plates will be farmed at sea; by 2040, global offshore wind capacity will have increased fifteen-fold; and by 2050, seaborne trade will have nearly quadrupled. Climate change effects including ocean warming, ocean acidification, sea level rise, and increased frequency of extreme storms threaten the ocean ecosystem and the livelihoods that rely on the ocean economy. An aspiration to balance sustainable economic growth, improved living standards, and ecosystem conservation has given rise to the term "blue economy" and an increased interest in the emerging bluetech area.

We conducted semi-structured interviews with leaders in bluetech and experts in the shipping, aquaculture, and offshore wind industries. We identified the main risks that climate change poses to these industries and analyzed current and future opportunities in technology and innovation to decarbonize these industries. A summarization of our findings can be found in Table A.

From this analysis, we developed the following takeaways: 1) Cross-sector partnerships allow companies to capitalize on advancements made in each individual industry, and should be pursued as a priority; 2) Digitization is a key element of improving efficiencies within all three sectors, and companies should look to bluetech hubs for promising digital innovations; 3) Utilizing economies of scale can drive down costs and reduce emissions; 4) All three sectors recognize that they have a role in increasing social equity and inclusion but so far have been slow to act toward that goal.

	Shipping	Aquaculture	Offshore Wind
Climate Change Impacts	Increased storm intensity, sea level rise, and changes in business strategy were the most mentioned climate change impacts.	Industry experts identified increased temperatures, increased storm intensity, acidification, sea level rise as impacts from climate change.	The offshore wind industry hasn't been negatively impacted by climate change, rather it has driven the demand for renewable energy and led some energy companies to partially or fully divest from oil and gas.
Sustainability Priorities	Industry experts all identified climate change as the most important sustainability priority for the shipping industry. Other priorities include air pollutants (including the IMO 2020 sulphur cap), biodiversity, and ship recycling.	Many experts mentioned limiting their impact on the surrounding environment as a sustainability priority. Alleviating wild stocks, fish feed alternatives, decreasing carbon footprint, and using sustainable packing were all identified as sustainability priorities for the aquaculture industry. In addition, many experts discussed the need for a social license.	Offshore wind interviewees all consider the offshore wind industry inherently sustainable, but still recognize minimizing wildlife impacts and improving energy storage as priorities for the industry. Additionally, a majority of the offshore wind developers and OEMs in the U.S. have sustainability reports and specific carbon reduction targets.
Climate Change Mitigation	Speed optimization, mega ships, marginal improvements to increase efficiency, secondary energy sources, and digitization are being used to lessen the industry's carbon emissions. Hydrogen, biofuels, and methanol were identified as promising low carbon fuel sources.	Using macroalgae, integrated multi-trophic aquaculture, renewable energy, partnering with offshore wind, sustainable packaging were all mentioned as promising innovations and technologies. Creating a more efficient environment and incorporating digitization and automation will help mitigate climate change.	Turbine improvements (e.g., floating, larger turbines), turbine recycling, digitization and automation, vessel improvements, and green hydrogen were all identified as areas where there is promising technology being developed that will improve efficiencies or expand offshore wind.
Social Impacts	COVID-19 has revealed inefficiencies along the supply chain. Experts are hopeful that the industry will invest in technologies that will improve efficiency while lowering carbon emissions. Although increasing diversity and inclusion is a stated industry priority, few metrics are actually reported and there needs to be more actionable change.	COVID-19 revealed areas of vulnerability in their supply chains and affected market dynamics. Industry experts discussed the opportunity for aquaculture to help with food security and create jobs. Experts also acknowledged the usual buyers of production from aquaculture and how accessibility to the industry should be increased.	The offshore wind sector has been minimally affected by the COVID-19 pandemic. Offshore wind experts recognize the industry's role in addressing environmental justice and job creation in the U.S. They also noted that some companies are having conversations about diversity and inclusion and some have set diversity targets, however much of this work is still in the early phases.

Table A. Summary of findings from the shipping, aquaculture, and offshore wind sectors.

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Introduction

Changing Human Use of the Environment

The ocean is a major contributor to the global economy, and if it were a country it would have the seventh largest economy in the world (Hoegh-Guldberg et al., 2015). It provides us with valuable resources and services such as food, transportation, energy, and tourism. As the world's population continues to expand, increasing pressure will be placed on the ocean's valuable resources. It is predicted that by 2030, nearly two-thirds of the fish on our plates will be farmed at sea (World Bank, 2013); by 2040, global offshore wind capacity will have increased fifteen-fold, becoming a $1 trillion industry (IEA, 2019); and by 2050, seaborne trade will have nearly quadrupled (Patil, Virdin, Diez, Roberts, & Singh, 2016). Healthy ocean ecosystems will be vital for sustaining the world's future population; however, climate change, overfishing, loss of biodiversity, and degrading habitats threaten nature, livelihoods, and lives (Konar & Ding, 2020). An aspiration to balance ecosystem conservation with sustainable economic growth and improved living standards has given rise to the term 'blue economy' (Voyer et al., 2018).

The portion of the economy that relies on the ocean as an input or takes place on/in the ocean is referred to generally as the 'ocean economy' (Kildow & McIlgorm, 2010). Conversely, the 'blue economy' is often used to refer to a portion of the ocean economy that emphasizes *sustainability* and *social equity*; however, the definition of blue economy often varies - with some stakeholders confounding the blue economy with the ocean economy (Voyer et al., 2018). In order to dispel confusion regarding what constitutes the blue economy, this paper will adhere to the principles of a sustainable blue economy outlined by the World Wildlife Fund (World Wildlife Fund, 2015). According to this definition, a blue economy is "a marine based economy that provides social and economic benefits for current and future generations… restores, protects and maintains the diversity, productivity, resilience, core functions, and intrinsic value of marine ecosystems… [and] is based on clean technologies, renewable energy, and circular material flows" (WWF Baltic Ecoregion Programme, 2015).

Impacts of Climate Change

Certain gasses such as carbon dioxide (CO_2), methane, and nitrous oxide cause a "greenhouse effect" in our atmosphere, trapping energy in the form of heat. Increased anthropogenic greenhouse gas emissions have intensified this greenhouse effect and caused the

average global temperature to rise (Denchak, 2019). The ocean functions as a climate regulator by absorbing the excess energy in the form of heat (Magnan et al., 2015). According to the Fifth Assessment Report published by the Intergovernmental Panel on Climate Change (IPCC), the ocean has absorbed roughly 93% of the extra energy created by increased carbon dioxide and other greenhouse gas emissions (IPCC, 2019). As a consequence, the ocean, coastlines, and coastal communities are being disproportionately impacted by the effects of climate change. Major impacts of climate change on the ocean are outlined below.

- **Ocean warming:** According to the IPCC, the average rate of ocean warming has more than doubled since 1993 and marine heatwaves have doubled in frequency since 1982 (IPCC, 2019). Though ocean warming is not homogenous across the globe. The 2019 IPCC assessment found that the Southern Ocean accounted for 35-43% of the total heat gain in the upper global ocean between 1970 and 2017 (IPCC, 2019). Ocean warming has occurred particularly at the surface which, when coupled with the addition of freshwater from melting glaciers and ice sheets, has made the surface waters of the ocean less dense than the deep waters. This causes a stratification that inhibits the normal mixing of surface waters with the nutrient-rich deep waters (Kaartvedt & Titelman, 2018).
- **Sea level rise:** Rising atmospheric and oceanic temperatures are causing the global sea level to rise in two ways: 1) glaciers and ice sheets are melting and adding water to the ocean, 2) the volume of the ocean is increasing as a result of thermal expansion (Nicholls & Cazenave, 2010). By the end of the century, the global mean sea level is expected to rise at least 1 foot above the mean level in 2000 (Lindsey, 2021). Higher sea levels can cause devastating effects to coastal communities including increased storm surges, destruction of infrastructure such as ports and wastewater treatment facilities, salt intrusion into drinking water sources, flooding, and loss of habitat for fish, birds, and plants (OW U.S. EPA, 2014).
- **Increased frequency of extreme storms:** Rising sea surface temperatures are also intensifying tropical cyclones, including hurricanes and typhoons (Kossin, 2018). Severe storms coupled with higher sea levels create more devastating storm surges often leading to loss of life in coastal communities (Nunez, 2019).

- **Ocean acidification:** Not only does the ocean absorb excess heat but the chemistry of the ocean also allows it to function as a global "carbon sink," meaning it can absorb atmospheric CO_2 (Kapsenberg & Cyronak, 2019). It is estimated that the ocean has absorbed about 28 percent of the excess carbon dioxide produced by anthropogenic activities over the last 250 years (IPCC, 2014). Increased carbon dioxide dissolved in the ocean lowers ocean pH, a phenomenon known as ocean acidification (Gravinese et al., 2019). Ocean acidification makes it difficult for organisms such as corals, crabs, and oysters to produce the minerals necessary to create their hard shells and skeletons (OAR U.S. EPA, 2016). This can have a cascading effect on the ocean ecosystem, potentially affecting fish populations and aquaculture.
- **Changing migration patterns and geographical ranges of marine species:** Global climate change has also affected the distribution and migration patterns of marine species. As the ocean's temperatures rise, many marine species are moving toward the poles where the water is cooler (Poloczanska et al., 2013). Marine species migration patterns and distribution in the water column have also been impacted by changes in ocean currents and stratification as a result of rising temperatures (Kaartvedt & Titelman, 2018; Xavier et al., 2016). Shifts in fish stocks have, and will continue to severely affect coastal communities and small island nations that rely on marine protein for their diet (He & Silliman, 2019).

Global Push for Decarbonization

As concerns about climate change increase, the relationship between anthropogenic activities and changes in ocean ecosystems is being incorporated into government regulations and industry goals. International organizations, nations, and companies have adopted goals and policies aimed at lowering carbon dioxide and other GHG emissions in an effort to mitigate climate change and lessen the detrimental effects highlighted above.

In 2015 the United Nations (UN) member states adopted the 2030 Agenda for Sustainable Development and set 17 Sustainable Development Goals (SDGs) to "achieve sustainable development in its three dimensions - economic, social, and environmental" (UN, 2015). These SDGs include:

- Goal 7: Ensure access to affordable, reliable, sustainable and modern energy for all

- Goal 9: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation
- Goal 11: Make cities and human settlements inclusive, safe, resilient and sustainable
- Goal 13: Take urgent action to combat climate change and its impacts
- Goal 14: Conserve and sustainably use the oceans, seas and marine resources for sustainable development

As the name implies, the 2030 Agenda aims to have full implementation of these goals by the year 2030 (UN, 2015). The goals highlighted above have brought more attention to sustainable innovation, particularly within the growing blue economy (Bennett et al., 2019).

Additionally in 2015, the Paris Agreement was adopted by 196 state parties in an effort to combat climate change (UNFCCC, 2015). Participating parties agreed to limit global warming to below 2 degrees above pre-industrial levels while pursuing efforts to limit the increase to just 1.5 degrees (UNFCCC, 2015). The agreement provides a framework for monitoring, reporting, and expanding climate goals for each individual country and encourages developed nations to assist developing nations in their efforts (Denchak, 2021). In 2021 the U.S. re-entered into the agreement, establishing climate change mitigation as a top priority. In the same year, President Biden also laid out a robust national climate action plan, pledging $2 trillion in investments over the next four years and supporting policies aimed to achieve a carbon neutral nation by 2050 (Biden, 2021).

Individual states in the U.S. have also set goals for climate change mitigation, often focusing on renewable energy sourcing. For example, in 2018, California established a goal to rely entirely on zero-emission energy sources for its electricity and become carbon neutral by 2045 (Domonoske, 2018). Additionally, many states in New England have established renewable energy goals with some setting specific goals for offshore wind energy procurement. Massachusetts currently has an offshore wind procurement authorization of 3,200 MW, Connecticut has begun a procurement of 2,000 MW of offshore wind energy, and Rhode Island has committed to purchasing 400 MW of offshore wind from a newly proposed wind farm (Wilson, 2020).

Industry organizations and individual companies have also pledged to reduce carbon emissions. In 2018 the International Maritime Organization (IMO) adopted an initial strategy to halve GHG emissions from ships by 2050 compared to a 2008 baseline and phase them out

completely as soon as possible (IMO, 2018). Private companies have also announced carbon or GHG emissions reduction targets. For example, A.P. Moller Maersk, a maritime shipping company, has set out to achieve net zero carbon dioxide emissions by 2050 (Maersk, n.d.). Although some companies have yet to take significant steps toward achieving these goals, this represents an important first step toward aligning private corporations with global decarbonization goals.

Emergence of Bluetech

With the growing blue economy has come an increased interest in the emerging bluetech area. Bluetech can be broadly defined as any technology that is applied to the ocean (stakeholder interview, bluetech hub), but often focuses specifically on technology that drives environmental, social, and economic sustainability within the ocean (CIC, 2020). Bluetech plays an important role in achieving the SDG targets for sustainable ocean development (Hansen et al., 2018) and addressing ocean-related challenges in areas such as shipping, ports, fishing, aquaculture, offshore renewable energy, and plastic pollution (Sea Ahead, n.d.).

The larger bluetech ecosystem consists of not only investors and startups, but also innovation hubs, accelerators, and incubators that help develop and support startups and accelerate investment in ocean technologies (Hume, 2020). The bluetech ecosystem is growing worldwide, and there are now more than 120 incubators, accelerators, and other marine-focused innovation hubs (The Liquid Grid, 2021). These can be explored using the virtual Innovation Ecosystem tool.

Research Objective and Scope

There are at least a dozen different sectors operating within the blue economy (European Commission, 2020; Patil et al., 2018). To narrow our scope, we focused on three - shipping, aquaculture, and offshore wind. We chose these specific industries for a few key reasons:

1) They have all experienced significant growth in recent years and are projected to continue that growth.
2) They will each play a crucial role in supporting a growing global population.

3) Each presents unique opportunities and challenges to contribute to decarbonizing the ocean economy.
4) They represent three large sectors within the ocean - transportation, seafood, and offshore energy.

We limited the geographic scope to the U.S. when feasible. However, all industries have an international component and therefore a global perspective was necessary. Specifically, shipping is an international activity by nature and the five largest companies are based outside of the U.S. (Shin et al., 2019).

Using these sectors, we wanted to answer two main research objectives. Our first objective was to look at the current efforts and future opportunities within the shipping, aquaculture, and offshore wind sectors to contribute to decarbonization and thus mitigate climate change. To answer this, we identified a number of sub-questions including 1) Is climate change a main sustainability priority for the industry 2) do companies within each sector have stated climate plans and emission reduction targets, and 3) how are companies using innovation and technology to reduce emissions?

Our second main objective was to determine the risks that climate change (e.g., sea level rise, biodiversity loss, increased storm intensity) poses to each of these sectors. This is important as the effects of climate change can serve as a driver for decarbonization and creating technological innovations that make these industries more resilient. Determining the biggest effects of climate change on each industry and how they are planning to adapt to future effects will allow us to gain insight into how each of these industries views the importance of climate change mitigation. If they believe the effects of climate change will be disastrous or pose a business risk, they will likely be more inclined to invest in low carbon technology.

Methods

We used both qualitative primary and secondary research methods to complete this study. We began with secondary research, which included a preliminary review of scientific papers, industry reports, and industry databases. Next, we collected primary research by interviewing shipping, aquaculture, and offshore wind energy industry leaders and bluetech innovators.

Review of Literature

We started with a current review of the literature to build foundational knowledge on each industry's relationship with climate change and technological innovations. The goal was to familiarize ourselves with each of the industries and the key sustainability challenges they each face. We searched through scholarly databases, including Google Scholar and Duke University's Libraries Catalog, to conduct the review. We used a standardized set of key terms and phrases, as shown in Table 1. We also found scientific articles and industry reports through databases created by our advisors on this project. We reviewed both peer-reviewed and non-refereed literature and reports produced by bluetech hubs, government agencies, academia, and non-governmental organizations. We reviewed the literature on each industry and the blue economy to develop an understanding of where each industry was in their process of developing climate change initiatives. We also researched how each industry planned on employing innovations to adapt to and mitigate climate change.

Industry/Topic	Phrases
Blue Economy	"ocean economy decarbonization," "blue economy decarbonization," "ocean technology," "blue economy and climate change," "blue economy and technology"
Shipping	"shipping technology," "shipping innovation," "shipping technology decarbonization," "low carbon shipping," "sustainable shipping," "shipping and climate change," "shipping fuels"
Aquaculture	"aquaculture technology," "aquaculture innovation," "aquaculture technology decarbonization," "low carbon aquaculture," "aquaculture supply chain," "sustainable aquaculture," "aquaculture and climate change," "finfish aquaculture technology and climate change," "shellfish aquaculture technology and climate change," "kelp aquaculture technology and climate change"
Offshore Wind	"offshore wind technology," "offshore wind innovation," "offshore wind technology decarbonization," "low carbon offshore wind," "offshore wind supply chain," "offshore wind sustainability," "offshore wind and climate change"

Table 1: Search terms for literature review.

Interview Process

The second step of our qualitative process was to conduct semi-structured interviews. We interviewed twenty-four individuals from stakeholder groups identified in Table 2. We identified individuals within these stakeholder groups through our initial background research, by attending conferences and presentations, and through introductions made by Duke faculty. We reached out to these individuals by email or LinkedIn Messenger. Additionally, some stakeholders provided us with their contacts within the industry or bluetech sector that would potentially be willing to speak with us. This helped us reach contacts that may not have been as accessible before. Overall, we interviewed twelve stakeholders in the aquaculture industry, six in the offshore wind industry, six in the shipping industry, and two in the bluetech hub sector.

We used a semi-structured interview method where we had set questions, but questions were open-ended and allowed us to ask follow-ups (Appendix C-F). We also tailored each interview to the stakeholder and industry we were interviewing. Each interview was completed over Zoom and lasted thirty to sixty minutes. We had three parent level themes to our questions, climate change adaptation, climate change mitigation, and COVID-19/social impacts. Our questions highlighted what we might not have gathered from background research such as interviewees' opinion of the industry's status with climate change and where each industry was planning on going in respect to climate change.

Industry/Topic	Stakeholder Groups	
Blue Economy	• Bluetech hub founders	
Aquaculture	• Non-governmental organizations • Shellfish companies • Seaweed companies • Aquaculture innovator	• Aquaculture tech hubs • Finfish companies • Federal government • Academia
Shipping	• Maritime shipping companies • Consulting agencies • Ports	• Shipping associations • Trade associations
Offshore Wind	• Offshore wind producers • Non-profit organizations	• Consulting agencies • Turbine manufacturers

Table 2: Key stakeholder groups represented in our interviews.

Institutional Review Board

Before starting the interview process, we needed approval from the Duke University Campus Institutional Review Board (IRB) because our research included human subjects. Since there were no risks associated with our research, we were allowed to apply for an exemption to the full IRB review. In line with IRB protocol, we designed an informed consent document to share with participants how their information would be used, clarify that their participation was voluntary, and asked for permission to record (Appendix B). At the beginning of each interview we confirmed that we had permission to record and they understood they had the option to end the interview at any time. For confidentiality, we have kept interviewees' identities anonymous.

Analysis

Each interview was recorded on Zoom and through Otter.ai. We used the Otter.ai software to transcribe the interviews. After the transcription was checked for clarity, the recordings were destroyed for confidentiality. The transcriptions were then uploaded to NVivo 12 for analysis. Interviews from the individual industries were initially only compared to those within the same industry. Each industry had the same four parent themes with two to five subthemes under each parent theme (Tables 3-5). After the individual industries were analyzed,

we collectively compared our results and studied if there were any overlaps. Once the analysis was completed and the industries were compared, we developed key takeaways from our qualitative research of the literature review and stakeholder interviews.

Parental-Level Theme	Subthemes
Sustainability Priorities	• Climate Change • Other
Climate Change Impacts	• Sea Level Rise • Increased Storm Intensity • Changes in Business Strategy • Other
Climate Change Mitigation	• Efficiency • Digitization • Alternative Energy Sources
Social Impacts	• COVID-19 • Environmental Justice • Diversity and Inclusion

Table 3: Parent-Level Themes and Subthemes from shipping industry interviews.

Parental-Level Theme	Subthemes
Sustainability Priorities	• Environmental Impact • Fish Feed • Alleviating Wild Fish Stocks • Social License • Other
Climate Change Impacts	• Increased Temperatures • Increased Storm Intensity • Acidification • Sea level Rise • Adaptation to Climate Change Impacts
Climate Change Mitigation	• Microalgae • Integrated Multi-trophic Systems • Digitization • Efficiency • Other
Social Impacts	• COVID-19 • Diversity and Inclusion • Job Creation

Table 4: Parent-Level Themes and Subthemes from aquaculture industry interviews.

Parental-Level Theme	Subthemes
Sustainability Priorities	● "Built in" Sustainability ● Wildlife Impacts ● Energy Storage
Climate Change Impacts	● Increased Demand ● Expanded Renewable Portfolio
Climate Change Mitigation	● Turbine Improvements ● Turbine Recycling ● Digitization/Automation ● Vessel Improvements ● Green hydrogen
Social Impacts	● COVID-19 ● Social Equity

Table 5: Parent-Level Themes and Subthemes from offshore wind industry interviews.

Limitations and Challenges

We had limitations and challenges throughout our research. Although we surpassed our original goal to interview sixteen stakeholders in the bluetech sector, aquaculture, shipping, and offshore wind industries, the small sample size still does not represent all of these sectors as a whole. We reached out to numerous contacts in each industry, but many emails and messages went unanswered. The unanswered emails could have been because of multiple reasons, but most likely from COVID-19. We were also limited in time due to a firm deadline to complete this study. To further this research, a larger sample size from each industry would need to be completed.

Shipping

Approximately 90% of global trade is transported by maritime shipping and it is, as one industry expert noted, "the backbone of the economy" (stakeholder interview, bluetech hub). However, the maritime shipping industry also accounts for approximately 2-3% of global GHG emissions annually - emissions comparable to whole nations such as Germany (~2.2%) or Japan (~3.3%) (Christensen, 2020). The IMO estimates that if no efforts are made to decarbonize the

shipping industry, emissions could increase up to 250% by 2050 (IMO, 2014). To restrict global warming to less than 2℃, the shipping industry needs to develop and start on a pathway toward decarbonization (Tatar & Özer, 2018). In this section we identified the impacts of climate change on the industry, the current sustainability priorities, promising decarbonization technology and innovation, and how a low carbon shipping industry can contribute to social equity.

Climate Change Impacts

Both the literature and interviews with industry experts revealed four subthemes within the larger parent-theme of climate change impacts. Sea level rise and increased storm intensity were the two most mentioned climate change impacts, with some literature and interviewees discussing spatial shifts. Changes in business strategy was another widely discussed subtheme.

Sea Level Rise

Although sea level rise does not necessarily affect ships - as one industry expert stated: "ships float" (stakeholder interview, shipping association) - ports are increasingly worried about the potentially destructive forces associated with rising sea levels (stakeholder interview, ports). Loss of infrastructure due to increased erosion, destructive storm surges, and salt intrusion could cost the industry billions of dollars. One industry expert noted that "just in San Pedro Bay we're talking about many billions of dollars worth of infrastructure that is potentially at risk from long term impacts" (stakeholder interview, ports). Additionally, massive storm surges that result from dual climate change effects, higher sea level and severe storms, can cause supply chain delays. A stakeholder recalled the aftermath of Superstorm Sandy in 2012 and how it "decimated the New York and New Jersey supply chain from the maritime standpoint [because] there was so much debris for days you couldn't bring in vessels" (stakeholder interview, shipping consulting agency). The potential economic consequences of these supply chain disruptions are an important factor in the industry's concern about climate change.

Increased Storm Intensity

All 6 industry experts interviewed for this study acknowledged that increased frequency of severe storms is the most significant impact of climate change on the industry's operations in the present moment. Severe storms can cause containers on ships to shift and at times topple

overboard. One industry expert referenced the fact that Maersk lost 750 containers as recently as January 2021, when a ship encountered a storm while traveling from China to Los Angeles (stakeholder interview, ports). This was not an isolated incident, in November of 2020 another container ship encountered a storm and lost $220 million worth of cargo (Paris, 2021). While it is not abnormal for some containers to be lost or damaged because of storms, "those kinds of shipping losses [aren't] really normal" (stakeholder interview, ports). According to the World Shipping Council, the average number of containers lost at sea since 2008 is 1,382 (World Shipping Council, 2020). In contrast, maritime insurance executives have estimated roughly 3,000 containers were lost at sea between December 2020 and January 2021 (Paris, 2021).

Spatial Shifts

Global climate change has also created shifts in weather patterns on land that are affecting the agriculture industry and, in turn, the shipping companies that transport agricultural goods around the globe. Climate zones are predicted to shift toward the poles, increasing yields in higher latitudes and decreasing yields in lower latitudes (Anderson et al., 2020). Some shipping companies are worried about how this might affect their operations. An industry expert noted,

> The good news for us is that, you know, we can assign ships to different routes, [but] the tough news is figuring out what are the right routes, what are the right ships, and making sure that there are ports that can handle those ships accessible to say, the farmers in that region or that manufacturers in a given region" (stakeholder interview, maritime shipping company).

Climate change also affects species distribution in the ocean which may lead to conflicts between the shipping industry and other ocean stakeholders. One industry expert recollected a series of ship strikes on the endangered Northern Atlantic Right Whale stating, "because of climate change they went [a few] years ago up into the St. Lawrence Seaway which they never have done before and 12 of them were killed by ships that one season" (stakeholder interview, shipping consulting agency). The shipping lane then needed to be moved in order to avoid the endangered whale (NOAA, 2018). Global fish stocks have also shifted as a result of climate

change impacts on ocean temperature and currents (He & Silliman, 2019). Future changes in species distribution of commercial fish stocks will undoubtedly lead to conflicts between the shipping and fishing industries as well.

Not only is climate change presenting challenges to the industry, it is also presenting opportunities for new shipping routes and increased shipping windows through the poles. An industry executive spoke with cautious excitement about how "the windows that we have to deliver the fuel into the northernmost communities [in Alaska] during the summer are growing longer" (stakeholder interview, maritime shipping company). Thinning arctic sea ice due to climate change has presented the opportunity for new trans-Arctic navigation routes that may shorten transportation time and distance, resulting in lower GHG emissions (Wang et al., 2020). Importantly, traffic in the Arctic would result in serious environmental and social impacts. Noise pollution, invasive species from ballast water exchange, and oil spills could severely impact marine mammals and the indigenous peoples who rely on them (Ng et al., 2018)

Business Strategy Changes

The impacts highlighted above - sea level rise, increased storm intensity, agricultural shifts, etc. - have or will affect shipping operations and infrastructure for the most part. But climate change is also impacting how the shipping industry does business. A few industry experts noted how in the past customers would choose to work with a shipping company based on which company would get their goods where they needed to go the fastest and the cheapest. An expert working for a shipping company spoke about the fact that their customers are demanding sustainable options stating,

> "We're seeing customers stepping up to the plate, and for the first time being willing to pay more for a net-zero carbon product... Nike is saying zero is the target - and they're saying that now - so is IKEA, so is H&H and Levi's, and Disney and, gosh, a huge list of our biggest shippers are now saying, zero is the target and a few of them are even stepping forward and saying yes, we are willing to pay more today to ship our product on net carbon neutral" (stakeholder interview, maritime shipping company).

According to a 2020 consumer insight survey, 73% of surveyed consumers wanted to reduce the impact they have on the planet, a 10% increase from the year before (GlobeScan, 2020). Though studies have also shown that consumers don't want to sacrifice performance, convenience, or price in order for sustainable products (De Socio, 2021). Companies are now focusing on how to create smart, fast, low-cost strategies that incorporate sustainability to attract more customers. This can obviously pose a challenge since strategies and technologies that incorporate sustainability are often not 'fast.'

Maersk, often cited as a leader for sustainability in the shipping industry in our interviews, offers an innovative "Eco Delivery" option for its customers. Through this option, customers purchase carbon neutral biofuel that Maersk will use to power certain ships (Maersk, n.d.). Low carbon and carbon neutral fuels at the moment are not available at scale to use in all ports around the globe and therefore not all goods are able to be delivered aboard ships powered by carbon neutral fuels. A shipping company industry expert used an example of a customer saying, "I want these bows and containers that go between say Vietnam and Long Beach, California to be shipped at carbon neutral… but the fuel is only available in Rotterdam" (stakeholder interview, maritime shipping company). Instead of only allowing an eco-delivery option to customers who need to ship goods from ports that have access to biofuels, Maersk calculates the carbon footprint created by shipping the goods along the preferred route and the customer purchases enough biofuel to effectively cancel out those carbon emissions. As opposed to carbon offsets that often provide future carbon reduction (through controversial programs like tree planting programs), this method provides direct carbon savings and is referred to as "insetting… because it is actually reducing the amount of petroleum-based fuel that we purchase today" (stakeholder interview, maritime shipping company). Some scholars have also shown that the carbon offsets used to achieve net zero or carbon neutral goals often do not capture the amount of carbon they are offsetting (McLaren, 2019). This should be taken into consideration when evaluating the stated goals and actions of companies hoping to achieve 'net zero' emissions through these types of programs.

Sustainability Priorities

While this paper emphasizes the necessity of decarbonization, we felt it was important to decipher how the shipping industry views climate change and decarbonization relative to other

sustainability priorities. In an analysis of this topic, we found that the vast majority of literature and interviews discussed climate change as the top priority for the sustainability industry at the moment. Because of this, we identified "climate change" as the main subtheme under sustainability priorities with all other sustainability priorities grouped into the subtheme "other."

Climate Change

According to public sustainability reports, four of the five largest shipping companies (representing over 60% of the global fleet) list climate change, emissions, or decarbonization as a top material issue. These include A.P. Moller Maersk (referred to as Maersk), China Ocean Shipping Company (COSCO), CMA-CGM, and Hapag-Lloyd. Mediterranean Shipping Company (MSC) did not explicitly state climate change or a related issue in their materiality assessment but lists "environment" as one of their four sustainability pillars and emphasizes working toward the UN Sustainable Development Goals (SDGs) including SDG 13 (Climate Action) and SDG 14 (Life Below Water). Additionally, three out of the five companies have established specific carbon emissions reduction goals: CMA-CGM has pledged to become carbon neutral by 2050; Hapag-Lloyd's goal is a 20% reduction by 2020 compared to a 2016 baseline (their 2020 emissions data has not been published at the time this paper was written), and Maersk has a goal of reaching net-zero emissions by 2050. While MSC does not have a specified emission goal, the 2019 sustainability report implies that it supports the IMO target of a 50% carbon emissions reduction by 2023 from a 2008 baseline and is enacting policies to help achieve that goal. COSCO is a Chinese state-owned shipping company and aligns its goals with China's emissions reductions.

When asked their opinion on sustainability issues for the industry as a whole, five out of six shipping industry experts interviewed believed climate change was the top issue. One expert stated "I think the whole shipping industry has really recognized that climate change *is* the challenge" (stakeholder interview, maritime shipping company) and another commented that "there are a lot of aspects of shipping that touch on sustainability, but probably the biggest one is the carbon emissions that come from the burning of the bunker fuel" (stakeholder interview, shipping consulting agency). All 5 of these industry experts also cited other sustainability issues that will be discussed in the following sections, but climate change was emphasized as the most urgent and material to the industry at the moment.

Industry experts discussed increased regulation, customer demands, talent acquisition and retention, and risk management as the main reasons behind the focus on climate change. With the International Maritime Organization's goal of 50% carbon emission reduction by 2050, the pressure is on the shipping industry to create solutions now. Because the lifespan of a ship is normally 20-30 years, "a lot of companies think that whatever technology is going to get us there, it needs to be decided upon by 2030 in order to meet the 2050 goals" (stakeholder interview, shipping association). As 2030 gets closer, meeting the IMO's 2050 goal becomes even more of a worry, and therefore a priority, for shipping companies.

As stated in the above section, customers are demanding shipping companies offer low carbon or zero carbon shipping in order to appeal to consumers. For the same reason consumers are demanding low carbon shipping, employees are demanding the companies they work for contribute to a more sustainable economy (Aziz, 2020). Studies have shown that 64% of millennials won't take a job if a company doesn't have a strong corporate social responsibility (CSR) policy and that most millenials would take a pay cut to work at an environmentally sustainable company (Aziz, 2020). An industry expert emphasized this point.

> "Millennials want to work for companies that are sustainable, that are socially responsible, and that are good corporate citizens - we know that… and if I can't attract talent that is young and went to Duke, or went to Middlebury or went anywhere else that's a top tier academic institution, if I can't get them to work for me, because you would rather work for Tesla, or SpaceX or Nicola or whatever company then I have a problem" (stakeholder interview, maritime shipping company).

Research has also shown that workers who identify with and support their company's CSR policy perform better on the job (Korschun et al., 2014). Companies that do not invest in an ambitious and salient CSR policy will find themselves at a disadvantage.

One expert believed safety was a main driver behind the industry's push to decarbonize because "it's abundantly clear to anyone who's read the science and believes in science that climate change is posing a real existential safety threat not only to the communities in which we operate but also to our businesses [because] infrastructure is at risk" (stakeholder interview, maritime shipping company). As mentioned previously, the shipping industry is already losing

millions of dollars worth of cargo due to severe storms. Climate change is also posing a threat to port infrastructure. In 2021 Superstorm Sandy shut down the Port of New York and New Jersey for more than eight days and caused severe damage to waterfront buildings and infrastructure (Izaguirre et al., 2021).

Other Sustainability Issues

Other sustainability challenges mentioned both in literature and in interviews with industry experts were air pollutants (including the IMO 2020 sulphur cap), biodiversity, and ship recycling. In 2017 the IMO announced that as of January 1, 2020 the sulphur content allowed in the fuel oil used on ships would be reduced to 0.5% m/m (mass by mass) from the previous limit of 3.5% (*IMO 2020 – Cutting Sulphur Oxide Emissions*, n.d.). Meeting this stricter regulation was a top sustainability priority most likely because the shipping companies' sustainability reports referenced in this paper were published in 2019 or 2020 (reporting on 2019).

Climate Change Mitigation - Technologies & Innovation

An industry expert put it best when they said that in order to reach the sustainability goals outlined above and decrease the risks from climate change impacts "it's going to require us to reinvent shipping" (stakeholder interview, maritime shipping company). Figure 1 illustrates the emissions gap that would occur if the shipping industry continues with business-as-usual emissions and no innovative solutions are employed by the industry going forward. Bluetech hubs, maritime shipping companies, ports, and other shipping industry stakeholders are all working to develop technologies and innovative solutions to lower the industry's carbon emissions. Through background research and interviews with shipping industry experts and bluetech hub leaders we identified three broad categories of climate change mitigation technology and innovation: efficiency, digitization & automation, and alternative energy sources.

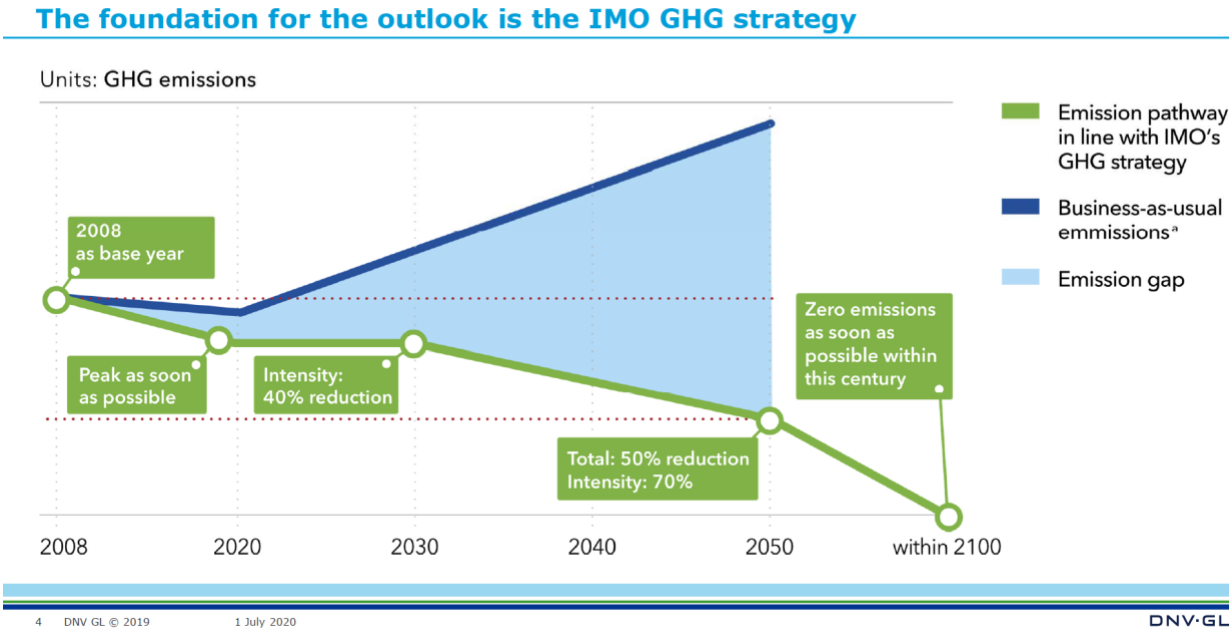

Figure 1: Emissions gap between IMO's GHG reduction strategy and a scenario where the shipping industry continues with 'business-as-usual' emissions. (credit: DNV GL)

Efficiency

Technologies & innovations within this sub-category are those that allow for the maximum productivity while using the least amount of energy (Dewan et al., 2018). All shipping industry experts, in addition to the two bluetech leaders, highlighted the importance and appeal of increasing a ship's efficiency. Efficiency is a "two for one" as a bluetech hub founder described. According to some studies, mature energy efficiency measures in existence today can reduce emissions per ship by 20-30% depending on the type of ship (*Decarbonization in Shipping*, n.d.). In addition to curbing emissions, improving efficiency often cuts the cost of fueling the ships (Dewan et al., 2018). Interviewed industry experts spoke to the importance of keeping costs down stating "shipping is a very low margin business. A lot of the competition is on price because the owners of cargo are prioritizing costs in order to deliver their goods to market in a way that is palatable to the end consumer" (stakeholder interview, maritime shipping company). More bluntly, "shippers only think about the bottom line and cutting costs" (stakeholder interview, ports). The savings earned by using less fuel can outweigh the cost of employing efficiency measures. Background research and interviews with industry experts

revealed three promising technologies and innovative measures that improve efficiency: speed optimization, mega ships, and marginal improvements.

Speed optimization: Shipping companies are optimizing speed for fuel efficiency by employing slow steaming and adjusting speed to arrive at ports during certain time windows. Slow steaming is broadly defined as when a ship operates at a speed lower than the ship was designed to sail (normally around 20-24 knots), though some stakeholders have more stringent definitions often with a maximum speed of 18 knots (Lee, 2014). According to an IMO study, there was a 14% decrease in international shipping emissions between 2008 and 2014 largely due to voluntary slow steaming (Tirschwell, 2019). Lately, the term 'slow steaming' has been replaced with the term 'speed optimization' because slowing down too much can actually increase GHG emissions and some stakeholders, including the IMO, believe speed optimization is a more descriptive term for the practice (Psaraftis, 2019). A port stakeholder noted that many ship operators are opting-in to their voluntary speed reduction program because they can report back to their customers and shareholders that they are increasing efficiency and saving money.

> "Operators want their consumers to see that they are pushing forward with more sustainable practices so they opt in to the speed reduction… they like the optics of increasing profits but also increasing efficiency" (stakeholder interview, ports)

Shipping companies are also adjusting speed, so they arrive at ports when there is assured availability of berths and port services. Although this concept is used by many companies and is not often given a name, CMA-CGM uses the term "Just in Time Arrival" (JIT). JIT combines speed optimization with digitization (discussed below) to ensure ships arrive at port at a certain time to minimize ship's wait time at port. CMA-CGM found that their ships used up to 23% less fuel when employing the JIT method. An industry expert noted the importance of innovative solutions such is this by stating,

> "If you look out to sea and there are about 50 ships at anchor waiting to get into the port… that has an impact because idle ships produce emissions and their not actually

doing work which is bad economically and environmentally" (stakeholder interview, shipping association).

Mega ships: As illustrated in Figure 2, container ships have been getting larger over the past 50 years. This is because of two main reasons: 1) larger ships can carry more cargo which translates to more profits and 2) larger ships have been found to be more energy efficient on a per TEU (twenty-foot equivalent unit) basis. When a vessel doubles in size the fuel consumption typically only increases by about two-thirds, which means the per unit fuel consumption is less when shipped on a larger vessel (Bouman et al., 2017). When larger vessels are equipped with efficient technologies and innovations and operate at slower speeds, the fuel savings per TEU is further improved. The World Shipping Council found that a 1500 TEU vessel operating roughly 50 years ago consumed 178 grams of fuel per TEU mile while a modern 12,000 TEU vessel consumed only 44 grams of fuel per TEU mile (*Carbon Emissions FAQ*, n.d.).

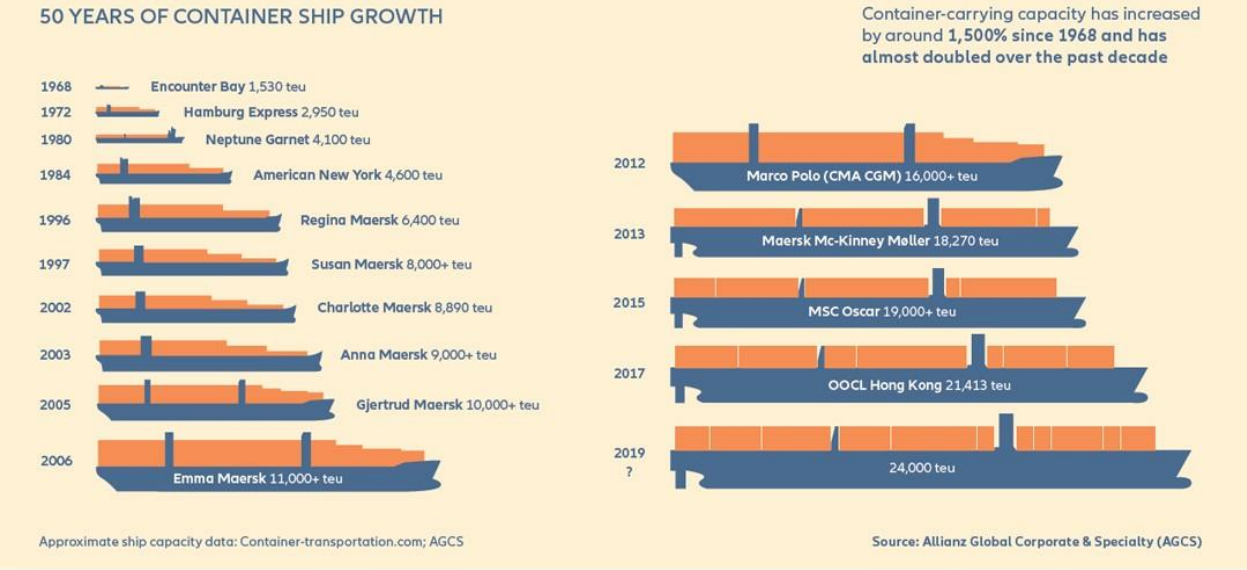

Figure 2: Emergence of "Mega Ships" through the last 50 years. (credit: AGCS)

Larger vessels are appealing to shipping companies mainly due to the financial benefit from the concept of economies of scale. There is a marginal savings per container when you increase the size of the ship, so companies can transport containers at a lower per unit cost (Bouman et al., 2017). Shipping companies have therefore been focusing their efforts to increase efficiency on

these larger ships. A port stakeholder noticed that they "are seeing larger vessels coming in that hold more containers; less vessels but larger and they are making less trips and increasing efficiency that way" (stakeholder interview, ports).

Maersk recently launched their Triple E or EEE vessels, the Es standing for economy of scale, energy-efficient, and environmentally improved. These vessels are over 18,000 TEU and emit 20% less CO2 per container shipped when compared to most energy efficient vessels on the water today (Macguire, 2013). CMA CGM added a 23,000 TEU ship powered by Liquid Natural Gas (LNG) to their fleet in 2020. LNG may emit up to 20% less CO2 emissions than traditional bunker fuel, though that is debated in the literature and will be expanded upon later in this paper.

Marginal Improvements: Many companies are embracing the concept referred to as the "aggregation of marginal gains" (Clear, 2018). This concept comes from the thought that if you make many small incremental changes, it will result in a vast improvement overall. Marginal improvements in the shipping industry include a waste heat recovery system, a modified bulbous bow, LED lighting, more efficient propellers, anti-fouling coatings, and air bubble lubrication. An industry expert cited a partnership between the Port of Los Angeles and Maersk where they did emissions testing before and after modifying a vessel with marginal improvement technologies such as "changing the bulbous bow to make it more efficient at reduced speeds, installed LED lighting, changed the propellers in the back to be more efficient" (stakeholder interview, ports). These improvements decreased the ship's fuel consumption by over 10% which translates to emissions reductions (Sanfield et al., 2016). Marginal improvement technologies and their potential emissions reductions are outlined in Table 6.

Marginal Improvement	Short Description	Potential Emissions Reduction
Waste Heat Recovery	Captures the exhaust gas from the engine and uses it to run a turbine connected to a generator	Can cut CO_2 emissions by approximately 1-20% (Bouman et al., 2017)
Modified Bulbous Bow	Changing out bulbous bows designed for normal speed (20-24 knots) to those designed to work best at slow speeds (<20 knots)	Reduces fuel consumption by 3-5% (Park & Cho, 2017)
LED Lighting	Switching traditional incandescent lighting to LED	1.5-3% energy savings (Bouman et al., 2017)
Propeller Design Optimization	Increasing size and number of blades, adding propellers, changing the angle, adjusting the pitch/diameter ratio and more	The optimized propeller design on Maersk's EEE ships has reduced fuel consumption by 4% (Maersk, 2020)
Anti-fouling coating	The bottom of the ship is covered with a coating that prevents the colonization or growth of organisms that attach to the hull	It is estimated that biofouling can increase fuel consumption up to 40%, this technology reduces this risk (MSC, 2019)
Air bubble lubrication	Air bubbles are distributed across a ship's hull to reduce resistance and drag	1-15% CO_2 emissions reduction (Boouman et al. 2017)

Table 6: Marginal improvement technologies to increase efficiency in the shipping industry and related potential emissions reductions.

Digitization & Automation

The shipping industry has been slow to embrace the digital age. As one industry expert reflected, "I remember I was at a conference maybe just four years ago [2016], where somebody said that in our industry we sent 80,000 faxes a month...and when was the last time you saw a fax?" (stakeholder interview, shipping association). The industry has been reluctant to shift from analog to digital partly because there is a fear of temporarily disrupting logistics that may result from a learning curve and partly because of immature satellite technology (stakeholder interview, bluetech hub). Recently though, the shipping industry has employed digitization as a way to improve efficiency, communication, and safety. The risk of temporarily disrupting logistics is outweighed by consumer demand for faster and more sustainable shipping, emissions

regulations, and investor appreciation for socially responsible companies. Digitization has been used to improve communication, efficiency, and weather routing. For the sake of clarity and brevity, digitization, digitalization, and digital transformation are all grouped together under the term "digitization" throughout this paper.

As mentioned previously, many shipping stakeholders are aware of inefficiencies at ports that result in wasted fuel consumption, emissions, time, and money. A bluetech industry expert emphasized the need to combine speed optimization with timely ship to shore communications by stating,

> "Vessels spend a lot of time waiting around outside of ports… and you only have a narrow window to make your delivery out to [the ports], and of course if ships are idle, they're burning and wasting a lot of fuel, and you may as well not optimize any routes" (stakeholder interview, bluetech hub).

Navigating the growing container ships in and out of port is an increasingly complex process, as illustrated in Figure 3. Immediate digital communication between ships and ports allows for smooth logistics and a more efficient port stop. Top shipping companies are using digital communication techniques such as phone apps to choreograph port calls and ensure no fuel, time, or money is wasted (Sudal & Paris, 2018). Artificial Intelligence (AI) can also be used to improve efficiency during cargo offloading. Shipping companies and ports can use AI to offload containers from vessels in a systematic manner that reduces the crane movements and therefore reduces energy consumption (stakeholder interview, ports).

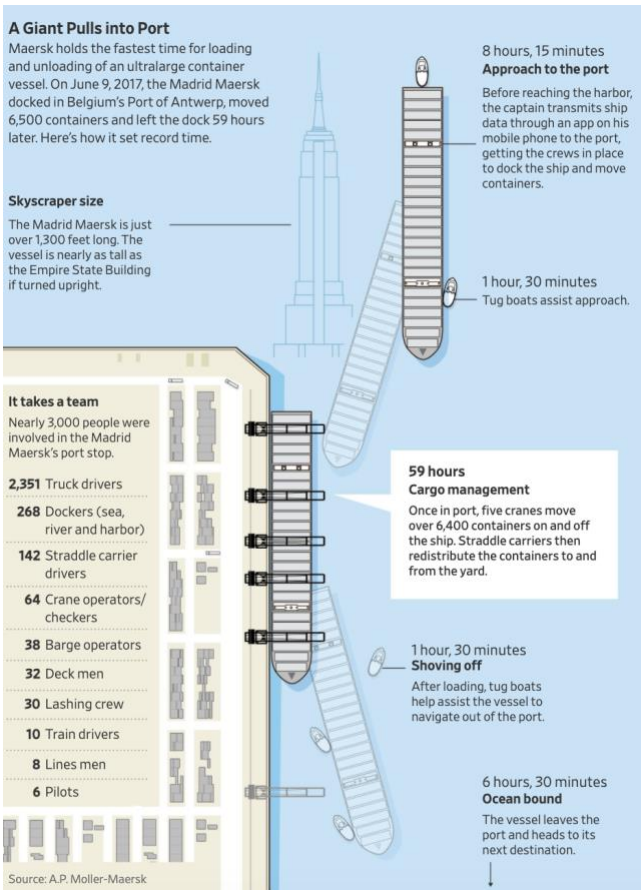

Figure 3: Illustration of a cargo ship pulling into port. (credit: Maersk)

Many container shipping companies are installing digital sensors and software in their engines and equipment to provide real-time data and monitoring on efficiency. One industry expert mentioned how equipment monitoring is being used to reduce energy consumption needed to keep certain goods like produce and pharmaceuticals cold while being shipped: "the cold chain is being maintained on these transatlantic and transpacific voyages in individual containers that can monitor [efficiency] and provide real time data on it, and so we're going to see more of that" (stakeholder interview, shipping association). In 2019 MSC installed their StarConomy temperature control software throughout its refrigerated containers (reefers), and has found that it reduces energy reefer consumption by up to 50% (MSC, 2019). Hapag-Lloyd created their Fleet Support Center department for Digital Solutions in 2013 to devise strategies and software for digital monitoring and data collection (Hapag-Lloyd, 2019). Through the implementation of a software that maximizes the carrying capacity of their ships, Hapag-Lloyd's fuel consumption per slot decreased from 2.75 tonnes in 2018 to 2.59 tonnes in 2019 (Hapag-Lloyd, 2019).

Weather reporting is becoming more accurate, reliable, and prognosticating with the advancement of digitization in the shipping industry as well. More advanced weather routing makes it possible to avoid storms and create more efficient shipping routes which decreases fuel consumption and increases worker safety. A few studies have shown that advanced weather routing and subsequent route planning can decrease CO_2 emissions up to 48% at times (Bouman et al., 2017). When asked about exciting emerging technologies in the shipping industry one industry expert spoke about interest in emerging weather reporting technologies:

> "There are a lot of really interesting technologies going into predicting the weather in ways that we've never seen before [and] within probably just a handful of years we're going to be able to predict the weather even more accurately and even further out than we've ever thought possible, and a lot of that is being driven by the maritime industry and the focus on that space" (stakeholder interview, shipping consulting agency).

In 2019 the IMO and the World Meteorological Organization (WMO) held the first International Symposium on "Extreme Maritime Weather: Towards Safety of Life at Sea and a Sustainable Blue Economy" (WMO, 2020). This symposium highlighted advances in *impact*-based weather forecasting (a shift from 'what weather will be' to 'what it will do') and discussed innovations in digital delivery of weather data to ships in real-time (WMO, 2020).

Alternative Energy Sources

When speaking of the groups of technologies and innovations that could lead to a low carbon shipping industry, one industry leader said, "I think that it's important to think about the transition to zero carbon along two pathways that are working in parallel with each other" (stakeholder interview, maritime shipping company). Many of the technologies and innovations we have gone over fall into the first pathway: retrofitting. A ship can be retrofitted with new propellers, a modified bulbous bow, sensors, and a top-of-the-line anti-fouling coating during the routine periodic dry-dock traditionally used for maintenance. The second pathway is building completely new ships designed to run on low carbon fuel. This second pathway is the method needed for adopting alternative energy sources.

Historically, the most commonly used fuel type in the shipping industry has been Heavy Fuel Oil (HFO) which also goes by the names bunker fuel, bunker oil, fuel oil, heavy fuel among others (Degnarain, 2020). With new IMO regulations and the 2050 goal to reduce carbon emissions by 50%, the race is on to produce a low emissions fuel at a low cost. Liquid Natural Gas (LNG) is the only low carbon fuel choice that can compete with HFO in price and availability and therefore it has already been used in numerous vessels as companies try to lower their carbon emissions (DNV GL, 2019). Studies have shown that LNG has the potential to emit up to 30% less CO_2 than traditional bunker oil (Bouman et al., 2017). However, the process of getting the LNG from "well-to-tank" runs the risk of releasing unburnt methane (a methane slip) which negates the benefit of lower "tank-to-propeller" CO_2 emissions because methane has a greenhouse effect 25-30 times higher than CO_2 (DNV GL, 2019). One industry expert spoke about his concern with the actual environmental benefit of LNG:

> "So, if you actually look at what we call the well-to-wake emissions of natural gas, we start to see a completely different picture of the [GHG] savings of natural gas as a fuel. The EPA estimates that we have about one and a half to 2% of fugitive methane emissions across our natural gas ecosystem in the U.S. and the Environmental Defense Fund estimates that we have between three and 5% fugitive emissions. Now why are those numbers important? Well it's not that much, 5%, [but] at 3% fugitive emissions rates, natural gas becomes as polluting as diesel… at 5%, it becomes as polluting as coal." (Stakeholder interview, maritime shipping company).

However, the lifecycle GHG emissions associated with LNG paint a different picture for climate change. For this reason, LNG was not included in our list of promising alternative fuels for shipping. Through our literature review and interviews with industry experts, we identified hydrogen, biofuels, and methanol as the most promising low carbon fuel sources for the shipping industry. Cold ironing and batteries/electrification were noted as promising secondary energy sources.

E-Hydrogen: Hydrogen is often boasted as the cleanest fuel when produced using renewable energy (also known as e-hydrogen) (DNV GL, 2019). When one shipping industry expert was

asked about their opinion on what fuel will become the industry standard, they mentioned hydrogen because of its zero-carbon emissions and because "it's operationally similar to diesel equipment so you can preserve the current operational modes and terminals [and] make use of the efficiencies" (stakeholder interview, shipping association). There are two major problems with hydrogen as it is now: 1) it has a low energy density and therefore a large volume of fuel is required to make long trips, and 2) 95% of today's hydrogen is produced from fossil fuels (DNV GL, 2019). The low energy density means it is not currently feasible for deep-sea voyages, however, it is already being used by vessels in short-sea applications such as ferrying (Timperley, 2020). At the moment, hydrogen is primarily produced from natural gas. This makes it expensive and means its well-to-tank emissions are comparable to LNG and thus not an effective climate solution for the shipping industry (IEA, 2019). Producing hydrogen from renewable energy, though, is even more expensive mainly because of the high cost of renewable energy (DNV GL, 2019). As renewable energy costs go down, there is a growing interest in electric hydrogen produced from solar and wind. Though some studies have found that widespread use of hydrogen as a fuel is not feasible and therefore investments should be concentrated on other, more scalable alternative fuels (Dufour et al., 2009). Electric hydrogen production, specifically in relation to offshore wind energy, will be discussed in greater detail on page 72.

Biofuels: Biofuels, including biogasses and biodiesel, are fuels made from biomass (e.g., corn, algae, and standard cooking oil). Some biofuels, like biodiesel, can be used in place of or blended with traditional fuels to lower the carbon emissions with little to no modifications to the engine (World Maritime News, 2019). While the CO_2 emissions from "tank-to-wake" from combusting biofuel is zero according to the IPCC, the life-cycle GHG emissions vary widely depending on the feedstock used to make the biofuel (Cherubini et al., 2013). The majority of biofuels used for transport today are "first-generation biofuels" made from crops such as corn, soybeans, and sugarcane (Kumar et al. 2018). The actual environmental benefit of using these fuels is under debate because bad agricultural practices can lead to pollution from runoff and additional GHG emissions. Additionally, growing crops for fuel causes land-use competition with agriculture used for human consumption, a social equity concern especially in marginalized communities and undeveloped nations (Mukherjee et al., 2020).

More recently, “advanced” biofuels (also referred to as second-, third-, or fourth-generation biofuels) are being researched and implemented in the shipping sector. These biofuels are those produced using non-food biomass such as algae and industrial waste (Mukherjee et al., 2020). These biofuels offer the same low carbon benefits as first-generation biofuels but do not present the agricultural or land-use concerns. However, the technology is nascent, and scalability is under debate (Kumar et al. 2018). Regardless, many shipping companies are already using biofuels in their fleet or are investing time and money into progressing biofuel development. As one industry expert noted, “CMA CGM for example has gone all in...the head of innovation at CMA CGM said hey biofuel/ bio gases are where we're headed, because we can get LNG ships ready today, and then pivot those all the biogas” (stakeholder interview, maritime shipping company). Maersk’s Eco Deliver option, discussed earlier, also uses biofuel produced from cooking oil waste in Europe (stakeholder interview, maritime shipping company).

Bio-Methanol and E-Methanol: Methanol, when made using renewable energy or biomass, is another low carbon fuel choice mentioned in both the stakeholder interviews and much of the literature. Methanol is a simple alcohol that can be made from a number of different feedstocks including natural gas, coal, and biomass or it can be made by renewable energy that combines hydrogen and CO_2 (DNVGL, 2019). When methanol is made from LNG or coal the emissions are much higher than LNG but when created from biomass (bio-methanol) or renewable energy (e-methanol), the emissions are significantly lower (Svanberg et al., 2018). Therefore bio-methanol and e-methanol are the only types of methanol we found to be promising. Methanol is attractive because it is a liquid at ambient temperatures, it has low emissions and is naturally biodegradable, and it has a higher energy density compared to hydrogen (stakeholder interview, maritime shipping company). Maersk recently announced that it will launch the world’s first carbon neutral liner vessel in 2023 which will run on bio- and e-methanol (Linnet, 2021).

Secondary Energy Sources: Two other technological innovations were highly mentioned in the literature and stakeholder interviews: cold ironing and batteries/electrification. These alternative sources of energy are not seen as viable for propulsion of vessels in the maritime shipping industry but we felt they were worth mentioning because they are being adopted on a wide scale as a secondary source of energy in an attempt to reduce emissions. Cold ironing is the term used

to describe when a ship "plugs in" to shore power while in port. This reduces emissions because the ship is not being powered by HFO, a particularly polluting fuel. One stakeholder mentioned how the technology is so promising, that they "have been a part of IMO discussions surrounding global standardization for plugging in" (stakeholder interview, ports). Electric batteries are also being used to reduce the use of the main engine by way of peak shaving. Many cargo ships have equipment such as refrigerated containers, radar, and computers that require power. When this equipment is powered on it creates a spike, or a peak, in energy usage. These peaks cause the main engine to work harder, combust more fuel, and release more CO_2 into the environment. But as one industry expert explained, "if you've got a battery on board, you can shave that peak by taking it out of the battery. So peak shaving is dealing with those spikes or peaks by having energy stored that can be used on immediate demand… It's not enough to actually run the ship but it can take those spikes away" (stakeholder interview, maritime shipping company). Studies have shown that cold ironing can reduce emissions by 3-10% and peak shaving can improve efficiency up to 20% (Bouman et al., 2017).

Social Impacts

During the development of this paper the world experienced multiple major events that shifted the paradigm by which many people view the world. We felt it was necessary to include a review of how industries within the blue economy - namely shipping for this section - were affected by the COVID-19 pandemic and how they might contribute to a more equitable post-pandemic world.

COVID-19

Although many industries saw economic hits due to the pandemic, the shipping industry saw an overall increase in consumer demand. As one industry expert noted,

> "The container vessels started slowing down at the beginning of the pandemic because the demand was down and the manufacturing was down and everyone was trying to figure out what to do. Then as the stay at home orders were still in place demand through online shopping increased so now they are seeing record breaking numbers" (stakeholder interview, ports).

Reduced staffing to allow for social distancing has revealed inefficiencies along the supply chain (stakeholder interview, ports). Industry experts are hopeful that because the pandemic has made these inefficiencies more obvious, the shipping companies and ports will invest more money in technologies that will improve the flow of the supply chain and reduce emissions along the way. One shipping industry expert mentioned how, because of COVID, they are now able to digitally communicate with U.S. Customs whereas before they had to have a customs agent come aboard the ship, which took a lot of time at port. One industry expert believed that because of COVID the shipping industry has "jumped ahead 10 years and now things are never going to be the same. We're going to do a lot more of this [digitization]" (stakeholder interview, shipping consulting agency). This will hopefully lead to a more streamlined supply chain, increased use of other digital technologies like sensors, and less time a ship needs to spend at port.

Environmental Justice

When asked how the shipping industry might increase environmental justice and equity, we received a variety of answers from industry experts. Many industry experts mentioned how reducing emissions will improve the health of communities surrounding ports which are traditionally marginalized and have been impacted by harmful air pollutants. Some shipping companies are also focusing on increasing economic security in marginalized communities. One industry expert spoke about how their improved refrigerated containers were able to keep produce like avocados and bananas cold long enough to travel from a rural community in Kenya to European markets without spoiling (stakeholder interview, shipping company).

Diversity and Inclusion

Many industry experts also mentioned prioritizing diversity and inclusion throughout the maritime shipping industry. One interviewee mentioned the business case for being more inclusive:

> "we need to look really more holistically, to find the best talent regardless of what their provenance looks like... because that's what we need if we're going to win, in terms of our market share, or customers, if we're going to win in terms of our employee base retaining

and attracting the right people. That's what we're gonna do if we're gonna win as a company" (stakeholder interview, maritime shipping company).

Although increasing diversity and inclusion is a focus for many shipping stakeholders, as one industry expert noted, "we still need to do better" (stakeholder interview, maritime shipping company). All five of the top shipping companies have sections in their Corporate Social Responsibility or sustainability reports that focus on diversity and inclusion but only 1 out of the 5 report metrics beyond gender diversity within their workforce. CMA CGM also reports metrics on the nationalities of its employees but does not include racial identification in this metric (CMA CGM, 2019). Additionally, all five of these companies' diversity and inclusion goals focus only on increasing gender diversity.

Maersk, the largest international shipping company and the company identified as a leader in corporate sustainability by four out of five industry experts interviewed, is attempting to signal the importance of diversity and inclusion. To increase awareness of LGBTQ rights they have painted two of their vessels in a rainbow (stakeholder interview, maritime shipping company). However, it should be noted that some scholars have debated the benefits of virtue signaling by companies and emphasized the harm it can cause when implemented without creating changes in company behavior (Theriault, 2020). Maersk announced in its 2020 corporate sustainability report that it will conduct its first global inclusion survey to gather data that will allow the company to better understand discrimination, harassment, diversity, and inclusion in its workforce (Maersk, 2020). Although data collection and virtue signalling can be useful to include in a diversity and inclusion plan, the industry is far behind the global trend and needs to implement more actionable change.

Aquaculture

The global population is estimated to grow to 9.6 billion by 2050, and therefore there will be a need to feed an increased number of people (Kobayashi et al., 2015). In 2017, the U.S. was ranked 17th in aquaculture production in the world, but comparatively the U.S. relies heavily on importing fish products (National Marine Fisheries Service, 2020). If the U.S. wants to feed its growing population, it should increase the amount of aquaculture production domestically. With

one of the largest Exclusive Economic Zones (EEZ), the aquaculture industry in the U.S. has the potential to increase the amount of aquaculture farms and potentially help mitigate climate change with these farms (U.S. Department of Energy, 2019).

The aquaculture industry is vast, and there are many different sectors within aquaculture. We focused specifically on ocean aquaculture (also referred to as mariculture) in the U.S. We interviewed various leaders from shellfish, kelp, and finfish aquaculture. All three have different priorities and environmental impacts but are all impacted by climate change. Once we understood how many challenges the industry faces because of climate change, we were able to understand how they could move forward in the future. In order for the industry to succeed, it needs to both mitigate the challenges associated with climate change and help achieve global decarbonization goals. Technologies and innovations can help overcome these challenges and reach these goals. In this section we identified the climate change impacts on aquaculture, sustainability priorities of the industry, promising technology and innovation, and how the industry can contribute to social equity.

Climate Change Impacts

Climate change is a severe threat for aquaculture, an industry that relies heavily on the ocean for production. The literature review and stakeholder interviews revealed five subthemes within the larger theme of climate change impacts. These subthemes are: increased temperatures, increased storm intensity, ocean acidification, sea level rise, and adaptation to climate change impacts.

Increased Temperatures

Of the 12 industry leaders interviewed, 7 mentioned that the increase of ocean temperature had a direct impact on aquaculture, while one leader said that rising temperatures had not affected their business yet. For finfish, leaders noted that they have seen temperatures affecting their farms by stating, “we've certainly seen a change in the temperature of the waters where we raise our fish” (stakeholder interview, finfish company) and “we are definitely seeing water temperatures coming up” (stakeholder interview, finfish company). Aquaculture species are strongly affected by temperatures because they are cold-blooded and cannot regulate their body temperatures (Boyd, 2018). Temperature affects their growth and how and if they will

survive (Boyd, 2018). An industry leader explained, “because bivalves are cold-blooded, there's the effect of temperature on respiration rate. How much oxygen they utilize, and [is based on] the pumping rate, how fast they pump” (stakeholder interview, shellfish farmer). Climate change will affect bivalve aquaculture if temperatures continue to increase like they are now.

Certain kelp farms in the U.S. see warming effects more than others. One farm is especially worried about moving the growing season every year:

> “We put seed in the fall and harvest season in the spring. The start of the harvest season has been moving up a week and a half every year. And there are not that many weeks for it to continue to move up until the season is totally gone, or we're forced to move further and further offshore into colder waters. So I definitely think [there are] some serious threats that climate change poses to the industry as well, and it's going to be a lot of creative innovation to figure out how we can adapt our current growing methods to work with changing waters.” (stakeholder interview, seaweed company).

As ocean temperatures are rising, kelp farmers are losing time in their season to grow. As there is less and less time to grow, they will have less product to sell, and climate change will have an even larger impact than it is now.

Increased temperatures have also increased sea lice populations and the number of algal blooms which results in adverse effects on the industry (Godwin et al., 2020, Fu et al., 2012). Sea lice are parasites that specifically feed on Atlantic Salmon (Godwin et al., 2020). Researchers have found that as temperatures increase, sea lice increase in abundance and affect the growth and survival rate of their hosts (Godwin et al., 2020). With rising temperatures, harmful algal blooms are more frequent (Fu et al., 2012). The algal blooms often contain toxins and are dangerous to those who are eating seafood (Berdalet et al., 2016).

Increased storm intensity

Global climate change is increasing the severity of storms. Stronger storms can increase storm surge and wave attenuation (Bricknell et al., 2021). Aquaculture structures like salmon cages or floating oyster bags will have to be built stronger to withstand these stronger storms (Bricknell et al., 2021). An industry stakeholder noted that, “what we have seen is with climate

change, we've seen more frequent storms and we've seen more powerful storms. And that messes up everything, whether we're talking infrastructure, whether we're talking closures of water" (stakeholder interview, shellfish farmer). Increased storm intensity creates a large influx of freshwater to coastal areas from flooding. A shellfish farmer explained how bivalves are 'hardy' animals, but they cannot switch salinity quickly. "The [bivalves] can live in 10 parts per 1000, and then they can live where we are in, 31 to 33 parts per 1000. But what they have a hard time doing is going from 33 to 10 in like a two-week period" (stakeholder interview, shellfish farmer). If this change does occur, farms have to close down because it is not safe to eat the clams or mussels. When aquaculture facilities have to shut down it affects the amount of product they can sell and affects their income especially in smaller farms (stakeholder interview, shellfish farmer).

Increased storm intensity can damage gear and cause farmers to lose their product. "Indirect impacts of storms would be shutting down restaurants [and would] damage processing facilities" (stakeholder interview, federal government). Increased intensity of weather events makes it difficult for coastal aquaculture farmers complete daily tasks. A stakeholder recalled that "we've seen changes in currents and weather patterns that impact both our fish and our ability to harvest fish and go through our normal daily activities" (stakeholder interview, finfish company). Intense storms also create the loss of habitat that most shellfish farms rely on (Mackenzie, 2007). An industry expert noted that they are being negatively affected by the "loss of sandbars and shifting sandbars and barrier islands which create a lot of that green oyster habitat" (stakeholder interview, aquaculture non-governmental organization). Shifting of geology can disrupt the habitat and ecosystems farms are using to grow their product (Filgueira et al., 2016).

Acidification

The increase of CO_2 in the atmosphere has increased the amount of CO_2 in the ocean and, in turn, increased ocean acidification (Gravinese et al., 2019). Heavily calcified organisms are more affected by ocean acidification than other marine organisms (Kroeker et al., 2013). Growth and development decrease as acidification increases in the water (Kroeker et al., 2013). Ocean acidification also creates more susceptibility to diseases in farmed stocks (Bricknell et al., 2021). Several industry leaders mentioned acidification has a significant impact on the success of aquaculture (stakeholder interviews, shellfish farmer, federal government, aquaculture

academic). A shellfish aquaculture industry leader mentioned they were not seeing the effects of acidification as much as other areas in the U.S. They said, “we don't really have that big of an issue with ocean acidification, which we're really fortunate with. I know the guys on the West Coast are dealing with it, and I think some guys up north are dealing with it” (stakeholder interview, shellfish farmer). Although they were not seeing impacts from ocean acidification, they did acknowledge the rest of the industry was dealing with it. Areas on the northern east coast of the U.S. are more worried about acidification on their larval populations.

> “Since we collect our seed by hanging ropes in the water and the little baby mussels attached to it. If [the pH] eventually impacted the recruitment of the seed, that would have a real big impact. So, it's the ocean acidification I think for us is a much bigger deal than the temperature changes” (stakeholder interview, shellfish farmer).

In comparison to shellfish aquaculture, one finfish aquaculture industry leader said, “you know things like ocean acidification and, and other matters aren't as big a challenge for us but we've certainly seen changes in the weather pattern both, you know above and below water” (stakeholder interview, finfish company). These farmers and companies might not be seeing acidification specifically, but it is occurring in their environments. Ocean acidification is creating stressful environments for all aquaculture species and it will affect the industry in more clear ways in the coming years. It is estimated that ocean acidification could cost the shellfish aquaculture industry 100 billion USD by 2100 (Narita et al., 2012).

Sea level Rise

Sea level rise was another climate change impact mentioned: “Sea level rise is a considerable impact. Most of the oysters that we grow are kind of in that intertidal sweet spot. And as sea levels overall rise, what's traditionally been the intertidal area can get flooded. And can affect how oysters grow and can certainly affect salinity.” (stakeholder interview, aquaculture non-governmental organization). As explained above, shellfish are vulnerable to pH changes. If sea level rise changes the pH of the environment, shellfish growers will need to be wary of how sea level rise will affect their farm. Specifically in bivalve aquaculture occurring on the shoreline, sea level rise can also change the nutrient dynamics of the water. Changing the

nutrient dynamics reduced the amount of phytoplankton in the water (Filgueira et al., 2016). Phytoplankton is one of the sources of food for bivalves. Sea level rise can also create problems for operations by damaging infrastructure (Filgueira et al., 2016). Infrastructure damage and changing the chemistry and nutrient levels of the water are impacts aquaculture farmers are facing from sea level rise.

Adaptation to Climate Change Impacts

When speaking with our interviewees on how climate change was affecting their farm and daily tasks, many discussed how they were adapting to these changes and impacts that were mentioned in the "Climate Change Impacts" section. Climate change is creating stressful environments for developing aquaculture species. It is important for aquaculture farms and facilities to adapt to these changes in climate. If they can adapt and increase their resilience to climate change, they will have a better chance of continuing to grow their products. Aquaculture companies are using new technologies and innovations to adapt to climate change impacts and other types of technology used to mitigate climate change are discussed on page 48. One oyster farmer explained that they use submerged, bottom cages because of the high energy area they are in (stakeholder interview, shellfish farmer). The bottom cages also prepare for high winds from increased intense storms created from climate change. In areas of sea lice, finfish farmers have created solutions to adapt to the increased number of sea lice. Sea lice directly and indirectly can cost more than $423 million annually in salmonid aquaculture (Costello, 2009). Sea lice is highly contagious and can easily spread to the whole farm and even nearby farms (Liu and Bjelland, 2014). Since sea lice live in the top of the water column, farmers have learned to submerge their cages below the top of the water column to decrease the issues with sea lice (stakeholder interview, finfish company).

Another adaptation with the finfish industry is adaptation to increased water temperature. When there is an increase of water temperature, the amount of oxygen decreases, but increases the amount of algae (USGS, n.d.). Less oxygen is harmful for the fish in the tanks. One company is working on adding oxygenation bubbling systems to their tanks. They have also found another solution with mussels and have studied how mussels react with their pumping or feeding rates in relation to temperature increases. The company puts sensors on the mussels to monitor if there is

a change in their feeding rate (stakeholder interview, finfish company). More sensor related technology will be discussed more on page 54.

Sustainability Priorities

Sustainable aquaculture practices are essential and necessary as the aquaculture industry grows and the need for food security grows (Jones et al., 2015). We have emphasized themes on climate change and decarbonization, but to mitigate climate change and to understand the impacts on aquaculture, we needed to learn the sustainability priorities of the industry and each aquaculture company we interviewed. Through interviews, we identified four subthemes under sustainability priorities: environment impact, fish feed alternatives, alleviating pressure on wild fish stocks, and social impacts. All other sustainability priorities that were mentioned were grouped into the subtheme "other."

Environmental Impact

From the literature and interviews with stakeholders, we found that the aquaculture industry is aware of their impact on their surrounding environment. Out of 12 stakeholders interviewed, 7 mentioned mitigating environmental impacts as a sustainability priority. As one industry expert said, "Since we really are on the front lines of a lot of these climate impacts and have been for a long time, [we are] being really cognizant of what our actual impact on the environment [is]" (stakeholder interview, aquaculture non-governmental organization). In the past, the aquaculture industry has had issues polluting the surrounding environments, specifically in salmon and shrimp aquaculture (White et al., 2004). Salmon and shrimp farmed at industrial scales have been particularly problematic because of the introduction of new species from escapees, waste discharge, and the transfer of disease (White et al., 2004). There are also aquaculture systems where excess fish feed is released into the ocean and the environment (Goldburg, 2001).

Fish escapes are also problematic due to their adverse effect on the surrounding environment. Farmed finfish are not usually native to where they are farmed so any fish escapes can introduce non-native and potentially invasive species to the environment (Atalah and Sanchez-Jurez, 2020). The introduction of non-native species can deplete the native population (Atalah and Sanchez-Jurez, 2020). Escapees of Atlantic Salmon in the North Atlantic area have

led to low genetic diversity in wild stocks (Atalah and Sanchez-Jurez, 2020). Farmed fish typically have low genetic diversity and if escapees mate with the native population this can reduce the species' fitness and future survival rate (Atalah and Sanchez-Jurez, 2020). In another area of the world, Atlantic Salmon escapees in Chile have led to predation of native populations (Atalah and Sanchez-Jurez, 2020). Protecting the surrounding environment is essential to finfish farms as one industry expert said, "we want to work in a way that we are leaving the environment better than when we started" (stakeholder interview, finfish company). Aquaculture farms have a history of impacting and drastically changing their surrounding environment (Ahmed et al., 2019). Although their goal is to not disrupt the surrounding environment, they have yet to put in hard work to show their commitment to habitat and biodiversity protection.

Unlike finfish aquaculture, shellfish and seaweed aquaculture do not have a large impact on the surrounding environment by not contributing to polluting the water (Jacquet et al., 2017). There is little concern that cultured bivalve shellfish may transfer disease to native populations, but growers are mindful of the possibility (Rice, 2008). A bivalve industry expert said, "[we] have this philosophy that [we] want to use native species, rather than introduced species upset the ecology...and also, pick and use local seed or seed species that are not going to threaten the environment by bringing in genetic mutations" (stakeholder interview, shellfish grower). These industry leaders spoke on the priority for their own company companies to leave as little impact as they can and find ways to mitigate them. These companies put their words into action to continue to have little impact on their surrounding environment.

Alleviating Wild Fish Stocks

As the demand for seafood increases, so does the stress on wild seafood stocks. In 2017, FAO reported 34.2% of the ocean's fish stocks are fished at unsustainable levels (FAO, 2020). Aquaculture producers use wild fish in their fish feed creating an added pressure to wild fish stocks (Naylor et al., 2021). In some areas of the world, fisheries used specifically for aquaculture feed can damage wild fish populations and create a loss of biodiversity (Naylor et al., 2021) Aquaculture can create new solutions to alleviate their pressures on wild fish stocks that are used for fish feed. Many different stakeholders mentioned reducing the stress on wild fish stocks was a priority for them. As stated in an interview with a finfish aquaculture expert, "Our goal is to use cutting edge technology to yield a product that not only helps alleviate the

pressure on wild fisheries and ocean ecosystems, but also eliminates environmental concerns associated with conventional salmon farming" (stakeholder interview, finfish company). New innovations with ingredients for fish feed can help eliminate these environmental concerns. One innovator in the aquaculture industry explained that they entered into the aquaculture industry to create solutions for vulnerable fish populations. They stated, "if you read literature or just read popular news, climate change is affecting where fish are, where they're migrating to, what they can tolerate. On top of the fact that fish by nature are highly vulnerable by season and from year to year... we [can] identify aquaculture as a solution" (stakeholder interview, aquaculture innovator). New innovators continue to create solutions to past issues in the aquaculture industry. Since 2000, aquaculture producers continue to decrease their dependency on wild fish stocks for their fish feed (Naylor et al., 2021). Reducing the dependency on wild fish stocks for fish feed has the potential to create a more sustainable industry.

Aquaculture has already surpassed the amount of fish produced by wild-caught fish, as seen in Figure 4 (FAO, 2020). This is promising as wild fish stocks cannot continue to supply all of the seafood demands from the growing population (FAO, 2020). A shellfish grower also explained in their interview why bivalve aquaculture is important:

> "For us with the increasing population that we have, we can't sustain the pressure we're putting on wild stocks, whether that be fish or shellfish. There are countless examples of people from our areas like the bay, or the gulf, or New York Harbor, where not only has pollution contributed to the death of shellfish, but overfishing was huge in contributing to that. And it's [shellfish aquaculture] the best in my opinion, one of the best-managed species... So in terms of population explosion and hurting wild stocks, shellfish aquaculture is the ultimate sustainable situation" (stakeholder interview, shellfish grower).

Bivalve and shellfish aquaculture can contribute to better water quality and reduce turbidity, which improves production in other species in the ecosystem (Ferreira et al., 2018). Shellfish aquaculture can supplement the need for seafood with the growing population. Researchers have found that aquaculture might necessarily replace wild fishery populations but provides additional production to wild fisheries (Longo et al., 2019). As the world's population continues to grow,

the pressure on wild stocks cannot be sustained, and the need for sustainable aquaculture is increasingly apparent (FAO, 2020).

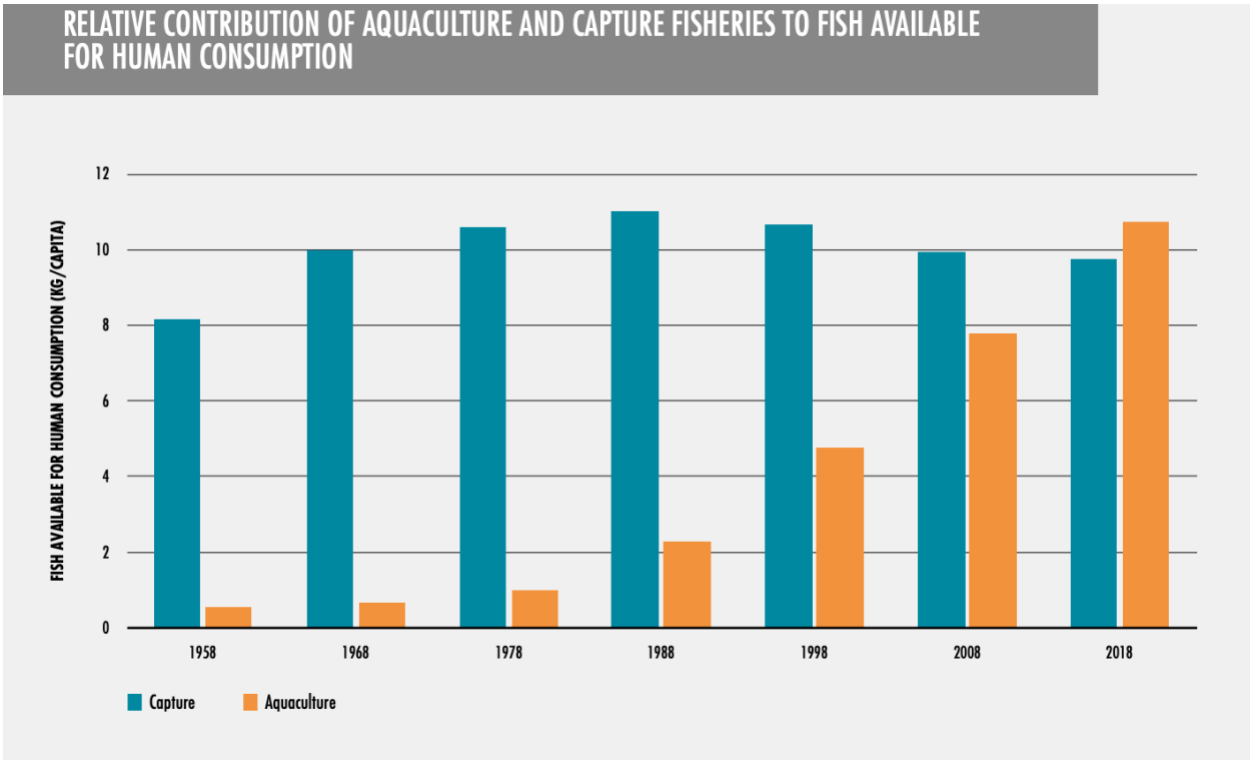

Figure 4: Aquaculture production in comparison to wild fish production from 1960 to 2018. (FAO, 2020)

Fish Feed

Aquaculture industry experts also identified creating a more sustainable fish feed as a top sustainability priority. Many diets of finfish aquaculture include fish meal, which often includes use of wild fish (Sarker et al., 2020). In the State of World Fisheries and Aquaculture (SOFIA), the Food and Agriculture Organization of the United Nations (FAO) reported that in 2018, 179 million tons of fish were produced from wild and farmed fish (FAO, 2020). Of the 179 million tons, 156 million tons were used for human consumption, while the rest were used for fishmeal and fish oil, the main ingredients in the fish feed (FAO, 2020). One stakeholder said, "I think to develop diets for aquaculture species that contain no fishmeal is, I think, a key to long-term sustainability" (stakeholder interview, federal government). Using less fishmeal can decrease the amount of pressure there is on wild fish stocks and decrease the cost of the fish feed (Sarker et

al., 2020). Currently feed for aquaculture is about 40-75% of the whole cost of aquaculture production (Sarker et al., 2020). Declining this price with other options and decreasing the pressure on wild fish stocks for fish feed will create a more sustainable industry (Sarker et al., 2020). Creating fishmeal that is more sustainable has been a topic of interest for bluetech hubs and innovators as well. For example, Sea Ahead, a blue tech hub in Boston, Massachusetts, is working with Beta Hatch, a company that is experimenting using insects in aquaculture feed (Sea Ahead, n.d. and Beta Hatch, n.d.). Soy and agricultural crops have been the most popular replacement, with insects and macroalgae being a topic of interest because they are more sustainable (Hoegh-Guldberg, 2019). Crops use large amounts of water and are also affected by climate change (Luck et al., 2011). Using soy and other crops for fish meal is simply shifting the stress on the ocean to the land and also is not as nutritionally as valuable as other options (Sarker et al., 2020). As one industry leader mentioned,

> "Sounds like we're shifting the environmental burden from the ocean and just moving it horizontally to land, and there are a whole host of problems with current agriculture too, especially the soy and corn. In the long term, that's a sustainability priority too to sort of reduce freshwater usage and harmful land-use practices and divert terrestrial crops and the fish components away from the aquaculture feed industry."

Other interviewees from the finfish aquaculture industry including a government employee and employees from finfish companies agreed that alternative fish feeds were a sustainability priority (stakeholder interview, federal government and finfish companies).

Social License

For many, sustainability incorporates a social license. The concept of a social license refers to "the degree to which aquaculture is accepted by neighboring communities and the wider society" (Hishamunda et al., 2014). Aquaculture not only affects the environment but also affects the adjacent and nearby communities. A social license was a priority for many stakeholders. A leader in the seaweed industry stated, "in order for us to have success in the water we also have to have successful relationships with people out of the water" (stakeholder interview, seaweed company). With this social license, aquaculture farmers aim to avoid disagreements and make

sure all voices are heard. An expert noted, “I think one of the number one priority is user conflict and how to avoid user conflict as the aquaculture industry expands.” (stakeholder interview, federal government). Planning for how ocean spaces will be used are creating conflicts between different stakeholders. Some stakeholders want to keep their oceanfront area free from development while others are in favor of aquaculture farms on the shore. Another industry expert explained how they attempt to be sustainable in a social way and avoid user conflicts. They explained where they choose the locations of their farms and the technology they use, stating “for the mussels, I invented a technology which is submersible rafts that can handle heavy, heavy seas. And so [I] like to go out in the ocean, miles from shore away from people's view and away from people's activities in an area, where there are no lobster gear around and create the perfect environment for mussels to grow, in an area where I have a social license, so to speak” (stakeholder interview, shellfish farmer). The social impacts of aquaculture are important to many industry stakeholders and will be discussed in the following sections.

Other

Stakeholders listed other sustainability priorities as well. One of the U.S.-based aquaculture facilities mentioned that a top sustainability priority was to decrease their carbon footprint by only shipping within the U.S. Another priority mentioned was the packaging of their product. As one expert stated:

> “We have a real challenge with packaging, a lot of what we have done, and a lot of that is legislative, but some of it is just logistical where you have temperature control is really important. And what we ship is wet, so we can’t use a lot of stuff that other food industries use for insulation like denim and some of the natural fibers because it gets waterlogged and is not effective [for refrigeration], so alternative packaging is a big one” (stakeholder interview, shellfish farmer).

In addition to packing, stakeholders included priorities like more efficient vehicles for shipping and more efficient boats to get out to their farm. Lastly, a priority for an industry leader was stopping the increased population of sea lice (stakeholder interview, aquaculture tech hub).

Climate Change Mitigation - Technologies & Innovation

It is apparent that climate change is affecting the aquaculture industry. To become a more resilient industry, the aquaculture industry needs to continue to find new technologies and innovations to mitigate these challenges. Through interviews and research, we know that many of the industry leaders are not specifically planning for climate change but are implementing some strategies or innovations to prepare. When asked if a farm had a plan for climate change, the leader noted it is hard to plan when climate change is unpredictable:

> "In order to put a plan together, you need to understand where you're going and without having that target in the future to say okay, if the temperature is going to change by a degree in five years, and so we need to do X. We don't have that. And we probably wouldn't necessarily [plan] unless there was more concrete data to anything. It is very reactive versus proactive" (stakeholder interview, finfish company).

It was surprising to hear that it was an ongoing pattern throughout our interviews. Many leaders acknowledged climate change was occurring and that their practices should limit their effects on the environment but did not necessarily have a plan to decrease their emissions like in the shipping and offshore wind sector. Some leaders mentioned where they could decarbonize certain areas of their production to keep their aquaculture certifications, which encourage them to limit their impact on the environment or they can potentially lose their certification (stakeholder interview, finfish company). Only one company we interviewed had a sustainability report, but no mention of a goal amount to decrease their emissions. Although, there was a mention of completing a life cycle analysis of their products in 2020. It is unclear if this actually occurred.

Another stakeholder commented that climate change is on their mind, but as a new company growing and making a profit is their priority, "I think she's [CEO] working on developing the longer outlook on climate will affect us down the road. But a lot of it's also focused on just growing the brand right now and working with our partner farmers so we can continue to have year over year success" (stakeholder interview, seaweed company). Many large-scale farms and companies, mostly within the finfish aquaculture industry, have sustainability reports or statements publicly available. An aquaculture technology hub explained

why this might be, “Maybe 80% of global production comes from small farm holders, who are there just to make a living for their families. I don't know that carbon reduction or any of that kind of stuff is on their agenda at all” (stakeholder interview, aquaculture tech hub). This does not mean small farmers do not have climate change on their minds since it does affect their daily routines, as seen in the previous sections. Many are implementing innovations and hope to keep implementing more in the near future with help from bluetech hubs and other industry leaders.

Through background research and interviews with industry leaders, we developed four broad subthemes: microalgae, integrated multi-trophic systems, digitization, and efficiency. All other innovations and technologies mentioned in our interviews were grouped into “other.”

Macroalgae

Macroalgae or seaweed aquaculture is one of the fastest-growing sectors and has opportunities for climate change mitigation (Duarte et al., 2017). 11 out of 14 aquaculture industry leaders and bluetech hub experts mentioned seaweed as an opportunity and innovation for the industry or were planning on using seaweed in their system in the future. One industry leader said, “Seaweed is a wonder crop that grows really quickly, it draws down CO_2 very quickly. It also captures what could be considered other kinds of contaminants like nitrates and runoff excess fertilizer, essentially for land” (stakeholder interview, bluetech hub). Although not scaled to that capacity, seaweed aquaculture can sequester CO_2 emissions from fossil fuels (Duarte et al., 2017). However, farming seaweed is not fully carbon capture because seaweed is removed from the environment and turned into another product. Organizations like Oceans 2050 study how much carbon is captured from seaweed farming (Oceans 2050, n.d.). In comparison, other companies like Running Tide are growing kelp and then permanently sinking the kelp to the seafloor (Running Tide, n.d.). Seaweed aquaculture is an exciting industry for climate change mitigation, “Depending on who you talk to the macroalgae, the carbon removal rate is 5 to 10 times that of what a tree is in the same environment. Clearly, they are tremendous organisms that remove carbon from their environment” (stakeholder interview, seaweed company). Some entrepreneurs are using this information to their advantage. For example, an artificial intelligence product and solutions company called Hypergiant created a bioreactor or system to convert raw materials to useful byproducts to offset carbon emissions from seaweed. The company found that

with their system seaweed was four hundred times more efficient at consuming carbon emissions than trees (Hypergiant, n.d.).

A few interviews discussed the opportunity of using cultured seaweed in the agriculture industry. Seaweed can help the agriculture industry decrease emissions by either improving the soil or use it for cattle feed (Duarte et al., 2017). Agriculture is responsible for 30% of global GHG emissions from anthropogenic pollutants (Tubiello et al., 2013). One kelp farm is investigating uses for their kelp, "We're exploring other uses for our kelp. I'm working on figuring out if we can create fertilizer out of it. To maybe help move land farms off of those more chemical fertilizers and stuff that comes from fossil fuels" (stakeholder interview, seaweed company). One company in partnership with an aquaculture technology hub is studying the use of the algae, *Asparagopsis taxiformis* and its effect on methane emissions from cattle. A study found that the addition of 2% of *Asparagopsis* to a cattle's diet can reduce 99% of the cattle's methane emission (Machado et al., 2015). This opportunity to include seaweed in cattle diet can create a new market for seaweed and can help grow the industry. The ability to reduce GHG emissions from agriculture is key to decreasing worldwide GHG emissions and help decrease the impacts of climate change. Companies should continue to explore the opportunity to reduce emissions from agriculture with seaweed aquaculture.

As discussed earlier, many farms are looking to change their fish feed to be more sustainable meaning more cost effective and less reliance on wild fish stocks. One industry expert explained "Aquaculture feed incurs about 40 to 70% of the costs along the supply chain, and they're also the largest environmental burden along the supply chain as well, so this is a really great leverage point for change" (stakeholder interview, aquaculture innovator). Companies like Verdant Seas are looking for ways to change fish feed ingredients with macroalgae while still creating the best feed for fish growth and survival (Verdant Seas, n.d.). Researchers working with Verdant Seas found a macroalgae blend for tilapia that eliminated fish oil and fishmeal. This combination increased growth rate while keeping costs low, which is a barrier to companies introducing macroalgae to their fish feed (Sarker et al., 2020).

Two interviewees mentioned the use of macroalgae to create biofuels. One interviewee commented on the potential for macroalgae growth in biorefineries and the use of the U.S. Department of Energy's (DOE) funding for macroalgae projects (stakeholder interview, aquaculture academic). In 2017, the DOE created the Macroalgae Research Inspiring Novel

Energy Resources (MARINER) to research opportunities for using macroalgae in energy production within the U.S. (Department of Energy, 2017). MARINER's goal is for the U.S. to create tools for macroalgae use and become a leading producer in macroalgae (Department of Energy, 2017). Macroalgae, especially sugar kelp because of the high amount of carbohydrates and percentage of water, is a good candidate to create bioethanol (Bellona Europa, n.d.). With the shipping industry working on using alternative fuels as mentioned on page 30, there is an opportunity to create innovative solutions with macroalgae to mitigate climate change.

All of these innovations are promising to the aquaculture industry. There is the question of scalability and how much we need to offset global emissions. During an interview, an industry leader asked, "What would the scale have to be to globally offset the scale that is present?" (stakeholder interview, aquaculture academic). The interviewee discussed that there is currently a large amount of GHG emissions present. To offset these emissions, there needs to be an increase of production of macroalgae aquaculture. As the industry grows, there is a potential to reach the scale.

Integrated Multi-trophic Aquaculture

Integrated Multi-trophic Aquaculture (IMTA) is another innovation to create a more sustainable industry and help mitigate climate change impacts (Chopin, 2013). IMTA is the process of farming different organisms like finfish, marine plants, bivalves, and other shellfish as seen in Figure 5 (Chopin, 2013). The use of IMTA has reduced waste products and increased water quality (Chopin, 2013). As waste and uneaten food from finfish aquaculture are an issue, it is important to find solutions to these issues. When nitrogen is released into the aquaculture system from waste, other organisms like kelp can use this waste for nutrients (Shpigel et al., 2018). Adding other trophic level organisms to an aquaculture farm can help sequester more carbon and nitrogen (Chopin, 2013). Both processes can end up helping mitigate climate change.

In addition to sequestering carbon and nitrogen, farmers have seen size changes in their organisms. One leader from a seaweed company commented:

> "Some of our farmers also grow mussels. They've had really good success growing kelp right next to mussels and found that the shells can be twice as thick. I do think there's this

kind of untapped potential that we haven't got into what other species could be grown near our kelp."

If the shell of organisms are soon impacted by acidification from climate change, an increase in shell width will be very helpful. There are many advantages to farming multiple trophic levels together.

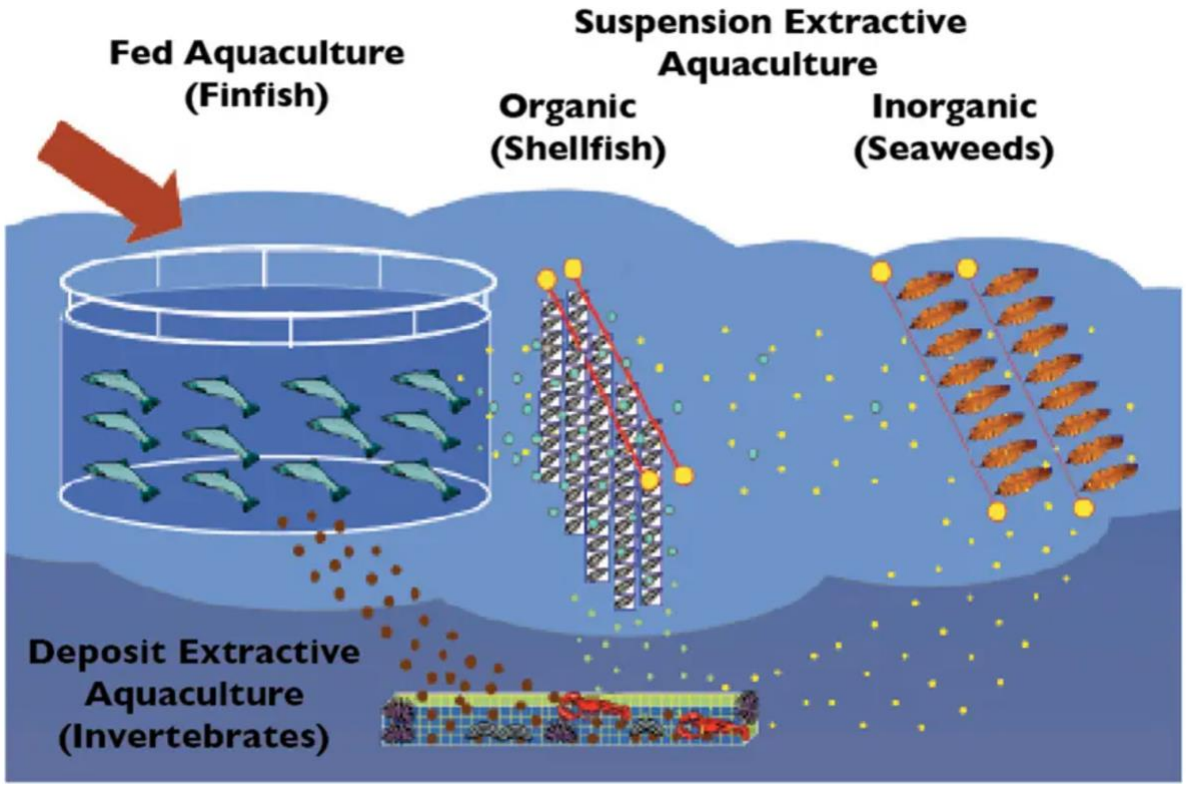

Figure 5: Diagram of finfish, shellfish, invertebrate, and seaweed working together in an IMTA system. All organisms working together to take in the waste from finfish aquaculture. (Chopin, 2013)

Efficiency

Two areas where GHG emissions are the most produced are in the supply chain and the production of fish feed (Macleod et al., 2020). Creating more efficient production will, in the end, decrease the amount of GHG emissions produced. All of the technologies discussed in this section will help make the industry become more efficient.

In 2017, the US imported over 90% of consumer seafood and estimated 50% of that came from aquaculture practices (Garlock et al., 2020). The shipment of seafood from forgein

countries increases carbon emissions along the aquaculture supply chain. Increasing the number of U.S.-based aquaculture farms will lower the demand for imported seafood. Although it depends on the system and equipment being used, researchers found that aquaculture production close to its markets reduces the impact on the climate (Liu et al., 2016). One finfish company described their product produced in the US in Maine ships to many stores in Maine, but also North Carolina and South Carolina (stakeholder interview, finfish company). Another company only ships their product to North America as well (stakeholder interview, finfish company). While speaking with a kelp farmer, they explained how much they were trying to move their production process, and their supply chain is within the state they produce in (stakeholder interview, kelp farmer). They also explained that "there's still work to be done to dive deeper into what we're doing to reduce our own carbon emissions" (stakeholder interview, kelp farmer). Another finfish company originally produced their stock in Europe, but after realizing the amount of GHG emissions they were creating flying to the US, they built a farm in Florida to further reduce their impact on the environment (stakeholder interview, finfish company). Most companies know there is more work to be done to keep decreasing their impact on the environment. Reducing the amount of seafood production, we rely on in other countries will lower GHG emissions from aquaculture.

Another innovation that falls under efficiency is choosing the best possible stock that will use resources efficiently. One aquaculture technology hub worked with a company to predict the metabolic rate of a salmon egg (stakeholder interview, aquaculture tech hub). GenitiRate created a technology to sort animals based on their metabolic rate (IMV Technologies, 2021). If the metabolic rate is high, salmon will have a higher feed conversion rate and the opposite for a low metabolic rate (stakeholder interview, aquaculture tech hub). If aquaculture farms want to use their feed more efficiently and use less food, they can now discard the high metabolic rate eggs to create the best stock.

Digitization and Automation

Digitization of the aquaculture industry can create a more efficient industry and help benefit products' economic input. Although we did not flag digitization as a major theme while reviewing the literature, it was frequently brought up by industry leaders during the interviews. One leader explained, "If you have a better idea of your inputs going in and then have a better

idea of what your output is going to be, and then the supply chain and then the delivery of your output, digitization can make that more efficient" (stakeholder interview, bluetech hub). Currently, many small aquaculture farms use pencil and paper to track their products. Some are looking to digitize their tracking in order to become more efficient. As they become more efficient, they will have fewer losses (stakeholder interview, bluetech hub).

Sensor technologies are another way the aquaculture industry is incorporating digital solutions into their operations. Interviewees mentioned how sensors are particularly useful within the finfish sector. Sensors can monitor the water quality and behavior of fish which are aspects especially important to monitor during the feeding process (Parra et al., 2018). Fish are highly susceptible to pollutants in the water, and some species are acutely sensitive to changes in water quality and temperatures (Harun et al., 2012). Dissolved oxygen is one of the more important factors to monitor because it must be at a certain level to support the respiration process for fish and other species (Simbeye et al., 2014). As temperature increases, the demand for dissolved oxygen increases because of changes in the solubility of gasses and the increased stress on animals (Simbeye et al., 2014). Researchers found changes in temperature rates can stress shrimp and create high mortality rates (Hernández et al., 2011). These researchers also found low dissolved oxygen concentration was associated with an increase in disease (Hernández et al., 2011). The ability to monitor these aspects of aquaculture helps detect changes in these variables early on.

Four interviewees mentioned sensors or monitoring their species as a key technology within the aquaculture industry. One interviewee in academia said new technologies are arising mainly in the bluetech scene, "There's definitely work being done in the sensor space in the [blue] tech space to try and identify disease before it hits your plate" (stakeholder interview, aquaculture academia). As mentioned in the 'Adaptation to Climate Change' section, one company used sensors on mussels (also referred to as biosensors) to measure the dissolved oxygen in the water. In one study, scientists researched how mussel valve opening and closing could be used to indicate environmental factors (Comeau et al., 2018). The study concluded that organisms like mussels could be used as indicators in monitoring conditions like toxic algal blooms (Comeau et al., 2018). An increasing number of sensor technologies are being created by cutting-edge companies in the aquaculture industry. Companies like Innovasea have created wireless sensors to track dissolved oxygen, salinity, chlorophyll, blue-green algae, turbidity,

colored dissolved, organic matter (Innovasea, n.d.). Innovations in sensor technology can help increase the understanding of aquaculture farms' environment and better protect stocks.

Digitization is also being used to innovate feed monitoring, which is particularly important within the finfish sector. As discussed earlier, the production of fish feed creates a large amount of GHG emissions. The cost for feed is also quite expensive and can account for roughly 50% of the production costs of finfish (Ballester-Moltó et al., 2017). For both environmental and economic purposes, it is crucial that farmers maximize the use of fish feed and minimize waste (Ballester-Moltó et al., 2017). Digital solutions to monitoring can increase this efficiency. One finfish industry leader described how using feed more efficiently is essential to them and how they use cameras to monitor their tanks:

> "We have cameras in the site above water and below the water...They can monitor the fish 24/7. And it also means [we can monitor] the amount of feed that we're using to feed the fish. They're able to feed much more efficiently. So when she's sitting in her office, looking at, she probably has probably three or four sites, she can measure how much feed is going into each site and compare...Compare water temperatures and how fish are performing, and how fish are eating. That has had a dramatic effect on the amount of feed we use" (stakeholder interview, finfish company).

Digital monitoring allows the staff to observe feeding behavior in real time so they can turn off the fish feed device if necessary. This optimizes the amount of fish feed used by ensuring little waste. In addition to cameras, autonomous underwater vehicles (AUV) have been used to monitor water quality and inspect cage netting quality (Bao et al., 2020). AUVs can also be programmed to understand and monitor fish behavior. When used during feeding, AUVs can help understand when fish feed should stop releasing into the water (Eichhorn et al., 2018). If companies prioritize their effect on the environment, they need to watch the amount of excess feed entering the environment. The use of sensors and AUVs can help optimize fish feed and monitor water quality to create the optimal environment for a species to live in.

In the supply chain, refrigeration creates a significant amount of emissions (Macleod et al., 2020). In a study on the carbon footprint of Norwegian seafood, researchers found that older refrigeration systems contributed up to 30% of the total carbon footprint (Winther et al., 2009). If

the efficiency and energy efficiency could be increased in the refrigeration part of the supply chain, fewer emissions will occur (Winther et al., 2009). One oyster farmer explained their use of sensors to detect the temperature during transit. They explained when the temperature dips below a certain degree, the sensor changes a different color, and then the recipient cannot sell that product (stakeholder interview, shellfish farmer). If this event occurs more than once, the company is inefficient and loses more products, and creates more emissions than it needs. If the company can make sure the temperature does not drop, they will optimize their stock.

Aquaculture farmers are also using phone applications and software to increase efficiency. One shellfish farmer hand delivers all of their products throughout all of North Carolina. To minimize the amount of time they are on the road, they use a phone application to calculate the shortest route possible (stakeholder interview, shellfish farmer). This not only results in an efficient use of time, but also decreases the amount of fuel used which in the end decreases the amount of carbon emissions from this delivery service. Other companies like Oyster Tracker have created software to manage all aspects of a shellfish farm (Oyster Tracker, 2021). The software puts all of a farm's activity in one place where they can compare environmental conditions, growth rates, and mortality. It can also predict their harvest and alert the company when equipment needs to be checked (Oyster Tracker, 2021). Creating a more efficient environment will decrease the carbon footprint of aquaculture farms. These applications can optimize a farm's production and produce fewer GHG emissions.

Other

In addition to the technologies and innovations discussed above, interviewees addressed alternative energy, partnering with wind farms, and sustainable packaging. One finfish aquaculture company was in the process of evaluating installing solar panels at their site (stakeholder interview, finfish company). Another international finfish aquaculture company explained that, while they are not ready to use solar or wind energy, they were in discussions with other companies that have created "electronic rig pulsion motors" for their vessels (stakeholder interview, finfish company). Other sectors within the aquaculture industry are incorporating the use of renewable energy as well. Mook Sea Farm, a shellfish farm in Maine, also installed solar panels on its farm (Island Institute, 2020). They have cut down their energy costs by 25% and predict to offset 100,000 pounds of carbon pollution each year (Island

Institute, 2020). When choosing suppliers for their product, one fish feed innovator prefers microalgae producers who are using solar panels or other energy-efficient options (stakeholder interview, aquaculture innovator). Industry leaders have also discussed the benefit of partnering with offshore wind companies. An industry leader mentioned that, "Norway is looking at using the infrastructure from the [offshore wind] industry to facilitate offshore aquaculture" (stakeholder interview, aquaculture tech hub). Although this type of partnership was not discussed in all of the interviews, we see this as an opportunity for both industries to grow.

Interviewees discussed the use of sustainable packaging as a priority for some companies. One finfish company is developing sustainable material for the packaging of their salmon:

> "The main packaging for HOG salmon and salmon fillets is expected to be made of fully recyclable or biodegradable material for domestic transportation. Together with a sustainability-minded supplier, we have developed boxes using 90% cellulose fiber and will only use sustainable material such as soy ink for prints. Inside every box, we anticipate there will be a 100% biodegradable bag containing all fillets or HOG fish packed in bulk."

Other farmers discussed the hardships with finding sustainable packaging because of how wet their product is when shipping (stakeholder interview, shellfish company). Using recyclable packaging could not withstand how we their oysters were when transporting them (stakeholder interview, shellfish company). With one company creating packaging from biodegradable material, there could be hope for other companies also to use similar or the same material.

Social Impacts

As we moved along through our research and interviews in 2020, significant events occurred throughout the world, and the lens through which people viewed the world changed. To incorporate current events and important issues, we reviewed how the aquaculture industry could create a more equitable industry and society and rebuild the industry in a more environmentally sustainable manner after the COVID-19 pandemic.

COVID-19

The COVID-19 pandemic affected sectors within aquaculture differently, though experts within all sectors experienced disruptions in their supply chain. One kelp aquaculture company shared about the pandemic, “I think it really calls for the importance of resiliency and how we design our businesses and our operations" (stakeholder interview, seaweed company). Although this seaweed company’s supply chain was mostly contained within one state, the company had issues with receiving lids for their jars because the manufacturer in China shut down (stakeholder interview, seaweed company). COVID-19 clearly showed the vulnerable parts of each company’s supply chain. One seaweed company learned how they could better prepare if there were to be another disruption in their supply chain in the future (stakeholder interview, seaweed company).

During the COVID-19 pandemic, aquaculture producers had to become more creative in their production. An industry leader explained that the markets disappeared during the COVID-19 pandemic in addition to the supply chain (stakeholder interview, aquaculture academic). They also explained how if a company had an online presence, they could more easily pivot how they sold their product while others had to become more creative (stakeholder interview, aquaculture academic). As restaurants were closed down, many farmers were selling their products right off the fishing pier. Once restaurants opened back up, there was still a disrupted supply chain, so restaurant chefs went straight to the source and bought shellfish from at the pier (stakeholder interview, aquaculture academic). A shellfish farmer also discussed the growth of the frozen food sector during the pandemic (stakeholder interview, shellfish company). The ability to shift in their production allows companies to be more resilient when there is a large disruption to the market like a pandemic.

Not all aquaculture farmers were lucky with the COVID-19 pandemic. One kelp farmer in Alaska explained how the state relies on the seafood and tourism industry (stakeholder interview, seaweed company). Both industries took a massive hit from the pandemic, and there was apparent economic damage that continues to be present. The pandemic also presented the kelp farm “an opportunity to have a sustainable renewable non-extraction based economic model, which is very beneficial” (stakeholder interview, seaweed company). Kelp farms are creating new products and not extracting from wild populations, creating a more sustainable industry. A shellfish farmer we interviewed found a positive aspect of the pandemic:

> "If there's any silver lining in this thing, it will be that people are eating more oysters and are responding to kind of our efforts to say, 'Hey, oysters are great for you. They're delicious and easy to prepare. As far as protein goes, it's as low impact as you can get compared to any other terrestrial protein, far fewer inputs compared to wild capture fish.'" (stakeholder interview, aquaculture non-governmental organization).

Their explanation and campaign of how oysters are better for the environment and a healthy option helped sell oysters and limit the pandemic's impact. They also explained that during the pandemic, farmers were trying to make people feel more comfortable with cooking oysters at home to help increase the demand for oysters (stakeholder interview, aquaculture non-governmental organization).

After being asked how the industry could build back in a more equitable and sustainable fashion, an aquaculture innovator shared what they hoped to happen:

> "I think, hopefully, in light of the pandemic, a sort of resetting of our mind [occurs] about what we want to eat, how we want to live, what choices we want to make to try and be better. I'm hoping people will be open-minded to the fact that aquaculture, at least in ours in our country, is really, really brand new... so I'm hoping that people will be open-minded to this industry growing." (stakeholder interview, aquaculture innovator).

The aquaculture industry has grown fast throughout the last few years, and people are just starting to understand the industry. An industry expert affiliated with an aquaculture innovator believes the consumers are ready for a change, and it is time for a wave of environmentally sustainable aquaculture practices (stakeholder interview, aquaculture innovator). Although COVID-19 pandemic disrupted many farmers and companies, there is hope that the disruption created a realization of the need for sustainable aquaculture in the U.S.

Diversity and Inclusion

We asked each industry leader in the aquaculture sector how they believed their own company or the industry as a whole could contribute to a more socially equitable society. Many industry leaders spoke about creating jobs and how they can help with the growing food security

issue. In comparison, some industry leaders gave roundabout answers and danced around how the industry is not diverse. While others discussed how many aquaculture products have been historically expensive and inaccessible to large populations. Some answers to our questions were promising, while others were disappointing and clarified the aquaculture industry has a bit further to go on accessibility to the products and accessibility to creating new aquaculture farms.

As discussed in sustainable priorities, it is important to many industry leaders to build and maintain a social license. One finfish company discussed "Building and maintaining [our] social license to operate is a critical success factor" (stakeholder interview, finfish company). They also discussed how stakeholder engagement through open communication was critical for success. Their involvement with community organizations and nearby universities allowed for collaboration (stakeholder interview, finfish company). The finfish company also tries to actively recruit new employees from their community (stakeholder interview, finfish company). In addition to their stakeholder engagement, the company joined the United Nations Global Compact and spoke about how they support the UN's human rights, labor, environmental, and anti-corruption principles.

One interviewee brought up the Shellfish Growers Climate Coalition (SGCC) through the Nature Conservancy, where shellfish growers can highlight how climate change has affected their lives and advocate for policy change (The Nature Conservancy, 2020). Many shellfish industry leaders are working in areas where it is a massive part of the culture. Many leaders are worried that they or their community might lose their identity if climate change destroys their industry. A shellfish farmer and leader from an aquaculture non-governmental organization described that:

> "A lot of places hardest hit by these climate impacts have a long history and heritage around oyster farming, and consumption is tied into the identity of these places...There are tragic examples of places that already have lost the natural resource, cultural resources, identity, and everything that was tied in with those natural resources. I mean, you can't replace that. [It] fires me up just to think about it. It's tragic, and it's happening right now" (stakeholder interview, aquaculture non-governmental organization).

As an industry hit hard by climate change, SGCC has provided a community where growers can come together and advocate for their industry. These coastal communities rely on the ocean and aquaculture for their resources, and they also have a strong connection culturally to these areas. Many in the aquaculture industry are not contributing the most to climate change but are feeling many of the consequences (stakeholder interview, aquaculture non-governmental organization).

An oyster company that is a part of SGCC has created a system to provide oysters all over the state of North Carolina. Their goal is to make oysters accessible to anyone. They do this by allowing customers to buy one oyster and not create a minimum amount to buy. They also hand deliver all of their products to their customer's doorstep (stakeholder interview, shellfish company). An academic in aquaculture explained that historically there was a barrier to the oyster industry as oysters were very expensive, and historically only rich, white communities could access the expensive industry (stakeholder interview, aquaculture academic). Knowledgeable of the industry's barriers and starting in the industry, their goal in academia is to make the education to create aquaculture farms or to join industry more accessible. They encourage students from all over the country and the world to learn more about the aquaculture industry (stakeholder interview, aquaculture academic). Additionally, one finfish company discussed food security. They do not just deliver healthy protein but provide food to those who cannot afford it and work with the local food bank to do this (stakeholder interview, finfish company).

Similarly, to the finfish company, an aquaculture innovator discussed that one of their main sustainability priorities was food security and was one reason why they started their company. They discussed how aquaculture is a solution to the growing population, and aquaculture supplies more seafood than fisheries (stakeholder interview, aquaculture innovator). The interviewee said, "If you care about food security problems and you care about where we're headed in terms of consuming seafood, we have to care about fish farming" (stakeholder interview, aquaculture innovator). Food security is a social justice issue, and aquaculture can be used to feed the growing population. Later on, in their interview, they discussed what their own company is doing for diversity. They said, "In terms of just internally within our company, two of our four co-founders are women, and I really take pride in this being a woman-led startup" (stakeholder interview, aquaculture innovator). They have also hired non-U.S. citizens for their California-based company for the reason to hear diverse voices in their decision-making

(stakeholder interview, aquaculture innovator). It is promising that these companies are adding women and other diverse voices but did not discuss how they were increasing racial diversity in their workplace. One company's sustainability report we found included a section on increasing diversity in their company, but specifically only mentions the percentage increase of women at the company (Atlantic Sapphire, 2019). More can be done within aquaculture to create a more diverse industry.

Job Creation

A kelp company saw that lobstermen were losing their industry to climate change impacts and decided to partner with lobster fishermen to provide them with an alternative source of income. It was especially important for success during the COVID-19 pandemic. The seaweed farmer explained about their business:

> "We're providing jobs here in the state of Maine. Especially in COVID, when a lot of businesses have struggled, we've actually been able to do decently well and continue to grow our retail outlets and hire more people onto our team. We're doubling what we grew from last year, so that's more money back into the pockets of local fishermen" (stakeholder interview, seaweed company).

They are helping create more jobs while producing a product that can help mitigate climate change. Another kelp aquaculture farm, GreenWave, created a model and approach to help many in the U.S. to create a successful aquaculture farm (GreenWave, n.d.). The approach can provide more opportunities to join the industry as startup knowledge can be a barrier to joining the industry. More accessibility to the aquaculture industry will increase the amount of aquaculture farms in the U.S. to help feed the growing population.

Offshore Wind

Offshore wind is expanding rapidly, and global installed capacity is expected to increase from 28 gigawatts (GW) in 2019 to 1000 GW by 2050 (IRENA, 2019). In the U.S., offshore wind is still a nascent industry, and there is currently only one operating commercial offshore wind farm – the five-turbine Block Island Wind Farm in Rhode Island (ICF, 2020). However, the

Bureau of Ocean and Energy Management (BOEM) has issued 16 leases for offshore wind energy along the east coast (ICF, 2020). Additionally, in January 2021 President Biden signed an Executive Order aiming to double offshore wind lease areas in federal waters by 2030 (Blunt and Keith, 2021). With the industry rapidly growing, offshore wind will play an increasingly important role in decarbonizing the U.S. energy grid and limiting global warming to 2 degrees celsius, as set forth in the Paris Climate Agreement (Cranmer and Baker, 2020). In this section, we identified how the offshore wind sector has been impacted by climate change, the current sustainability challenges, emerging decarbonization technology and innovations, and how the offshore wind industry can contribute to social equity.

Climate Change Impacts

The offshore wind sector is different from shipping and aquaculture in that it has not been negatively impacted by climate change. Rather, all of the industry experts we interviewed said the sector has benefited from climate change. The increasing recognition of the climate crisis and the need to mitigate it is helping to drive the demand for offshore wind. One interviewee noted that in the U.S. "renewable portfolio standard (RPS) targets and investment dollars are dramatically increasing… and the offshore wind industry can only benefit from that (stakeholder interview, offshore wind producer) and another noted that these trends are "driving the expansion of offshore wind in the Northeast" (stakeholder interview, offshore wind consulting agency). Currently, over half of the states have set a RPS which requires a specified percentage of the electricity that utilities sell comes from renewable energy (NCSL, 2021). Certain states even have goals specifically for offshore wind such as New York that aims to have 2,400 megawatts of offshore wind by 2030 (NCSL, 2021).

Climate change is also driving an increase in the percentage of renewables in energy company's portfolios. The most dramatic example is Ørsted, previously Danish Oil and Natural Gas. The company fully divested its oil and gas business in 2017 to pursue only renewable energy and changed its name to Ørsted to reflect this business shift (Ørsted, n.d.). One industry expert said that Ørsted's move away from oil and gas was "completely driven by climate change" (stakeholder interview, offshore wind producer). Other energy companies have not moved as quickly as Ørsted but are slowly moving into renewables (Peters, 2020). For example, in 2018 Statoil rebranded itself as Equinor to demonstrate its increasing investment in

renewables and a shift away from a solely oil and gas portfolio (Equinor, 2018). While this is a promising shift, it is important to note that this is also likely marketing. Equinor took "oil" out of its name, however the company is still one of the world's largest sellers of crude oil and the second largest supplier of natural gas to Europe (Equinor, 2020).

Sustainability Priorities

We asked stakeholders what they viewed as the main sustainability challenges within the offshore wind industry to gauge where climate change initiatives like decarbonization fit relative to other sustainability priorities. One theme that emerged from nearly all of the offshore wind interviews is the idea that offshore wind is a sustainable industry to begin with. To this point, one interviewee stated that "the goal is to displace fossil fuels generation, so I think [sustainability] is built in" (stakeholder interview, offshore wind developer). This idea that offshore wind is inherently sustainable sets it apart from shipping, aquaculture and many other industries in the blue economy that are by nature more polluting and are large contributors to climate change. Offshore wind is seen as a solution and continuing to expand the industry will help combat climate change.

Wildlife Impacts

While the idea that the offshore wind sector is inherently sustainable was nearly ubiquitous among the interviews, interviewees still identified areas that they saw as a challenge or an opportunity for improvement. The first area mentioned in two interviewers was minimizing impacts on wildlife, specifically marine mammals and migratory birds. Noise from pile driving during construction and collisions with turbine blades are both known to negatively affect marine mammals and seabirds (Best and Halpin, 2019). Minimizing wildlife impacts is of particular concern in the U.S. since there is only one operational commercial wind farm and therefore a lot of unknowns about how an increasing number of offshore wind turbines will affect wildlife (Bush and Hoagland, 2014). One interviewee spoke of their company's efforts to mitigate wildlife impacts saying, "We are trying to go well beyond regulation. We have marine mammal and avian experts on staff who are thinking about not just keeping within regulation but making sure we do not harm these animals" (stakeholder interview, offshore wind developer). Researchers have identified promising ways to minimize the adverse effects of offshore wind

construction and operation on wildlife through marine spatial planning (Best and Halpin, 2019) and technological advancements (Tsouvalas and Metrikine, 2016). However, there is still uncertainty and continued research will need to keep up with the pace and scale of wind development (Allison et al., 2019).

Energy Storage

The second area mentioned in two interviews was developing storage capacity for offshore wind. One interviewee explained "wind doesn't necessarily always flow when people are using energy the most, and so storage is going to be really important industry wide" (stakeholder interview, offshore wind producer). To ensure that clean energy is not wasted, it is crucial to improve the storage capacity. Hydrogen technology was mentioned as a promising solution to this challenge and will be discussed in further detail in the technology and innovation section of this topic section.

Climate Change & Sustainability Goals

To investigate what carbon reduction commitments offshore wind companies have set, we looked at publicly available sustainability reports. Specifically, we looked at 13 offshore wind developers and turbine manufacturers or original equipment manufacturers (OEMs) that are involved in projects within the U.S. Of the 13 companies, 10 had published sustainability reports or dedicated sustainability sections within their annual reports. Additionally, 9 of these companies laid out specific carbon reduction targets that they are working towards. EDF Renewables, U.S. Wind (a subsidiary of Italy-based Renexia SpA), and Copenhagen Infrastructure Partners don't have published sustainability reports or specific emission reduction targets. Additionally, EDP Renewables has a published sustainability report but only has vague carbon reduction goals.

A few specific carbon reduction targets that companies have set include:

- Equinor aims to reduce the net carbon intensity (from initial production to final consumption) of energy produced by at least 50% by 2050.
- Ørsted plans to reach carbon neutrality in total carbon footprint (scope 1-3) by 2040.

- GE plans to be carbon neutral in its facilities and operations by 2030.
- RWE Renewables intends to reduce Scope 3 emissions by 30% by 2030.

It's easy to set these goals but ensuring that companies follow through is crucial to obtaining results. As one industry expert commented, "it's really easy to shout these goals and a lot of companies have started to, but actually following through is much harder" adding that companies need to "set aggressive but attainable goals" (stakeholder interview, offshore wind developer). Without transparency and clear plans for how companies will actually reach carbon reductions, these goals can be construed as simply greenwashing.

Interviewees identified two main stakeholder groups that are driving these company-level sustainability commitments: investors and customers. One offshore wind turbine manufacturer mentioned that roughly 30 to 40% of their shares are owned by investors "who care deeply about the social and environmental sustainability of their investments." The need to meet the expectations of shareholders is pushing companies to continue to develop and meet sustainability goals including carbon reduction targets. This concept of shareholders influencing change in a corporation is known as shareholder activism and has been increasingly used to push for sustainability improvements. (Grewal, Serafeim and Yoon, 2016). The second driver is customer demand. In the case of offshore wind OEMs, one interviewee stated that "some utilities are implementing sustainability into their tender requirements…because they face pressure from the end users" (stakeholder interview, offshore wind OEM). These stakeholder groups are pushing companies to improve their sustainability.

Climate Change Mitigation - Technologies & Innovations

To meet their stated carbon reduction goals, companies will need to continue to invest in and adopt a number of innovative technologies. These technologies will help expand offshore wind capacity and improve efficiencies throughout the lifecycle of a wind farm, resulting in more energy production and less emissions. Through our background research and interviews with wind industry experts, we identified five subthemes of new and emerging technologies that are seen as having great promise. These subthemes are: turbine improvements, turbine recycling, digitization and automation, vessel improvement, and green hydrogen.

Turbine Improvements

One of the first technologies that nearly every interviewee mentioned as very promising is floating wind. Current offshore wind turbines use a variety of fixed-bottom structures that are attached to the seafloor but only viable in shallow water up to about 197 feet (ICF, 2020). However, in the U.S. nearly 60% of suitable offshore wind locations are at depths greater than 200 feet (Hockenos, 2020). Floating wind turbines will be crucial in expanding U.S. offshore wind capacity particularly in areas on the West Coast and in Maine where the waters are too deep for fixed turbines (ICF, 2020). Floating wind turbines also have the potential to produce more energy than current offshore turbines because the winds in deeper waters are more powerful and technology of the floating rigs enables them to carry larger turbines (Hockenos, 2020).

Equinor created the world's first floating wind farm, Hywind Scotland, which has been operating since 2017 (Equinor, n.d.). This project demonstrated the viability of floating turbines and has helped drive further innovation in the area that will help make the costs competitive. Several other floating offshore wind projects have now been deployed or are in advanced planning stages (ICF, 2020). However, as one industry expert pointed out "it is still largely an experimental technology" (stakeholder interview, offshore wind NGO). Another expert added, "there are tons of companies working on the technology now and it does need that to mature" (stakeholder interview, offshore wind producer). We will likely see the emergence of more floating wind farms globally before we see them in the U.S. One industry expert explained, "I think we're going to lag in the U.S. ... there's still a lot of shallow water area to be developed and developers are going to want it [new offshore lease areas] in shallow water because that's where it's cheapest" (stakeholder interview, offshore wind consulting agency).

Figure 6: Different offshore foundation types. Left to right: monopile, jacket, twisted tripod, floating semi-submersible, floating tension leg platform, and floating spar. (Credit: Josh Bauer/National Renewable Energy Laboratory)

Another turbine improvement technology trend within the industry is the production of increasingly larger turbines. Deploying larger, more powerful turbines, like one industry expert explained, "allows them [offshore wind developers] to install less turbines in any given lease area to meet their contractual agreements with states." (stakeholder interview, offshore wind NGO). Installing fewer turbines that produce the same amount of energy will reduce the costs of building and maintaining the wind farm (Reed, 2021), which will also likely drive down associated carbon emissions. However, the increasing size of wind turbines poses significant logistical challenges around how to transport and install the components (Verrengia, 2009).

Given the cost-savings of larger turbines and the appeal to offshore wind developers, wind OEMs have been competing to build the largest turbine. In 2018, GE announced their new 12-megawatt Haliade X offshore wind turbine, shown in Figure 7 (Reed, 2021). This was the largest and most powerful offshore wind turbine to date until Siemens Gamesa unveiled their new 14-megawatt model in 2020. (Parnell, 2020). Then in 2021, Vestas, the third offshore wind OEM active in the U.S., announced an even larger turbine (Lewis, 2021). Vesta's V236-15-megawatt model is now considered the largest turbine in the industry with its first prototype expected to be installed in 2021 (Durakovic, 2021).

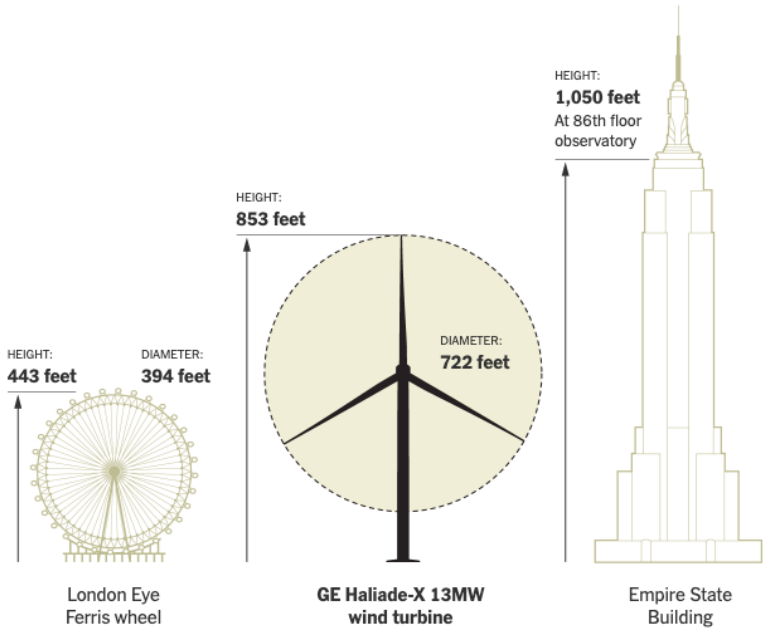

Figure 7: GE's largest offshore wind turbine, the Haliade-X. (Credit: General Electric)

Turbine Recycling

Another area that offshore wind OEMs are interested in is improving the recyclability of wind turbine components once they are decommissioned. Currently, wind turbines are between 85-95% recyclable, but the turbine blades are made of a composite material that makes them very difficult to recycle (Evwind, 2021). By improving the recyclability of the turbine blades, it could help the industry achieve zero waste turbines and lower the carbon payback for the lifespan of a wind turbine (Jenson, 2019).

In an effort to address this problem, the three wind OEMs involved in offshore projects in the U.S. – Vestas, Siemens Gamesa and GE – have all joined the DecomBlades project (Evwind, 2021). This project hopes to identify at least one sustainable, globally available, and economically viable path for recycling old turbine blades (Vestas, 2021). Vestas is also involved in the SusWIND Project which is focused on three main areas: 1) finding viable technologies for recycling existing wind turbine blades which are nearing the end of their life; 2) driving the use of more sustainable materials for turbine blades that have more potential for recyclability; and 3) developing new approaches for turbine blade design with end-of-life strategies in mind (Sustainable Composites, n.d.).

GE is also involved in an innovative project with Veolia North America looking to use turbine blades in cement production. A portion of the blades will be shredded and used to replace other raw materials during the cement process and the other portion will be used instead of coal to provide energy for the manufacturing process (Noon, 2020). This process could help cement manufacturers lower their CO_2 emissions by as much as 27% (Noon, 2020). This project is currently focused on using onshore wind turbine blades but could use offshore blades in the future once those turbines have reached the end of their lifespan.

Digitization & Automation

Digitization is increasingly being used within the offshore wind industry to improve operation and maintenance (O&M) efficiencies and optimize turbine performance. Offshore wind projects generate large quantities of data. As one interviewee mentioned that an individual turbine can have "a little less than 1000 different sensors" (stakeholder interview, offshore wind OEM). These different sensors are continuously collecting data on things such as environmental conditions and the performance of turbine components (Taylor-Smith, 2020). Offshore operators can then use this data, through different software and digital platforms, to remotely monitor and optimize their wind turbines (Wilson, 2018). Specifically, it can better inform the specific maintenance needs of each turbine and identify damages early which can reduce unnecessary site visits, decrease the time a turbine has to go offline for inspections or repairs, and save money.

There is also growing interest in using AI and machine learning to optimize energy production, forecast the life expectancy of a turbine, and improve O&M efficiency (Willige, 2020). These technologies can be particularly useful in identifying material fatigue, and/or weakening of a part. The part can then be replaced proactively during scheduled maintenance, reducing the risk and cost of unplanned repairs (Willige, 2020). AI and machine learning paired with remote monitoring have also been able to increase coordination among all turbines within a given site. For example, if one turbine has to go offline for maintenance the other turbines can be adjusted to maintain capacity. Additionally, each turbine's positioning can be adjusted to ensure an even flow of wind throughout the entire wind park (Willige, 2020).

Robotics and autonomous systems are another promising technology area for improving efficiency of offshore wind operations. The industry has already begun to use drones for turbine inspections instead of having someone manually climb and inspect the turbine. The drones not

only speed up the inspection process making it cheaper and more efficient, but they also make the inspections safer by not exposing technicians to unnecessary risks (Shell, n.d.).

Numerous companies are also working to develop technology that will further minimize the need for technicians and engineers to go out to offshore wind farms. It is estimated that between 80-90% of the cost of offshore operations and maintenance comes from having to get engineers and technicians to remote wind sites to find and address the problem (Cranfield University, n.d.). Reducing the need for people to go out to the wind farm will save money but also cut the emissions from the transportation vessels. One effort that is currently working on this challenge is the Multi-Platform Inspection, Maintenance, and Repair in Extreme Environments (MIMRee) project. The project, funded by Innovate UK, is working to bring fully autonomous inspect-and-repair missions to offshore wind farms. These missions would include unmanned vessels, drones, and "wall-climbing and blade-crawling" robots that together could perform routine inspections and maintenance while human operators remain onshore (MIMRee, 2020).

Vessel Improvements

The offshore wind industry relies on a number of different vessel types to construct, operate, and maintain a wind farm. These vessels, which typically run on diesel fuel, account for a large majority of the CO_2 emissions from a company's O&M. Ørsted, in 2019, reported 44 kilotons (kt) of CO_2 emissions from operations and maintenance of both their onshore and offshore energy assets (Ørsted, 2019). Of the 44 kt of emissions, 42 kt, or 95% of emissions, came from crew transport and service vessels that the company charters to reach their offshore wind farms. If offshore wind companies, like Ørsted, want to achieve their carbon neutrality goals, decarbonizing their vessels will be crucial.

The industry has begun to leverage technological advancements made within the transportation sector, as discussed in the shipping section above, to improve efficiency and decrease emissions when developing new offshore wind-specific vessels. In 2020, Volvo Penta announced that it would develop two hybrid crew transfer vessels (CTVs) for Ørsted. Each vessel will include a battery pack to support peak-shaving and allow it to run in electric mode while at low speeds or idling (Borrás, 2020). This hybrid technology is estimated to reduce CO_2 emissions by 127 metric tons compared to a diesel-powered vessel. (Volvo Penta, 2020). These vessels are expected to be operational in 2021 at a wind farm in the United Kingdom. One of the project partners noted that:

> "This pilot project will also open the door for increasing hybrid CTVs in the future. Previously, the size of electric motors and components were too big for CTVs. Our compact and lightweight technology has overcome this issue and solved the challenges faced by vessel designer" (Volvo Penta, 2020).

Decarbonizing vessels is not yet a large focus in the U.S. like it is in Europe since many projects are still in the construction or pre-construction phase (stakeholder interview, offshore wind developer). However, some companies are looking ahead and beginning to work on low carbon vessels for offshore wind farms in the U.S. The Finnish technology group, Wärtsilä, just announced in 2021 that it had designed the world's first Jones Act-compliant hybrid service operation vessel (SOV) to serve the U.S. offshore wind market (Durakovic, 2021). All vessels operating within American wind farms have to comply with the Merchant Marine Act of 1920, also known as the Jones Act, which requires all vessels moving between two points in the U.S. be built, owned, and crewed by U.S. citizens or permanent residents (Merchant Marine Act of 1920). The new SOV will include a range of new low carbon technologies, including shore-charging cold iron systems and a hybrid powertrain with an on-board battery storage system (Durakovic, 2021). This allows for peak shaving which lowers both emissions and maintenance costs. The SOV design also includes space to integrate fuel technologies such as hydrogen fuel cells if desired in the future.

Green Hydrogen

Green hydrogen was another promising technology area identified in many of the offshore wind stakeholder interviews. Currently, most of the hydrogen produced worldwide uses fossil fuels to power the electrolyzers that split water into hydrogen and oxygen (Cho, 2021). 'Green hydrogen' uses renewable energy instead of fossil fuels to produce hydrogen. Hydrogen has a number of potential uses, shown in Figure 8, such as powering power plants, fuel for transportation (including shipping as discussed on page 31), and storing excess renewable energy. One industry expert spoke specifically to the need for better storage:

> "One of the biggest things for offshore wind is storage. You know, the wind doesn't necessarily always flow when people are using energy the most. And so storage

is going to be really important industry wide. We are looking at a range of ways to do that including green hydrogen" (stakeholder interview, offshore wind developer).

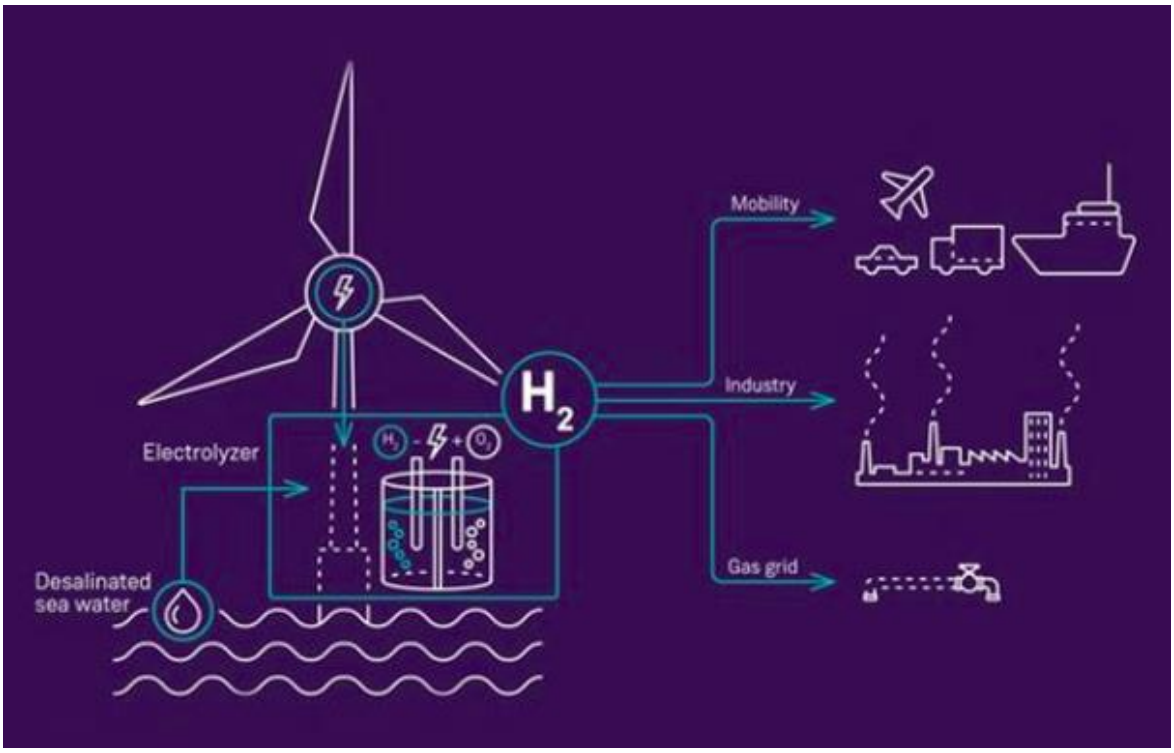

Figure 8: A turbine with built-in electrolyzer and potential uses for hydrogen. (Credit: Siemens Gamesa)

There are two main areas of interest for using offshore wind in hydrogen production. First, electricity from offshore wind farms can be used to power an electrolyzer onshore. And second, hydrogen could be produced within a turbine and then transported to shore instead of electricity. Siemens Gamesa, an offshore wind OEM, is currently working to integrate an electrolysis system into one of its turbines. The company is expected to invest approximately €120 million to develop this technology and have a full-scale offshore demonstration by 2025 or 2026 (Siemens Gamesa, n.d.).

There are still a number of key hurdles to integrating wind power with hydrogen power. More studies are needed to better understand how to best power an electrolyzer from a fluctuating power source like offshore wind. The biggest consideration, not surprisingly, is cost. In the U.S, green hydrogen costs three times more than natural gas and is also significantly more expensive than fossil fuel-produced hydrogen (Cho, 2021). One interviewee noted that the

technology is largely developed but "you need to look into the business case and investments" and that "if you start talking to utilities, they are sitting with their calculators trying to figure out what is the best time to go into this business" (shareholder interview, offshore wind OEM). Overall, it is unclear when costs will be low enough to see more green hydrogen paired with offshore wind energy.

Social Impacts

Given the significant developments that occurred during the development of this study in 2020, we felt it was necessary to include a brief review of how the offshore wind industry was impacted by the COVID-19 pandemic and how the industry can contribute to social justice.

COVID-19

Based on our interviews with industry experts, the offshore wind industry within the U.S. appears to have suffered very little due to the COVID-19 pandemic. According to one stakeholder "the offshore industry as a whole has been doing actually really well" and went on to explain how with the new Biden administration there has been "a lot of great focus on offshore wind which has allowed everyone's work the industry as a whole to move forward during COVID" (stakeholder interview, offshore wind NGO). Another interviewee explained how since their wind project is still in the preconstruction phase it wasn't impacted by the pandemic (stakeholder interview, offshore wind producer). While not mentioned in any stakeholder interviews, long-term effects on global and domestic supply chains could impact offshore wind projects when construction begins (Jones, 2020).

Environmental Justice

Given the recent expansion of offshore wind in the U.S., we wanted to understand how the industry can contribute to social equity. One of the first, and perhaps most evident, ways identified in our interviews is by providing a clean energy alternative to fossil fuel power plants. In 2020, roughly 60% of the electricity generated in the U.S. was from fossil fuels (EIA, 2021). Fossil fuel power plants emit not only greenhouse gases but also toxic air pollutants that can lead to a number of negative health impacts such as lung cancer, asthma, and other respiratory illnesses (Penney, Bell, and Balbus, 2009). These power plants are also disproportionately found

in disadvantaged communities (NRDC, 2018). One interviewee spoke to this point when they said:

> "It's not just clean energy, it's energy justice and environmental justice. Historically, what neighborhoods are the most foul emitting [power] plants in? Not in wealthy neighborhoods" (stakeholder interview, offshore wind producer).

Specifically, 78% of African Americans live within 30 miles of a coal-fired power plant (Toomey, 2013). Additionally, Latino communities, indigenous communities, and low-income communities are more likely to be located next to coal-fired plants (Toomey, 2013). Offshore wind, along with other renewables, play an important role in increasing the production of clean energy so we as a nation can transition away from harmful fossil fuels.

Diversity and Inclusion

Offshore wind experts also spoke positively about how their respective companies are tackling diversity and inclusion in the workplace. One interviewee said "We have a very high focus on gender equality, we have targets for the number of female leaders. We are very much focused on equal salary for equal work, and we just had an auditing company look at that" (stakeholder interview, offshore wind OEM). Another interviewee when referring to increasing diversity in the workplace said "It's nice that people on the leadership team care and are willing to have that conversation" (stakeholder interview, offshore wind producer).

When looking at offshore wind company's sustainability reports many also discuss social sustainability in addition to environmental sustainability. However, many companies only report on gender metrics and not racial diversity. For example, Avangrid Renewables, which is involved in the Mayflower Wind and Kitty Hawk projects in the U.S., is transparent about the percentage of women within its workforce and shares various initiatives it is using to improve representation (AVANGRID, 2019). One such initiative is WomENergy which "creates a diverse internal network of women across the company and empowers women with a strong support system" (AVANGRID, 2019). Avangrid Renewables also states that it invests in strategic partnerships to advance workplace diversity but does not disclose any specific metrics on racial diversity throughout the company like it does with gender (AVANGRID, 2019).

One interviewee mentioned the challenges their company faces when taking too firm of a stance on social equity issues when doing business in certain countries:

> "We try to affect this [social equity] in our factories and when we construct our turbines. But we are faced with other countries. We try to introduce this mindset to a variety of cultures and this can be more difficult. Equality by genders is more exotic in the Middle East and some places in Asia than say in Europe. It can be very differently understood in different cultures. So that's an area that we're trying to balance" (stakeholder interview, offshore wind OEM).

This quote highlights the complexity of company's addressing social equity. Offshore wind companies need to continue to push forward with diversity initiatives while still respecting other cultures' values.

Job Creation

The last area that interviewees identified as an opportunity for the offshore wind industry to contribute to social equity is through job creation. This is an area that has received a lot of attention recently, and we won't attempt to cover it in its entirety but rather give a brief overview. Given the expected growth of the offshore wind industry in the United States, there is a large potential for local job creation and economic development (Tegen et al., 2015). The American Wind Energy Association (2020) estimates that offshore wind project development, construction, and operations will support 19,000 to 45,000 jobs by 2025 and 45,000 to 83,000 jobs by 2030. One industry expert claimed that offshore wind "is going to be one of the biggest growth sectors of jobs" and went on to explain how they are contributing:

> "We have a market[s] group everywhere we operate, and they work very closely with departments of labor and training, and especially in the US. Each state's department of labor and training works very closely with every offshore wind company around what staffing needs are going to be and look like, training programs we can put in place, and how we can get ahead of that" (stakeholder interview, offshore wind producer).

There is little debate about whether the growing offshore wind industry will create jobs, however, there is a concern that many of the jobs will be created overseas rather than locally (Liang, 2020) and that not enough is being done to ensure that the job creation will benefit marginalized populations (Shemkus, 2020).

	Shipping	Aquaculture	Offshore Wind
Climate Change Impacts	Increased storm intensity, sea level rise, and changes in business strategy were the most mentioned climate change impacts.	Industry experts identified increased temperatures, increased storm intensity, acidification, sea level rise as impacts from climate change.	The offshore wind industry hasn't been negatively impacted by climate change, rather it has driven the demand for renewable energy and led some energy companies to partially or fully divest from oil and gas.
Sustainability Priorities	Industry experts all identified climate change as the most important sustainability priority for the shipping industry. Other priorities include air pollutants (including the IMO 2020 sulphur cap), biodiversity, and ship recycling.	Many experts mentioned limiting their impact on the surrounding environment as a sustainability priority. Alleviating wild stocks, fish feed alternatives, decreasing carbon footprint, and using sustainable packing were all identified as sustainability priorities for the aquaculture industry. In addition, many experts discussed the need for a social license.	Offshore wind interviewees all consider the offshore wind industry inherently sustainable, but still recognize minimizing wildlife impacts and improving energy storage as priorities for the industry. Additionally, a majority of the offshore wind developers and OEMs in the U.S. have sustainability reports and specific carbon reduction targets.
Climate Change Mitigation	Speed optimization, mega ships, marginal improvements to increase efficiency, secondary energy sources, and digitization are being used to lessen the industry's carbon emissions. Hydrogen, biofuels, and methanol were identified as promising low carbon fuel sources.	Using macroalgae, integrated multi-trophic aquaculture, renewable energy, partnering with offshore wind, sustainable packaging were all mentioned as promising innovations and technologies. Creating a more efficient environment and incorporating digitization and automation will help mitigate climate change.	Turbine improvements (e.g., floating, larger turbines), turbine recycling, digitization and automation, vessel improvements, and green hydrogen were all identified as areas where there is promising technology being developed that will improve efficiencies or expand offshore wind.
Social Impacts	COVID-19 has revealed inefficiencies along the supply chain. Experts are hopeful that the industry will invest in technologies that will improve efficiency while lowering carbon emissions. Although increasing diversity and inclusion is a stated industry priority, few metrics are actually reported and there needs to be more actionable change.	COVID-19 revealed areas of vulnerability in their supply chains and affected market dynamics. Industry experts discussed the opportunity for aquaculture to help with food security and create jobs. Experts also acknowledged the usual buyers of production from aquaculture and how accessibility to the industry should be increased.	The offshore wind sector has been minimally affected by the COVID-19 pandemic. Offshore wind experts recognize the industry's role in addressing environmental justice and job creation in the U.S. They also noted that some companies are having conversations about diversity and inclusion and some have set diversity targets, however much of this work is still in the early phases.

Table 7. Summary of findings from the shipping, aquaculture, and offshore wind sectors.

Key Takeaways

1) **Cross-sector partnerships allow companies to capitalize on advancements made in each individual industry.**

Throughout this paper we have identified promising technologies and innovative strategies each industry - shipping, aquaculture, and offshore wind - can implement to mitigate carbon emissions. The benefits from these technologies and innovations are amplified when the offshore wind, shipping, and aquaculture industries work together through partnerships.

Maersk and Ørsted have partnered to create a charging buoy powered by offshore wind that would supply overnight power to Ørsted's service vessels (Durakovic, 2020). This buoy will be tested in the latter half of 2021 but both parties are optimistic about the buoy's potential to reduce emissions in the maritime industry (Durakovic, 2020). The technology for wind-powered shore-base charging stations could be generated from this pilot project and implemented at all U.S. ports as the offshore wind industry grows and as cold ironing becomes the norm in the shipping industry.

In Europe where crowded seas have already become a concern, research on the benefits of combining aquaculture and offshore wind farms have gained attention with some private projects already underway (Farmer, 2021; Jansen et al., 2016). Beyond reducing competition for space, research has shown that integrating offshore wind and aquaculture farms can lower costs associated with O&M (van den Burg et al., 2017). In a multi-use space with aquaculture and offshore wind, one vessel can be used to transport maintenance crews for both industries. One study found a 10% reduction in O&M costs from this multi-use strategy (van den Burg et al., 2017). Although research has only been done on how this partnership can reduce cost, it is reasonable to assume it will result in lowered carbon emissions as well due to the decreased transportation time.

Some shipping companies have invested in algae biofuel production research and development. However, as one industry expert noted, "the jury is still out" on the feasibility of producing bio-methanol from seaweed at scale because the cost of production is still much higher than that of HFO or LNG (stakeholder interview, maritime shipping company). The hope is that this research will lead to an algae biofuel production method that is able to produce a large amount of oil in the most cost-effective manner.

Recommendation: Companies within the offshore wind, shipping, and aquaculture industries should pursue innovative cross-sector partnerships to advance decarbonization technologies and increase scale. For example, offshore wind companies in the U.S. should partner with ports to supply power for ships while cold ironing. Offshore wind farms within the U.S. should also partner with aquaculture farms to decrease O&M costs, reduce competition for space, and increase the scalability of the aquaculture industry. Finally, shipping companies should increase investments in and expand partnerships with seaweed aquaculture innovators.

2) **Digitization is a key element of improving efficiencies within all three sectors.**

Through our analysis of the literature and interviews with experts, we found that digitization can be used in all three sectors to improve efficiency and decrease carbon emissions. A leader in a bluetech hub mentioned how the "low hanging fruit is efficiency" because it is easy to create the business case to executives and shareholders when a technology not only lowers emissions, but also cuts costs or increases productivity (stakeholder interview, bluetech hub). In all three industries, incorporating digital applications improves operations by choreographing the movement of ships, cars, or personnel. This decreases distance traveled and cuts down on time and resources wasted. Additionally, monitoring equipment such as sensors have been used in all three industries to ensure equipment is properly maintained and operating at the most efficient level. Digitization has also been used across the board in these industries to predict and monitor environmental conditions. This element of digitization will be particularly necessary in the future as the impacts of climate change become more extreme.

Although each industry is employing digitization in an effort to improve efficiency and reduce carbon emissions, the industries are doing so in varying capacity. As mentioned in the sections above, the shipping and aquaculture industries have been slow to adopt some digital technologies. These industries in particular should continue to invest in technologies and innovations that allow them to continue to improve efficiency through digitization.

Recommendation: Companies in all three industries should look at blutech hubs for the latest and greatest in digital innovations. Bluetech hubs are often associated with incubators that foster

promising startups that improve sustainability within the blue economy. By following digital technologies backed by these incubators, companies will be informed of the most promising and most innovative trends in digitization.

3) **Utilizing economies of scale can drive down costs and reduce emissions.**

Over the last couple decades, shipping vessels have increased dramatically in size. As the size of the ship increases, there is a marginal savings per container so companies can transport shipping containers at a lower per unit cost. While economies of scale typically focus on the financial benefits, research has shown that incorporating larger vessels also reduces carbon emissions (Lindstad, Asbjørnslett, and Strømman, 2012). Similarly, in the offshore wind industry, advancements in technology have allowed turbines to get increasingly larger and more powerful. Bigger turbines mean fewer need to be installed and maintained to produce the same amount of energy, saving time and money while lowering related emissions.

While shipping and offshore wind are currently benefiting from increasing scale, seaweed aquaculture is still relatively nascent in the U.S. and will need to be scaled to meaningfully contribute to decarbonization. Seaweed farming is the fastest growing aquaculture sector and offers a number of opportunities to mitigate climate change, as discussed in the macroalgae section above. Increasing the size of the industry will lower costs which is necessary for macroalgal biomass to be an economically viable energy source (Kim, Stekoll, and Yarish, 2019). Barriers to seaweed expansion include limited suitable habitat and user conflicts within state waters (Duarte et al., 2017), and regulatory uncertainty (Upton, 2019).

Recommendation: To address these concerns and scale up seaweed production, we recommend the Biden administration develop an executive order prioritizing the expansion of seaweed aquaculture into federal waters. The executive order should direct federal agencies to streamline permitting processes, provide additional support and funding as allowed within existing appropriations, and generally educate the public about the beneficial uses of seaweed.

4) **All three sectors recognize their role in increasing social equity and inclusion but are so far slow to actionable change.**

Continued conversations throughout the last year and specifically during the COVID-19 pandemic have brought attention to the conditions and poor treatment of communities of color, women, and other underrepresented communities. This has led the shipping, aquaculture, and offshore wind industries to increase their social equity and inclusion work. And leaders within these industries have discussed and mentioned the need for increasing diversity. While it is encouraging that companies are incorporating social equity and inclusion into their governance strategy, there is still work to be done to create a more inclusive environment. All three industries discussed increasing diversity, specifically in leadership positions. When talking about diversity in their company, many interviewees did not go beyond gender diversity. Companies in the shipping and offshore wind industries have created initiatives to increase representation of women in their workforces (stakeholder interview, offshore wind OEM; Heseltine, 2020). In the aquaculture industry, one company's sustainability report included a section on increasing diversity, but specifically only mentions the percentage increase of women at the company (Atlantic Sapphire, 2019). Although the company promotes a diverse workplace, it did not mention any diversity besides gender diversity. In the shipping industry, CMA CGM was the only of the top five shipping companies that reported metrics beyond gender diversity (CMA CGM, 2019). Similarly, in the offshore wind industry, Avangrid Renewables advocates for diversity in the workplace, but does not discuss racial diversity in the company (AVANGRID, 2019).

It is promising that these companies are incorporating diversity and inclusion into their sustainability reporting, but we believe they can do more to improve racial diversity in the workplace. One aquaculture academic is creating more accessible education for those wanting to create an aquaculture business (stakeholder interview, aquaculture academic). The companies in these three industries could incorporate an inclusion survey to understand their workforce and communities that surround them like one maritime shipping company has included in their future corporate sustainability reports (stakeholder interview, maritime shipping company). These industries should work towards being more accessible to those who have been historically left out of the aquaculture, offshore wind, and shipping industries.

As these companies and industries are growing and gaining more momentum, there are more and more opportunities to join. These industries are creating jobs during a time when many people have lost their jobs due to the COVID-19 pandemic and as climate change takes jobs away from other industries. If these sectors can keep increasing, jobs will be created throughout the supply chain. Creating new jobs can provide an opportunity for the shipping, aquaculture, and offshore wind sector to diversify their employees as well.

Recommendation: To address these concerns and inequalities, we recommend these three sectors create definitive goals to increase not only gender diversity, but also racial diversity. These goals should be SMART - specific, measurable, achievable, relevant, and time-bound (Sridhar, 2016). Additionally, companies can conduct internal diversity audits to hold themselves accountable and identify gaps in their current actions.

Conclusion

Through background research and industry leader interviews, we identified climate change risks, sustainability priorities, and carbon reduction opportunities in the shipping, aquaculture, and offshore wind industries. Additionally, we learned how each industry has been impacted by the COVID-19 pandemic and how they are contributing to social equity. From our analysis, we identified four key takeaways 1) Cross-sector partnerships allow companies to capitalize on advancements made in each individual industry, and should be pursued; 2) Digitization is a key element of improving efficiencies within all three sectors, and companies should look to bluetech hubs for promising digital innovations; 3) Utilizing economies of scale can drive down costs and reduce emissions; 4) All three sectors recognize that they have a role in increasing social equity and inclusion but so far have been slow to act toward that goal.

This paper identifies broad opportunities within each industry to reduce carbon emissions in an effort to mitigate climate change, however we suggest further research be done. Additional research should focus on quantifying carbon reductions that could be achieved from the adoption of emerging technologies in each industry. Academic institutions should hold companies accountable by researching progress toward their stated climate goals or commitments. This research should include an analysis of the associated benefits (or lack of benefits) from the realization of these goals.

Overall, new technologies and innovations create promising opportunities for decarbonization in the shipping, aquaculture, and offshore wind industries. As these industries continue to grow, we hope they recognize their crucial role in creating a more sustainable *blue* economy.

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Appendices

A. Interview Recruitment Email

Hello [insert name],

My name is [insert name] and I am a master's student at the Duke University Nicholas School of the Environment studying Coastal Environmental Management. I [insert how you came across their name]. I am working with two other master's students to conduct interviews as a part of our master's project titled "A Deep Dive into Blue Innovation for Global Decarbonization." Due to your expertise in [insert sector], we would like to invite you to be a part of this project.

I am hoping to talk with you more about your views on how innovation is shaping climate adaptation and mitigation in the [sector]. Specifically, we are interested in how your company is responding/plans to respond to the impacts of climate change and employing new technologies to reduce carbon emissions.
We can talk for as long as you like, but I expect our conversation will take about an hour. We will ask for your permission to audio record the conversation so we can transcribe it for our analysis.

I have attached information about our research and the interview process. Please let me know if you would like to participate in this project or if you have any questions. I look forward to hearing from you.

Thank you,
[insert name]

B. **Informed Consent**

Introduction: This research is being conducted by Sage Riddick, Lisa Snodgrass, and Megan Swanson. We are master's students at the Duke Nicholas School of the Environment and are conducting interviews as a part of our master's project.

Purpose: We are interested in learning about your views on sustainable innovation in the blue economy and how it may contribute to global decarbonization. Additionally, we are interested in the biggest risks from climate change to maritime shipping, energy, and aquaculture and how they have shaped innovation in the blue economy. Lastly, we are curious about how these innovations may contribute to broader social and societal goals.

Procedures: If you agree to participate in our master's project, we will ask you to talk about your opinions and experiences with the blue economy and emerging innovation that may contribute to a more sustainable blue economy. We will also ask questions about how your specific organization views climate change, innovation, and decarbonization. We can talk for as long as you like, but we expect our conversation will take about an hour. We would also like your permission to let me audio-record our conversation so that we can focus on our conversation rather than taking notes.

Risks: N/A. There are no anticipated risks associated with participating in this research. *Benefits*: N/A. There are no anticipated benefits from participating in this research.

Confidentiality: We will not include your name or title in any products stemming from this research. However, we may attribute information from the interview to your organization/company/agency in our final report. By agreeing to an interview, you are confirming the consent of recording and using your organization's/company's/agency's name. If you are uncomfortable with this but still wish to participate, we will only attribute information from your interview to your general industry. Our report will be stored in the Duke University's library database and will be presented to professors and students at Duke University in May 2021.

Voluntariness: Your participation in our research is of course voluntary. Please feel free as well to skip any questions you do not want to answer or stop the interview at any time, for any reason.

Compensation: N/A

Questions: Please let us know if you have any questions. You can contact us by email at sage.riddick@duke.edu, lisa.a.snodgrass@duke.edu or megan.j.swanson@duke.edu.

For questions about your rights as a participant contact the Duke Campus Institutional Review Board at campusirb@duke.edu. Please reference Protocol ID# 2021-0202 in your email.

C. Interview Questions - Aquaculture Industry Leaders

1) What are the sustainability priorities for the aquaculture industry? Where does climate change fit, relative to other priorities?

Climate Change Adaptation

2) What have you seen as the main impact of climate change on your business so far? What do you anticipate will be the primary climate-related risks in the future?
    a) Has climate change affected market dynamics? (e.g. increase or decrease in product demand, costs, prices, regional changes, etc.)
3) Do you currently have a plan to adapt to the changing conditions caused by climate change, for example increases in temperature? What are your specific strategies and/or plans?
    a) When was this plan created? Where is it stated, is it available online, can you send it to us? (We will adjust this question as needed depending on what we know about the company's plan/strategies)
    b) What types of technologies is your company implementing to adapt to climate change effects?
    c) If you don't have a plan, why not? Do you expect to have a climate plan in the future?

Climate Change Mitigation/Decarbonization

4) What role do you see your business playing in the effort to move toward a carbon free/ low carbon global economy?
    a) Have you evaluated the potential for reducing emissions by encouraging a shift from high carbon meat toward fish sources? Are you making this argument to shareholders or customers?
    b) How important are low carbon products to your shareholders or buyers?
5) Do you currently have a plan to reduce emissions of carbon in your operations, likely through your supply chain? Do you have any stated goals?
    a) How much are investing to reduce carbon emissions?
    b) Are you seeing general trends within the aquaculture sector to reduce carbon emissions?
6) What types of technologies are your company implementing to combat climate change? Or What technologies are you seeing in the aquaculture field in general?
7) What types of changes have you seen in regulations and certification systems that include climate solutions and incentives to combat climate change?
    a) If yes - How are these regulations affecting your business/organization?

Social/COVID Impacts

Considering the current state of the world with the coronavirus pandemic and the renewed emphasis on social justice, we wanted to ask a little bit about how these issues play into your business.

8) How do you see your industry contributing to broader social equity goals, i.e. food security and more jobs?
9) Some articles we've read have said the economic downturn caused by the pandemic has created an opportunity to build the economy back up in a sustainable way. What role do you see your industry playing in trying to emphasize sustainability in building the economy back up? [job creation, stimulating the economy]

D. Interview Questions - Shipping Industry Leaders

1) What are the sustainability priorities for the shipping industry? Where does climate change fit, relative to other priorities?

Climate Change Adaptation

2) What have you seen as the main impact of climate change on your business so far? What do you anticipate the primary climate-related risks will be in the future?
3) What do you think are some of the most exciting emerging technologies that will allow the shipping industry to adapt to climate change?

Climate Change Mitigation/Decarbonization

4) In a recent article published by DNV-GL, it concluded that the IMO's goal of reducing shipping GHG emissions by 40% by 2030 and then 50% by 2050 is not feasible without the IMO implementing further regulations in the near term. In your opinion, what regulations should the IMO be prioritizing in the near term? What about in the long term?
5) Studies have shown that consumer demand will play a large part in incentivizing the shipping industry to advance green technology. A study by Shell suggested customers implement an initiative to support "green ship operators". Have you seen this happening already? How else could consumers come together to generate enough demand for greener ships?
    a) Do you agree that customers will play a very important part in decarbonizing the shipping industry? Do you see demand from other areas (shareholders, policy, etc.)
6) It seems like there is a debate between whether shipping should use slightly lower carbon fuels and technology in the short term, such as LNG, then transitioning to much lower GHG fuels such as hydrogen or ammonia in the future and suffer the cost of transitioning a few times (possibly losing a financial advantage), or if they should wait it out for a mature carbon neutral fuel or technology and go all in on a transition once. What are your thoughts on that? What do you believe is the better choice?
7) What is your company's plan for reducing emissions? When was this plan created? Does it include investments or adopting specific technologies? How much are you investing in decarbonization over the next 2-5 years? *(We will adjust this question as needed depending on what we know about the company's plan/strategies)*
    a) Is this plan available for the public? Could you provide that plan to us?
    b) If you don't have a plan, why not? Do you intend to develop one in the future?
    c) If they have a plan: Have you had to increase your prices because of this? How are you offsetting this cost?
8) How do you view your climate goals and related performance relative to your peer companies? Is there a particular company that you view as a leader in decarbonization within the shipping industry?

Social/COVID Impacts

9) In our reading about the blue economy, one of the things people have talked about is the blue economy contributing to broader social and societal goals. How do you see your industry contributing to broader social equity goals, i.e. food security and more jobs?
10) How do you think the current COVID-19 pandemic will impact the shipping industry's efforts toward decarbonization? What role do you see technological innovation in your industry playing when trying to build back the economy more sustainably after the negative impacts of COVID-19? [job creation, stimulating the economy]

E. Interview Questions - Offshore Wind Industry Leaders

1. What are the sustainability priorities for the offshore wind industry? Where does climate change fit, relative to other priorities?

Climate Adaptation

2. What have you seen as the main impacts of climate change (i.e. increased storm frequency, sea level rise) on the offshore wind energy sector so far? What do you anticipate will be the primary climate-related risks in the future?
    a. Has climate change affected market dynamics? (e.g. increase in demand, prices, etc.)
3. Do you currently have a plan or measures in place to help your company adapt to the changing conditions caused by climate change? For example, increasing winds of storms?
    a. If yes, what is the plan? When was the plan created? Is the plan publicly available? Does it include investments? (We will adjust this question as needed depending on what we know about the company's plan/strategies)
    b. What types of technologies is your company implementing to adapt to climate change effects?
    c. If no, why not? Do you expect to implement measures in the future?

Climate Change Mitigation/Decarbonization

4. What role do you see your business playing in the effort to move toward a carbon free/ low carbon U.S. economy?
    a. How much of a focus is decarbonization for your company? Is decarbonization important to your shareholders?
5. From my research, the construction phase of the turbines accounts for the majority of the carbon emissions for a given offshore wind project, with operations and maintenance accounting for a relatively small percentage. Has [company] identified the main sources of carbon emissions during offshore wind development and operations?
6. Do you currently have a plan to decarbonize (or reduce the emissions of) your company's offshore wind activities, likely through your supply chain?
    a. If yes, what are your specific strategies to meet these goals? Does this plan include additional investments? How much are you planning on investing in decarbonization in the next 2-5 years? (will adjust follow up questions as needed depending on what we know about the company's plan/strategies)
    b. If no, do you plan to in the future?
7. What do you see as the main emerging technologies that will allow your company and the offshore wind sector to reduce its carbon footprint? Perhaps technology that would allow you to expand operations, design more efficient turbines or operate more efficiently?
    a. Commercializing floating wind
    b. Electrifying maintenance boats or using more sustainable fuel

8. How do you view your climate goals and related performance relative to your peer companies? Is there a particular company that you view as a leader in decarbonization within the offshore wind industry?

Social and COVID Impacts

Considering the current state of the world with the coronavirus pandemic and the renewed emphasis on social justice, we wanted to ask a little bit about how these issues play into your business.

9. How do you see the offshore wind sector contributing to broader social equity goals, i.e. clean, affordable energy, better air quality, more jobs?
10. What role do you see your industry playing when trying to build back the economy more sustainably after the negative impacts of COVID-19? [job creation, stimulating the economy]

F. Interview Questions - Bluetech Hub Founders

1) How do you define bluetech?
2) As I mentioned earlier, we are interested specifically in the shipping, offshore wind, and aquaculture sectors. Does [company name] specialize in one of these industries, or do you have a more broad focus? (Can adjust based on background research of each bluetech hub's focus)
3) How does your bluetech hub advance that industry/those industries?
4) Where do you connect with entrepreneurs in these industries? Where do you look for innovations?
5) Generally, what technological trends related to climate change adaptation or decarbonization do you see in the areas of shipping, offshore wind, and aquaculture [customize based on the specific hub]?
6) Which technologies do you see as the most compelling/promising to reach the goal to limit global temperature rise to 2 degrees? How would you prioritize these technologies?
    a) Specifically for the ocean energy, aquaculture, and shipping industries (adjust this if the hub specializes in one industry)
7) Where do you see investors putting the brunt of their money/what are they most excited about (i.e. technologies, companies, or industries)?
8) What do you believe are the main incentives and barriers to adoption of low carbon technology? Are these different for each of the different sectors we are focusing on (shipping, aquaculture, offshore wind)?
9) What role do you see technological innovation in your industry playing when trying to build back the economy more sustainably after the negative impacts of COVID-19? [job creation, stimulating the economy]