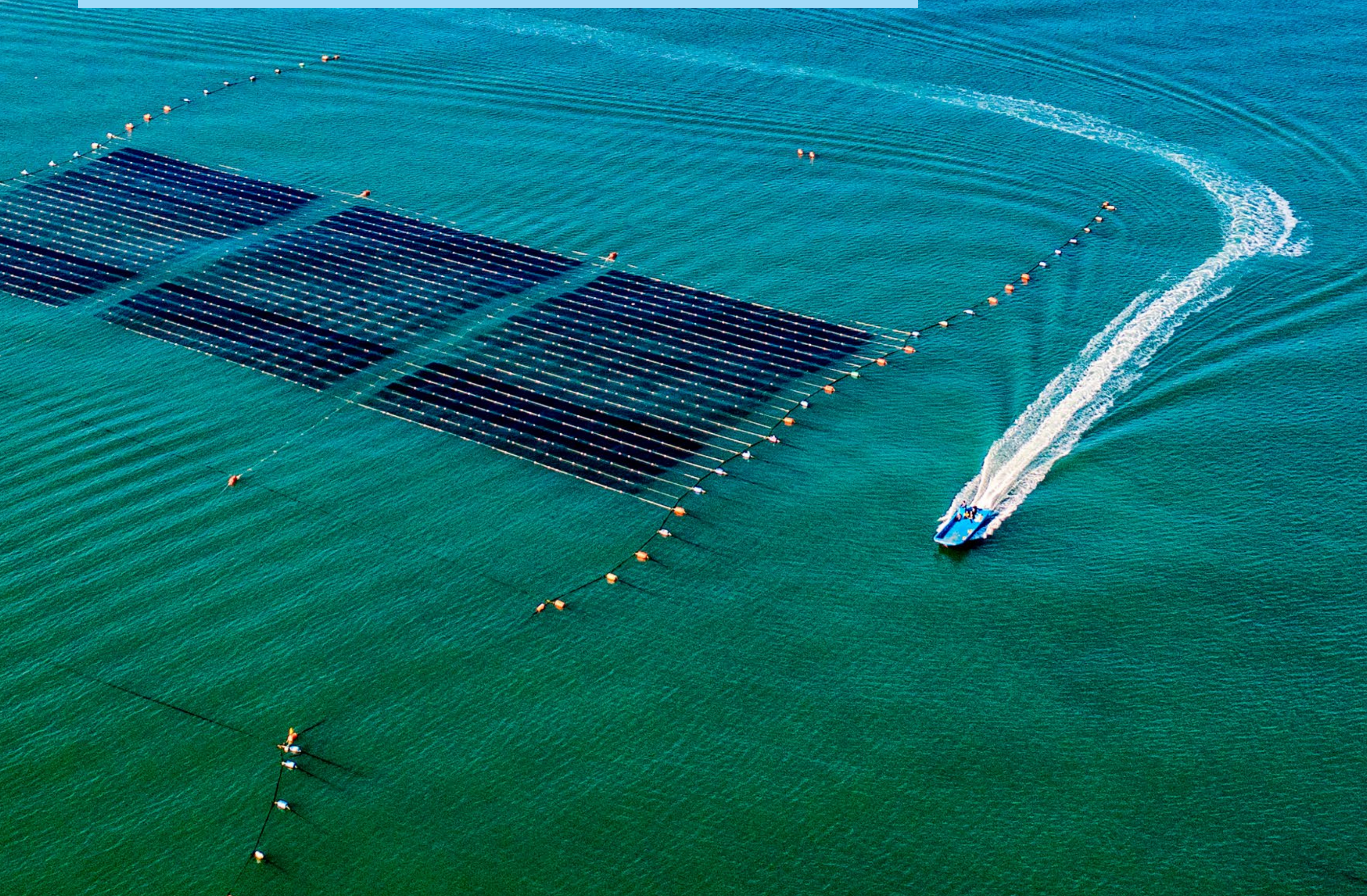
DNV

WHEN TRUST MATTERS

SEAWEED FORECAST

Ocean's Future to 2050



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CONTENT

KEY MESSAGES

1. **Seaweed production volumes will grow between 60% and 75% to 2050**
    a. Direct food consumption in Greater China and OECD Pacific remains the single most important use of seaweed, followed by food additives.
    b. Other uses like feed, biostimulants, and industrial products remain marginal drivers of seaweed production.
    c. Climate change vulnerability will impact regional farming practices and species selection, but adaptation strategies like selective breeding will help mitigate the most severe consequences.

2. **Seaweed demand forecasts based on official production statistics may be highly overestimated**
    a. Official statistics likely overestimate current seaweed production due to imprecise reporting in key producer countries, especially related to red seaweed used in food additives.
    b. We forecast a global production of seaweed between 34 and 63 Mt by 2050, depending on the reliability of official statistics.
    c. Lack of reporting standards and poor data quality in official production statistics underscore the need for supply chain traceability.

3. **The entire world seaweed demand in 2050 can be met by co-locating seaweed production with offshore wind farms**
    a. Seaweed production is a promising co-location option that can generate additional economic value while providing ecosystem services and simpler logistics than other aquaculture.
    b. Meeting world seaweed demand will require the same area as between 3.5% and 6.5% of the future area occupied by offshore wind.
    c. Offshore wind farms are already co-located with seaweed farms in China, and multi-use pilot projects are underway in Europe.

1 INTRODUCTION

The future of the Blue Economy will be shaped by several global transformations, with the ocean playing a key role in enabling more sustainable food and energy systems. Seaweed can play a key part in these transformations.

Seaweed represents an important food source in regions such as East Asia, and it can be used in the production of feed, food additives, pharmaceuticals, nutraceuticals, industrial feedstocks, materials, and biostimulants. Seaweed can have a comparatively low environmental impact compared to other types of seafood and agricultural products (Gephart *et al.*, 2021). Furthermore, seaweed provides important ecosystem services such as carbon dioxide sequestration (DNV, 2023c), improving water quality by extracting harmful nutrients such as nitrogen (Maar *et al.*, 2023), and creating valuable habitats for increased biodiversity (Hoegh-Guldberg *et al.*, 2023).

In this report, we forecast seaweed demand and production to 2050, based on updates in DNV's Ocean's Future to 2050 model (DNV, 2021), which takes a holistic approach to modelling the Blue Economy[1]. In East Asia, seaweed production has reached substantial volumes with rapid growth over the three last decades. In the rest of the world, seaweed cultivation starts from a very low baseline, and harvesting of wild seaweed still provides most of the supply.

As an alternative food supply chain that contributes to diversifying production, while minimizing environmental footprint, the EU sees seaweed cultivation as an important part of its aquaculture strategy (EU Commission, 2021). Similarly, the *High Level Panel for a Sustainable Ocean Economy* considers seaweed as an ocean-based climate action with respect to both marine ecosystems and dietary shifts (Hoegh-Guldberg *et al.*, 2023). For coastal communities in developing countries particularly, the seaweed sector could become an even more significant source of employment opportunities (FAO, 2022).

The perceived sustainability advantages of seaweed imply that the sector is likely to receive substantial attention from investors and policymakers in years to come. By providing a most-likely forecast of seaweed demand and supply, we aim to contribute to anchoring industry growth ambitions to an objective view of the prospects of the sector.

1 The Blue Economy is defined by the OECD (2016) as 'the sum of the economic activities of ocean-based industries, together with the assets, goods, and services provided by marine ecosystems'.

2 SEAWEED DEVELOPMENT TO 2050

We forecast between 60% and 75% growth in seaweed production by 2050. Seaweed products related to the world's food system will dominate among demand drivers.

We forecast seaweed to 2050 for 10 global regions and divide seaweed into two main types – red (*Eucheumatoids*, *Gracilaria* and *Pyropia* (nori)) and brown (*Saccharina* (kombu) and *Undaria* (wakame)). There is mounting evidence of overreporting of seaweed production (Langford, 2023; Jin, *et al.*, 2023), which makes it relevant to investigate the implications this has on the future of seaweed.

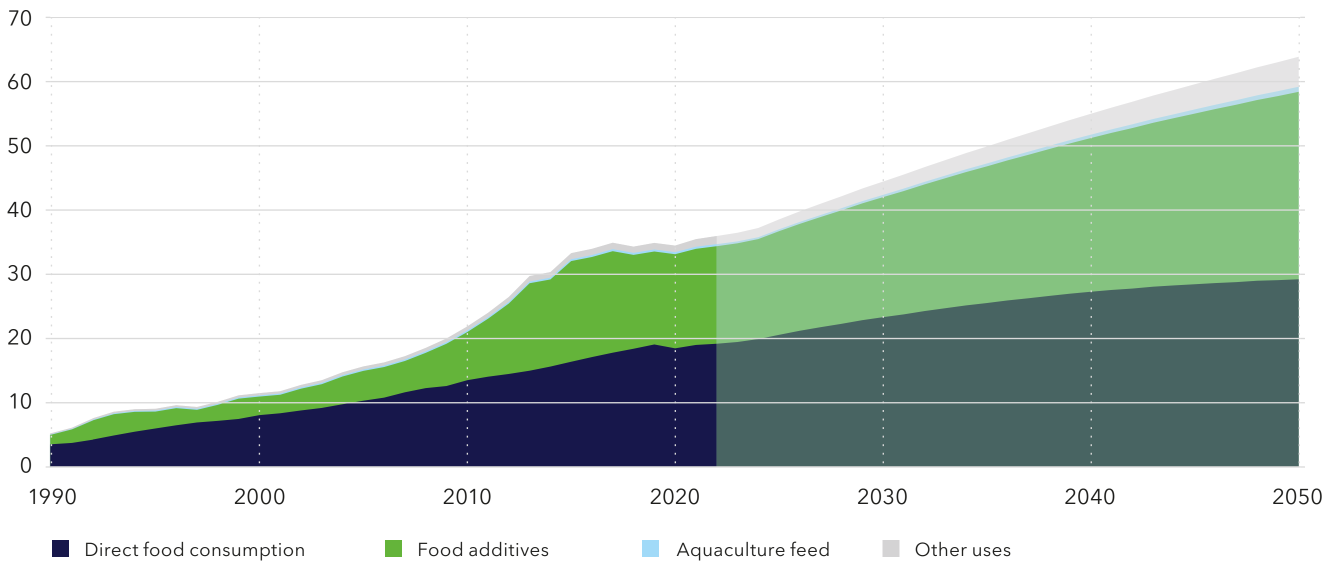
We first present results for the case where official production statistics from the Food and Agriculture Organization (FAO) are used as a baseline, before turning to a case where we adjust historical production data for brown seaweed to 80% and red seaweed to 20% of what is reported to the FAO.

Seaweed growth – based on official statistics
In the base case, we **use official production statistics** and forecast a growth of seaweed demand from 36 Mt to 63 Mt, indicating a growth of approximately 75% between now and 2050 (see Figure 1). The seaweed industry is driven by demand from four product categories in our model – direct food consumption, food additives, aquaculture feed (mainly abalone), and other uses (pharmaceuticals, nutraceuticals, industrial feedstocks, materials, and biostimulants). By product category, direct food consumption will remain the largest, followed by food additives, which comparatively grow much faster in terms of demand. All other uses grow only to constitute a slightly bigger fraction of the overall supply compared to today.

FIGURE 1

Seaweed demand by product type.

Units: **Million tonnes**



Demand for seaweed food products will still mainly come from countries in East Asia. In this part of the world, brown kelps, most commonly wakame and kombu, are used in soup, salads, and other dishes. The red seaweed nori is used primarily for sushi or as a snack.

Direct food sees limited increase due to little population growth in the main consuming regions. However, we expect a slight increase in per capita demand due to the perceived sustainability advantages of seaweed. Changes in food culture and taste for Asian food in Europe and North America could add to this trend (Frozen Food Europe, 2023). Concerns about iodine content for some key species limits the increase in direct food consumption in some regions where seaweed has not traditionally been part of the diet (EU Commission, 2022).

Euchematoids, a group of red seaweeds, are grown in tropical areas. Eucheumatoids are used to produce the gelling agent carrageenan, which is the main food additive that comes from seaweed. Food additives produced from seaweed will gain in market share over competing inputs, due to price reductions from scaling the production.

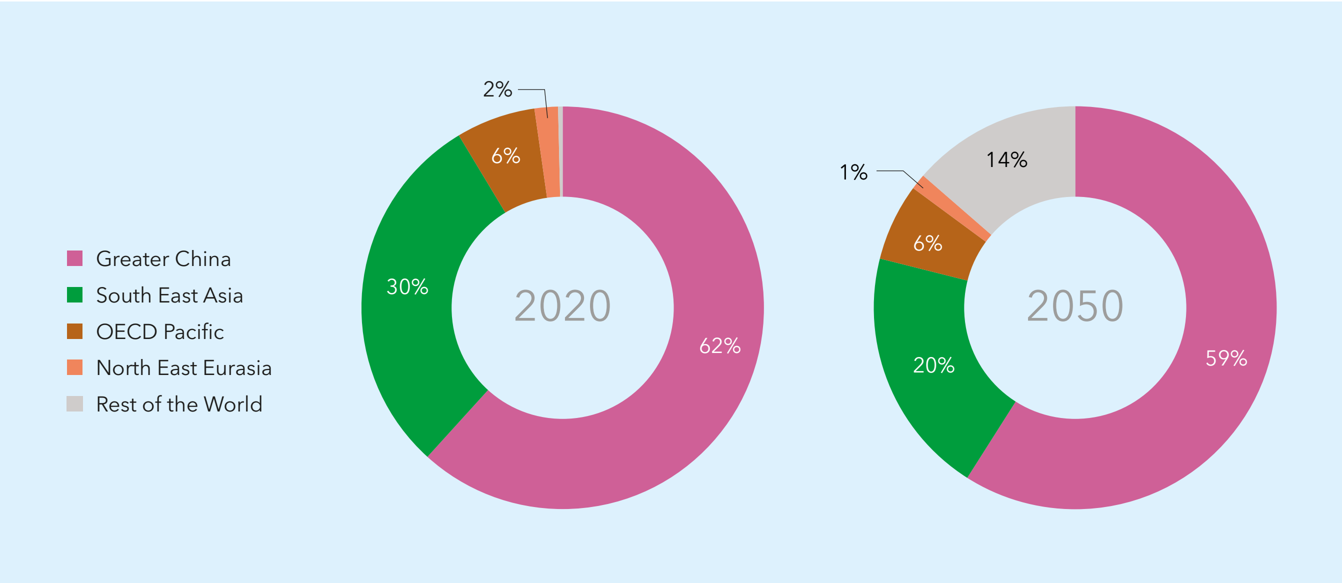
However, industrialized economies will not see rising per capita food consumption, meaning that the growth potential for additives is limited. Additives are also used in highly processed foods, for which there are also substantial consumer worries over health risks (Belton, *et al.*, 2020).

In terms of production, the top three producing regions remain the same: Greater China, South East Asia, and OECD Pacific (see Figure 2). China remains the largest player by a large margin, maintaining their share of production at 60% of the world supply, growing production from 20 Mt to 36 Mt. South East Asia's production grows only slightly, so their share reduces from 30% to 20% of the total. The rest of the world grows to 14% of the supply by 2050, but this kicks off only after 2035.

Regions outside of East Asia grow to 14% of the seaweed supply by 2050.

FIGURE 2

Regional seaweed production in 2020 and 2050.



Seaweed growth – alternative scenario: official statistics overestimate production
A large source of uncertainty in the seaweed sector is the low quality of global production data. For instance, several sources indicate that the Indonesian seaweed production volumes could be overstated by as much as five to seven times (Langford, 2023; Zhang *et al.*, 2023; Rieve, 2023). Similar reporting issues exist for Chinese production (Jin *et al.*, 2023).

In a second simulation run, we adjust for the claim that there is significant overreporting. Hence, in this case we ***do not* use the official production statistics**. Instead, we correct brown seaweed production to 80%, and red seaweed production to only 20% of the reported volume. In this case, seaweed production reaches 34 Mt in 2050, up from an estimated 22 Mt in 2020 (see Figure 3). This indicates a growth of almost 60%, which is less than in the base case.

Data quality, reporting, and uncertainty
There could be several reasons resulting in inaccurate reporting of production data, such as imprecise assumptions about the seaweed production stage, productivity rates, seasonal variations, and seaweed cultivation areas (Zhang *et al.*, 2023). For instance, the estimated area for seaweed farming in Indonesia ranges from 100,000 to 270,000 hectares (Langford, 2023). Production reporting based on farm area is also insensitive to seasonal and yearly variations, which can easily occur in production with short growth cycles. For instance, seaweed crops can fail, or farmers can choose not to plant new seaweed if the environmental conditions or market prices are unfavourable.

Similarly, Jin *et al.* (2023) found large discrepancies between reported seaweed cultivation areas by conventional national statistics and data acquired through remote sensing methods. Potential reasons for the difference include challenges in attaining accurate reporting from the large number of small-scale farmers, lack of standards for estimating farm area and production per area, and variation in cultivation techniques. Another factor contributing to imprecision is underreporting of yearly production by processors for tax-evasion purposes (Zhang *et al.*, 2023).

Solutions improving data accuracy and quality
In countries with data reporting challenges, remote sensing technologies, like satellite monitoring, can be an effective solution to obtain general production data at a regional or national scale. However, these monitoring techniques will not be accurate on a farm level if they are not able to pick up on details like the type of species produced or differences in vertical farm design. Production estimates based on remote sensing will still need to be verified against other data that document how much has been produced, sold, and exported.

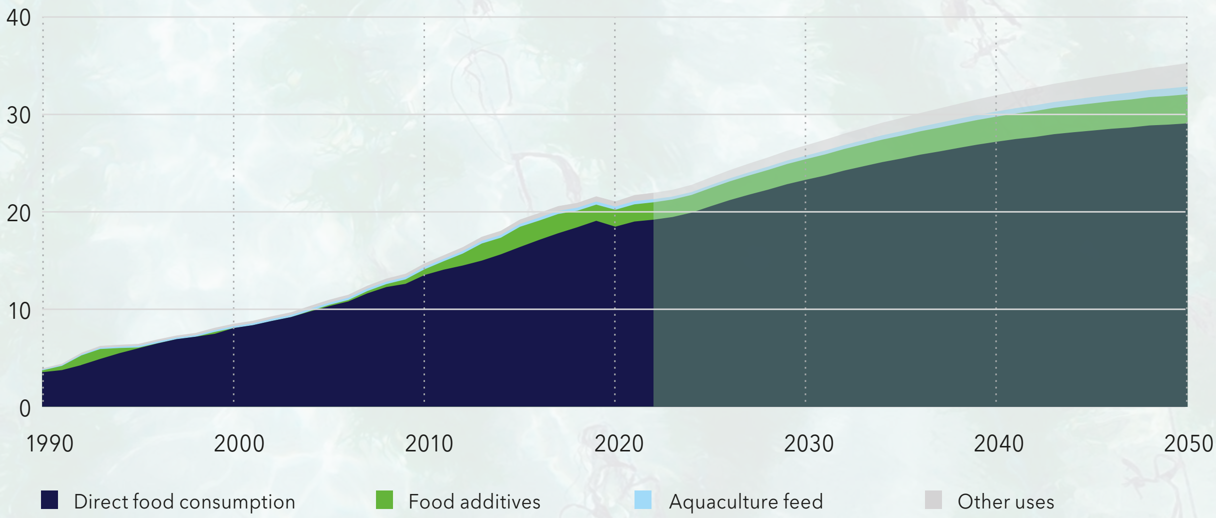
Food safety concerns and calls for greater supply chain transparency and control may alleviate the current challenges related to reporting of production. Consumers and large-scale retailers are increasingly concerned about transparency and control across food supply chains, and regulators are following suit. For instance, in the US, the Food Safety Modernization Act (FSMA) will introduce new requirements related to tracking food supply chains (DNV, 2024). The FSMA enters into force in 2026 and could be expanded to include products derived from seaweed. Commercial and regulatory pressure to improve supply chain traceability may also positively contribute to the estimation of production data but could be challenging in a sector with a large share of small-scale, artisanal operations.

Indonesian seaweed production volumes could be overstated by as much as five to seven times.

FIGURE 3

Seaweed demand by product type: alternative scenario*.

Units: **Million tonnes**



* assuming production of red seaweed globally is only 20% of what is reported, and production of brown seaweed globally is 80% of what is reported

3 CLIMATE IMPACTS AND BIOLOGICAL CHALLENGES

Global seaweed production is already impacted by extreme weather events like heat waves and typhoons, becoming more frequent with climate change.

In Zanzibar, marine heat waves and rising sea temperatures have already led to declining production, combined with the effect of low sales prices, disease, and pests (de Jogn Cleyndert *et al.*, 2021).

Similarly, in the Philippines, the combined impact of poor water quality and extreme weather events like heat waves and typhoons is catastrophic for farm infrastructure, and seaweed growth (The Fish Site, 2022).

Over time, farmers in some regions adjust to environmental changes by reducing the seaweed farming season, and thereby reducing their yields (The World Bank, 2023). In the case of Zanzibar, many farmers have opted to leave the industry (de Jogn Cleyndert *et al.*, 2021), with the result that production has declined to the levels observed in 2005 (FAO, 2022).

Poor seeding quality halts eucheumatoid production

Eucheumatoids are the only seaweed group that has seen a downward production trend in the last decade (FAO, 2022). As opposed to brown seaweeds, where seedlings are produced in a hatchery, the eucheumatoid seaweeds cultivated for carrageenan production have been vegetatively propagated since production started in the 1970s. New production cycles are commonly started from pieces of seaweed material from the previous cycle. Production in some of the major eucheumatoid-producing countries, like Indonesia and the Philippines, therefore typically consists of monocultures of the same species, with little genetic variation. This makes the production particularly vulnerable to diseases, pests, and environmental changes, which have had major impacts on productivity over the years. Lack of good-quality seedlings has been rated as the number one challenge for seaweed farmers in Indonesia and the Philippines (Hatch Innovation Services, 2024). Korean nori production experienced similar challenges in the 1970s, which were resolved through targeted breeding practices (Hwang & Park, 2020).

Furthermore, the majority of eucheumatoid seaweed is produced by local small-scale farmers (Hatch Innovation Services, 2022), with limited access to capital for investing in resilience innovation. The economic consequences of declining seaweed production can have a detrimental effect on these coastal communities. Several international collaboration efforts have been suggested as a measure to improve resilience in seaweed production through breeding programmes (Hatch Innovation Services, 2024; Hu *et al.*, 2021).

The kelp species *Saccharina* and *Undaria* (brown seaweeds), which are grown at an industrial scale today, are temperate species which thrive in colder waters. Like Eucheumatoids, these species are vulnerable to increasing sea temperatures and marine heat waves (Hu *et al.*, 2021). However, compared to eucheumatoids, kelp species have the advantage of having been selectively bred for centuries, and their life cycles are well-known in comparison (Hu *et al.*, 2021).

Looking forward

The future of seaweed farming will depend on the industry's ability to adapt to the major challenges it faces with poor seeding material, diseases, and increasing climate impacts. Adaptation strategies will have to include breeding programmes for more disease- and heat-resilient cultivars and moving cultivation to deeper or colder waters. It should be noted that these adaptation strategies will increase the up-front investment costs of seaweed farming, particularly in low-cost regions. In countries like Indonesia and the Philippines, where the majority of production is by local, small-scale farmers, this could result in considerable shifts in how seaweed production is organized. This also plays into the competitive landscape by reducing the difference in production costs between high-cost and low-cost countries.

The future of seaweed farming will depend on the industry's ability to adapt to the major challenges it faces with poor seeding material, diseases, and increasing climate impacts.

4 CO-EXISTENCE

The future of seaweed production will be impacted by the commencement of a race for space among the ocean industries, spurred on by the energy transition and the rapid increase in offshore wind.

DNV's Energy Transition Outlook (DNV, 2023a) finds that the global 2050 installed capacity for offshore wind will exceed 1,500 GW. DNV's Spatial Competition Forecast (DNV, 2023b) builds on that to estimate that around 275,000 km^2 of ocean area will be occupied by wind farms (see Figure 4). When including all other ocean industries with offshore installations (like oil and gas and marine aquaculture), the estimated space needed globally is roughly equivalent to the area of Poland (DNV, 2023b).

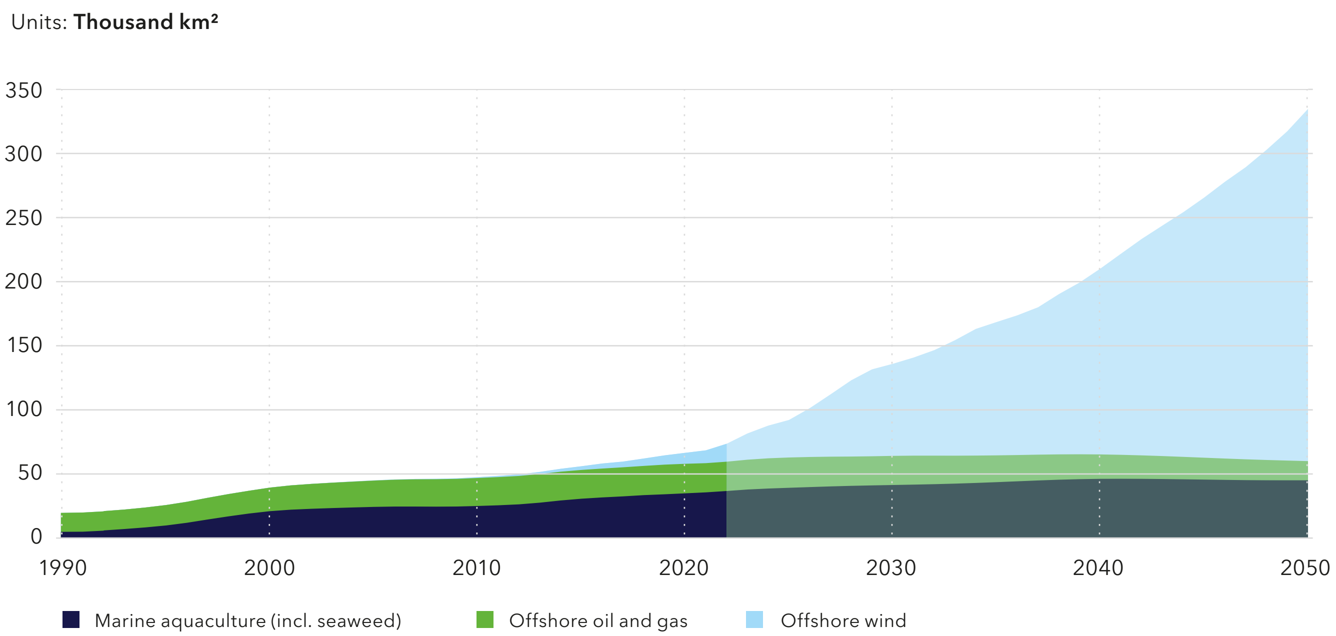
We find that the entire predicted demand for seaweed in 2050 could be met by placing seaweed farms within wind farms. Globally, the area needed to meet seaweed demand in 2050, is in the range of 3.5% to 6.5% of the offshore area needed for wind farms. This assumes an average global yield of 35 tonnes per hectare. Co-location would require that seaweed production which is currently happening in sheltered areas, like Eucheumatoids, would have to move farther offshore.

Co-locating seaweed cultivation with offshore wind can provide benefits like cost reduction through e.g. shared infrastructure, logistics, and emergency response. For offshore wind operators, seaweed can provide additional value creation from the offshore area and be a nature-positive contribution through the provision of ecosystem services. It fits well as a co-existence option to be considered, as offshore wind tenders increasingly consider co-existence and multi-use requirements (DNV, 2023b).

Compared to fish farming, seaweed cultivation can be more suitable for co-existence with offshore wind, as it involves fewer operations and a lower risk profile (van den Burg *et al.*, 2020). Although co-location provides opportunities, it can also pose risks for both industries, e.g. accidents and interference with industrial operations.

FIGURE 4

Marine area needed for offshore structures (seaweed included in marine aquaculture).



Uncertainty related to risk factors and technical feasibility can hinder co-location developments (O'Shea *et al.*, 2022). It is therefore important to target these uncertainties through trial projects.

Seaweed farms and offshore wind already make use of the same areas in several Chinese provinces, including Jiangsu, Zhejiang, and Fujian (see Figure 5). For instance, the Longyuan Rudong Intertidal Offshore Wind Farm (Jiangsu province) was developed in the early 2010s in an area already used for seaweed farming.

The EU Algae Strategy suggests that member states *'facilitate access to marine space, identify optimal sites for seaweed farming and include seaweed farming and sea multi-use in maritime spatial plans'* (EU Commission, 2022). In Europe, several plans are underway and seaweed farming pilots in offshore wind farms are subject to intensive research. As part of the EU lighthouse project OLAMUR (Offshore Low-trophic Aquaculture in Multi-Use scenario Realisation), the first harvest of seaweed at the Kriegers Flak wind farm took place in 2024 (Vattenfall, 2024). Furthermore, Amazon has funded a demonstration project for seaweed cultivation within a Dutch wind farm planned to be operating in 2024 (Casey, 2024).

Besides its co-use with offshore wind, seaweed can play a role within integrated multi-trophic aquaculture (IMTA) systems. In these systems, seaweed is farmed adjacent to or downstream from a fish farm, thereby extracting excess nutrients from spilt feed and fish waste. The additional nutrients can boost seaweed growth also during seasons when nutrient concentration in the seawater is low (SINTEF, 2023). In Norway, seaweed producers Folla Alger and Ocean Forest are testing these concepts.

FIGURE 5

Offshore wind turbines installed in the same location as seaweed farms in the Jiangsu province, China.
Source: NASA Landsat-8 scene, courtesy of TerraColor NextGen and U.S. Geological Survey.

5 CONCLUSIONS

Seaweed is seen as a sustainable source of food and increasingly as an alternative input in many supply chains. Seaweed can create employment opportunities in coastal areas and provide ecosystem services. In this forecast, we provide our objective view on the most-likely future for seaweed.

We find that seaweed production will grow between 60% and 75% to 2050, and the majority will still be produced in East Asia. New uses of seaweed are slowly entering the market, but direct food consumption and food additives will remain the main uses.

To anchor strategy development in the seaweed sector in more realistic data, there is a need for new reporting standards. Due to the high likelihood of official statistics being overestimated, we contrast a forecast based on official statistics with one in which we account for overestimation. We find that seaweed grows more slowly in the case where current statistics are believed to overestimate production. Ongoing initiatives aimed at improving food safety through increased traceability in the supply chain will likely improve the quality of reported data in the years to come.

The seaweed industry is facing severe challenges from climate change combined with poor seedling quality. These risks need to be mitigated through sector-wide efforts. Much of the seaweed is currently farmed with simple techniques, and the sector is ripe for industrialization. Introduction of new, innovative farming practices and breeding techniques can lead to major improvements in crop yields and resilience to environmental stressors.

The race for ocean space between offshore industries will be a major opportunity for seaweed industrialization, as the offshore wind sector increasingly considers co-existence. In 2050, the entire world's seaweed demand could theoretically be produced on a very small fraction of the world's offshore wind farm areas. Some players in the offshore wind industry are already experimenting with this.

In conclusion, our forecast finds that the seaweed industry will grow substantially in the years to come. The future of the industry will largely be determined by its ability to industrialize, improve transparency through the supply chain, and take advantage of synergies with other sectors in the Blue Economy.

THE TEN WORLD REGIONS

Key socio-economic drivers for our analysis are derived for the 10 regions shown on the map.

- North America (NAM)
- Latin America (LAM)
- Europe (EUR)
- Sub-Saharan Africa (SSA)
- Middle East and North Africa (MEA)
- North East Eurasia (NEE)
- Greater China (CHN)
- Indian Subcontinent (IND)
- South East Asia (SEA)
- OECD Pacific (OPA)

OUR APPROACH

What will the Blue Economy look like towards 2050? How can the Blue Economy contribute to serving a world population beyond nine billion in 2050? What are the key interlinkages between ocean-based industries, and the barriers to productivity arising from global ocean health challenges? What are the spatial requirements of the Blue Economy in 2050? To try to answer these questions, we have developed this forecast providing a systemic and balanced view of ocean-based industries between now and mid-century.

The *Seaweed Forecast* is the fifth instalment in the *Ocean's Future to 2050* series of publications. The previous four include the *Ocean's Future to 2050*, a complete overview of the Blue Economy; the *Marine Aquaculture Forecast*, a deep-dive into marine aquaculture; the *Spatial Competition Forecast*, a deep-dive into spatial planning and co-existence in the ocean space; and the *Seafood Forecast*, a deep-dive into the seafood value chain including both fisheries and aquaculture.

Where previous *Ocean's Future to 2050* publications provide a single 'best estimate' forecast, the *Seaweed Forecast* provides two alternative pathways, due to significant uncertainty surrounding the official production statistics.

Model description
We develop a system dynamics simulation model that mirrors key supply-demand relationships and interactions between ocean industries. Global trends like population growth and improving living standards drive the forecast of demand for goods and services provided by the ocean economy.

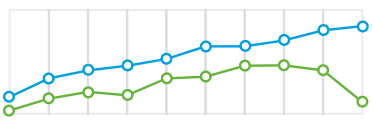
While this report focuses on seaweed farming, the model also includes sectors like capture fisheries, marine aquaculture, offshore energy, maritime, tourism, and desalination.

For most industries, the model considers feedback between demand, production, and infrastructure capacity, also moderated by interrelations between ocean industry and barriers to growth, like spatial constraints and climate change. For energy-intensive sectors of the Blue Economy, we look to the *DNV Energy Transition Outlook* (DNV, 2023a) for input data, examples being offshore energy and maritime.

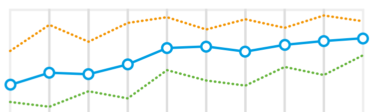
The seaweed sector in the model covers the farmed seaweed lifecycles, as well as the infrastructure required to farm. A simpler representation of wild caught seaweed is also included. Main seaweed product types included are direct food consumption, food additives, aquaculture feed, and other uses. Other uses encompass a wide range of emerging seaweed uses like pharmaceuticals, nutraceuticals, industrial feedstocks, materials, and biostimulants.

Sustainability and costs relative to other food products impact the demand for direct food consumption, while food additives demand is impacted by overall food demand. Interlinkages with other aquaculture systems is included under the aquaculture feed demand, whereas demand for other uses is driven by GDP.

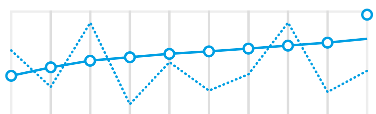
The model is populated with data from databases providing historical time series for supply and demand; industry reports; scientific articles; and the judgement of domain experts.



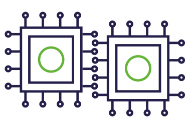
Our **best estimate**, not the future we want



A single forecast, not scenarios



Long-term dynamics, not short-term imbalances



Continued development of proven **technology**, not uncertain breakthroughs

Main **policy** trends included; caution on untested commitments.

Model **consumer behaviour** based on changes in costs and sustainability

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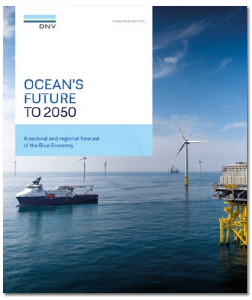

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