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Estimating production cost for large-scale seaweed farms

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ABSTRACT

Seaweed farming has the potential to produce feedstocks for many applications, including food, feeds, fertilizers, biostimulants, and biofuels. Seaweeds have advantages over land-based biomass in that they require no freshwater inputs and no allocation of arable land. To date, seaweed farming has not been practiced at scales relevant to meaningful biofuel production. Here we describe a techno-economic model of large-scale seaweed farms and its application to the cultivation of the cool temperate species *Saccharina latissima* (sugar kelp) and the tropical seaweed *Eucheumatopsis isiformis*. At farm scales of 1000 ha or more, our model suggests that farm gate production costs in waters up to 200 km from the onshore support base are likely to range between $200 and $300 per dry tonne. The model also suggests that production costs below $100 per dry tonne may be achievable in some settings, which would make these seaweeds economically competitive with land-based biofuel feedstocks. While encouraging, these model results and some assumptions on which they are based require further field validation.

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Introduction

Seaweed farming is considered to be a key potential contributor to the American Blue Economy, and an ecologically sound way to produce food and other products in many regions of the world (Bjerregaard et al., 2016). In the United States, research is currently focused on developing cultivation system for open ocean environments, selective breeding, autonomous monitoring of farms, improvement of hatchery protocols that can help unlock the potential seaweeds as feedstock for biofuel conversion (US Department of Energy [DoE, ARPA-E], 2021).

Liquid fossil fuel use accounts for more than 10 Gt y^{-1} of CO_2 emissions, and represents about one-third of global energy consumption (World Bank, 2021). Increasing production of liquid fuel from biomass in principle has the potential to reduce global carbon emissions by several Gt y^{-1}. Biofuel today is produced primarily from land-based feedstocks such as corn and sugarcane (US DoE, 2021; US Energy Information Administration [EIA], 2022). Global production of liquid biofuel stood at about 100 million tonnes of oil equivalent (Mtoe) in 2019 (International Energy Agency [IEA], 2021), or about 3% of global liquid fuel consumption. To make a meaningful dent in global carbon emissions via biofuel, biofuel production has to be increased by a factor of ten or more. That will require an order of magnitude increase in feedstocks.

Land-based production of biofuel feedstocks has several ecological disadvantages: it requires arable land to be diverted from food production, the application of fertilizer with its own carbon emissions footprint (DeCicco et al., 2016), and often the use of irrigation water, which is becoming scarce in many agricultural regions (Besharat, Barão, & Cruz, 2020; Rathmann, Szklo, & Schaeffer, 2010). Land-based biofuel production has also been linked to the transformation of carbon-rich ecosystems to monoculture (Searchinger et al., 2008) and to habitat degradation and loss of native species (Elshout, van Zelm, van der Velde, Steinmann, & Huijbregts, 2019). The carbon intensity of land-based biofuel feedstock production can range from 37.6 to 65.1 g CO_2e MJ^{-1} for ethanol from corn grown in the US (Scully, Norris, Falconi, & MacIntosh, 2021; Searchinger et al., 2008; US DoE, 2020) and 37 to 137 g CO_2e MJ^{-1} for methyl ester (biodiesel) from soybeans grown in Brazil (Castanheira, Grisoli, Coelho, da Silva, & Freire, 2015). As a result, net carbon emission reduction from replacing a tonne of fossil fuel with a tonne of biofuel from land-based feedstocks can be as low as 12% (ethanol

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from corn grain) or 41% (biodiesel from soybeans) (Hill, Nelson, Tilman, Polasky, & Tiffany, 2006). In some cases, net carbon emissions actually increase with land-based biofuel production when the cumulative impacts of land-use change are considered (Delucchi, 2011; Fargione, Hill, Tilman, Polasky, & Hawthorne, 2008; Searchinger et al., 2008).

A major challenge therefore is to increase biofuel feedstock production without putting additional burdens on agricultural and forest lands. Producing biofuel from algae offers the potential for lower ecological cost and better net carbon emission reduction (Correa et al., 2020; Dismukes et al., 2008). Until recently, most work in this area has focused on the production of microalgae in controlled onshore facilities (Hannon et al., 2010; Khan, Shin, & Kim, 2018). Here we investigate the potential for large-scale production of macroalgae (seaweed) biofuel feedstocks in open-ocean farms through a techno-economic analysis of potential production cost.

In the analysis that follows, we make no assumptions about market and non-market values of seaweeds. A seaweed farm growing biomass for biofuel production may generate revenue from markets for high-value compounds extracted from the seaweed before it is used as biofuel feedstock, and from environmental benefits such as the removal of excess nutrients and CO_2 from ocean waters (Chopin & Tacon, 2021); the net benefits, cost-effectiveness, and side-effects of ocean-based CO_2 removal via algae have yet to be demonstrated (Hurd et al., 2022; Troell, Henriksson, Buschmann, Chopin, & Quahe, 2022). Such incremental revenue may reduce the price at which such a farm would have to sell its biofuel feedstock in order to make a profit. We leave these considerations aside for the purpose of the present analysis and focus only on the immediate cost of production.

The research presented here is directly related to UN SDG Goal 7 (Affordable and Clean Energy), Goal 13 (Climate Action), and Goal 14 (Life Below Water). By assessing opportunities for seaweed-based biofuel production that leads to substantial net carbon emission reductions, we address anthropogenic contributions to climate change, promote access to sustainable energy for all, and contribute to strategies for the sustainable use of our oceans and marine resources. Our approach incorporates tenets from SDG Goal 12 (Responsible Consumption and Production), which promotes "life-cycle thinking", and Goal 15 (Life on Land) by evaluating an alternative to land-based production of biofuel feedstocks (see Duarte, Bruhn, & Krause-Jensen, 2021).

Seaweed farming background and production cost estimates

Global seaweed production reached 32.4 million dry tonnes in 2018 (Food and Agriculture Organization [FAO] of the United Nations, 2020). Much of this seaweed is harvested for human consumption; and almost all of it is farmed. Production is concentrated in relatively small, near-shore farms in Asia (Kim, Stekoll, & Yarish, 2019; Kim, Yarish, Hwang, Park, & Kim, 2017; Park, Shin, Wu, Yarish, & Kim, 2021). Most commonly, seaweed is grown by either attaching propagules or adhering spores to horizontal ropes or nets suspended just below the surface (Pereira & Yarish, 2008).

At the high end, annual yield from ocean seaweed farms is on the order of $1\,\text{kg m}^{-2}\text{ y}^{-1}$ dry weight (Bjerregaard et al., 2016) and our own calculations; see below); and the energy content of seaweed can potentially support conversion of dry seaweed biomass to liquid biofuel at a rate of $4–5\,\text{kg l}^{-1}$ (Das, Mondal, & Maiti, 2017). This means that seaweed-based biofuel production that reduces global liquid fuel carbon emissions by one third may require on the order of 4 million km^2 of seaweed farms – an area equivalent to all the agricultural land in use today in the United States.

Although this footprint is large even by agriculture standards, it represents less than 3% of the area of the world's exclusive economic zones (EEZs) and could in principle be accommodated in the US EEZ alone. But anything approaching this scale is not likely to be accomplished with small-scale farms, or in protected near-shore waters, which are already heavily utilized. For large-scale production of biofuel feedstock, seaweed farms will have to be scaled up significantly from current practice, and located in more exposed, open water. In this analysis, we therefore model the production cost of large (10 km^2, or 1000 ha) farms of the future that are designed to survive in exposed, open ocean conditions.

Early efforts to farm seaweeds for biofuel date back to the 1970s in the USA (Kim, Stekoll, & Yarish, 2019; Roesijadi, Copping, Huesemann, Forster, & Benemann, 2008; Sheehan et al., 1998); and the literature on production costs of large-scale seaweed farming goes back at least to the 1980s, when Feinberg & Hock (1985) completed a techno-economic evaluation of macroalgae cultivation for fuel production. Some more recent cost assessments for both tropical and cool temperate species are listed in Table 1 (We use "temperate" in the remainder of this paper to cool temperate species and seaweed farms). There are other studies that look in detail at small-scale farming of tropical species for the

Table 1. Seaweed farm production cost estimates from the literature.

Date	Crop	Location	Farm scale (hectares)	Yield (dry kg m^{-2} y^{-1})	Production Cost (2021 $ per dry tonne)	Source
1985	*Saccharina*	USA	5300	2.2	225	Feinberg & Hock, (1985)
2009	*Kappaphycus*	Mexico	<1	5.4	900	Valderrama et al., (2015)
2009	*Kappaphycus*	Indonesia	1	1.1	400	Valderrama et al., (2015)
2016	*Saccharina*	North Sea	4,000	2.0	2,000	van den Burg, van Duijn, Bartelings, van Krimpen, & Poelman, (2016)
2019	*Macrocystis*	Chile	10	1.9	610	Camus, Infante, & Buschmann, (2019)
2020	*Saccharina*	Sweden	2	0.35	10,000	Hasselström et al., (2020)

carrageenan market, generally at farm scales far below 1 ha (Fausayan, Muhidin, Sidu, & Arimbawa, 2018; Johnson, Narayanakumar, Abdul Nazar, Kaladharan, & Gopakumar, 2017; Nor, Gray, Caldwell, & Stead, 2020; Valderama, Cai, Hishamunda, & Ridler, 2013).

The estimates for large-scale farms (Feinberg & Hock, 1985; van den Burg, van Duijn, Bartelings, van Krimpen, & Poelman, 2016) are model-based, since no farms of that scale have been deployed. As a result, the yield and production cost estimates for the large-scale farms are derived from measurements taken at much smaller scales, on the order of 1 ha; their extrapolation to large scales should be treated with caution. There are no published estimates at all for biofuel-scale tropical seaweed farms; most studies of tropical farms focus on small operations in nearshore waters and regions with low labour costs. Most recent studies suggest dry weight yields of 2 kg m^{-2} y^{-1} or less; the higher value reported by Valderrama et al. (2015) for *Kappaphycus* farms in Mexico reflects farming structures that are unlikely to scale to deeper, exposed waters. Likewise, the $400 per dry tonne production cost estimated by Valderrama et al. (2015) for Indonesian *Kappaphycus* farms requires sheltered, nearshore conditions in a low-wage production environment. Finally, since the value ($ per dry tonne) of different types of algae for biofuel production are likely to differ, it is important to note that production cost numbers alone are not sufficient to assess their economic potential as biofuel feedstock.

Seaweed farming concept for biofuel-scale production

The design and operating concept for the future farms we model in this paper, and many of the model input values and assumptions, were developed by teams funded by ARPA-E's MARINER projects (US DoE, 2021) to investigate the feasibility of large-scale seaweed

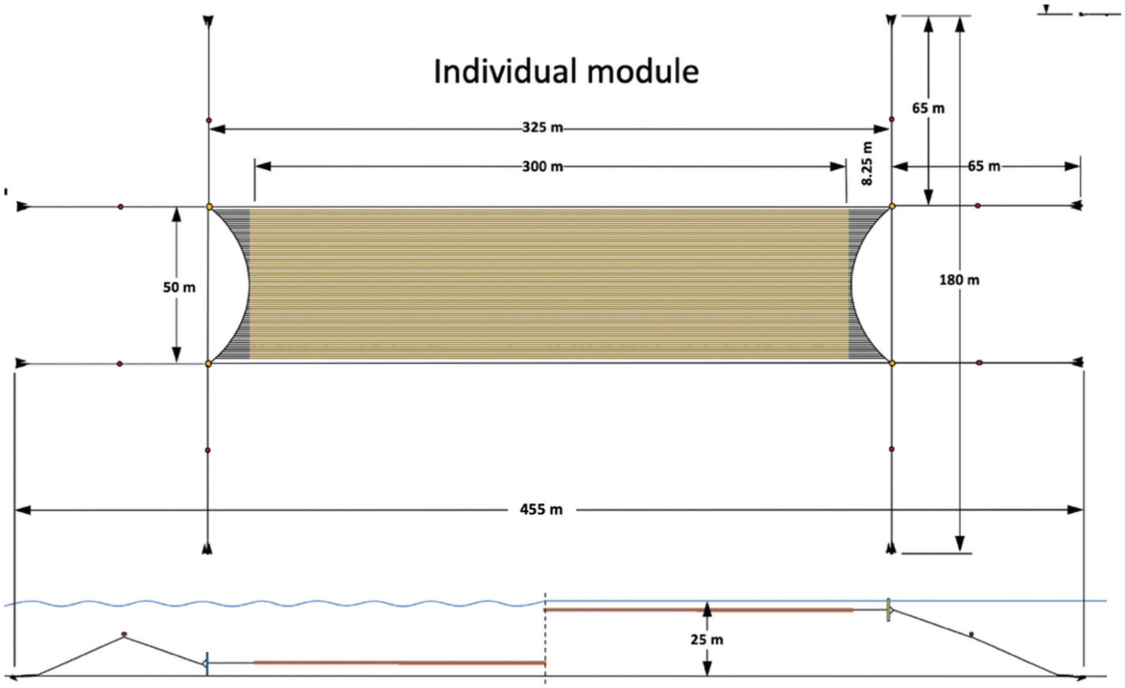

Figure 1. Individual farm module in top-down (top) and lateral (bottom) perspective. Bottom part of diagram illustrates "sinking" the module below wave energy zone in the event of a storm.

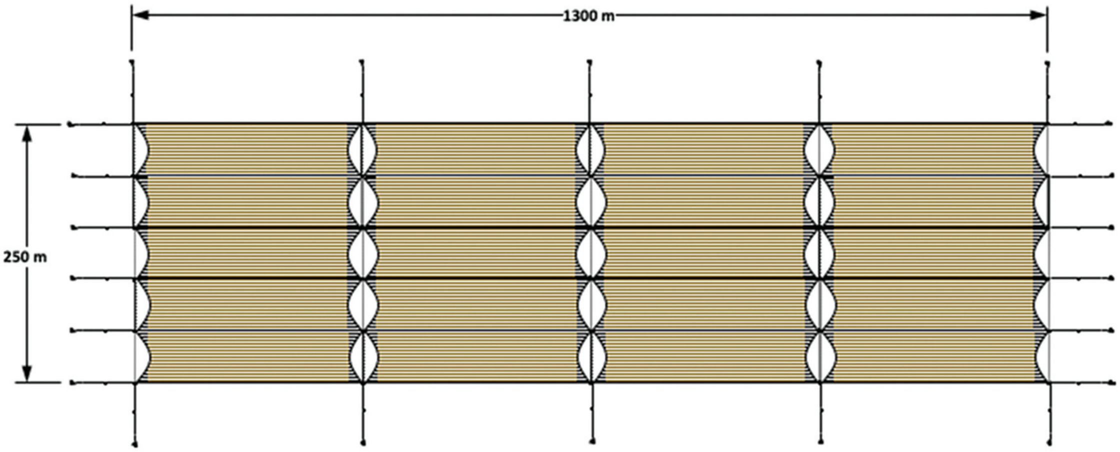

Figure 2. Four-By-Five array of modules. Combining modules requires larger anchors around the perimeter but reduces the number of anchor deployments versus individually anchored modules.

farming for biofuel feedstocks, using a combination of experience from existing seaweed farms and new concepts. The model farm consists of multiple modules (Fig 1), each of which supports a number of parallel grow ropes tensioned between two catenaries (Goudey, 2019). Individual modules may be several hundred metres long (in the grow rope direction) and 50–100 m wide. Multiple modules may be anchored adjacent to each other in a larger array (Fig 2). The grow ropes hold the crop in place. In temperate zones (kelps are at present grown mainly in the Northern Hemisphere), early life stage sugar kelp (*Saccharina latissima*) or similar species are encouraged to attach naturally to seed string in a nursery, and the seed string is then wound around the grow rope; or the early life stage is bound to the grow rope using an adhesive in a direct seeding procedure. In the tropics, red algae (*Eucheumatopsis isiformis* or similar species) are physically held to the grow ropes with ties or tube nets (Hayashi et al., 2017).

In tropical settings, year-round seaweed growth is possible (although growth rates and yields may vary by season), and we model farms that harvest and replant modules continuously, on harvest cycles of one to two months. With kelp in temperate settings, out planting generally happens in the fall (Northern Hemisphere) and harvest in spring, for a single crop per year. In both cases, the core farm infrastructure (mooring anchors and lines, catenaries, and other structural lines) is permanently deployed, while grow ropes may be removed/replaced between harvests.

In the tropical farm, a fleet of full-time purpose-built farm boats handles planting, harvest, and farm maintenance. These boats are small, with a crew of four, and operate in multiple 8-hour shifts each day when the weather permits. Crews are rotated on and off the boats, shuttled from a shore base or a floating "hotel" ship at the farm site.

In temperate farms, where periods of intensive work during out planting and harvesting are separated by extended periods of relatively little farm work (during the winter growing season, and during the summer fallow season), the farm boats may double as fishing vessels when they are not needed on the farm. These boats are larger than the tropical farm boats, with 200 tonnes of payload capacity, and support a larger crew that works in shifts and stays on site for days at a stretch.

Harvested biomass is aggregated by the farm boats (temperate) or by drone tugs (tropical) in barges or floating transport bags at the farm site, and eventually delivered to a processing facility, which may be on a floating platform near the farm site. The drone tug (Fig 3) has been prototyped by C.A. Goudey and Associates, and provides an efficient low-speed, uncrewed means to move large amounts of biomass from harvest sites to an aggregation or processing facility. Our analysis ends at the farm gate; our goal is to estimate the production cost of the seaweed biomass, aggregated and "wet", at the farm site.

Model structure

Sub-models for farm gear and boats calculate the capital and operating cost of farm gear and farm boats from input data described in the following section. An operations sub-model calculates personnel and fuel requirements for farm operations. An onshore sub-model estimates costs associated with nursery operations and onshore support services. A biological yield sub-model calculates the biomass yield per year. The process flow is illustrated in Fig 4.

Figure 3. Drone tug prototype developed by C.A. Goudey and Associates (https://arpa-e.energy.gov/technologies/projects/autonomous-tow-vessels). [Photo credit: C. Goudey].

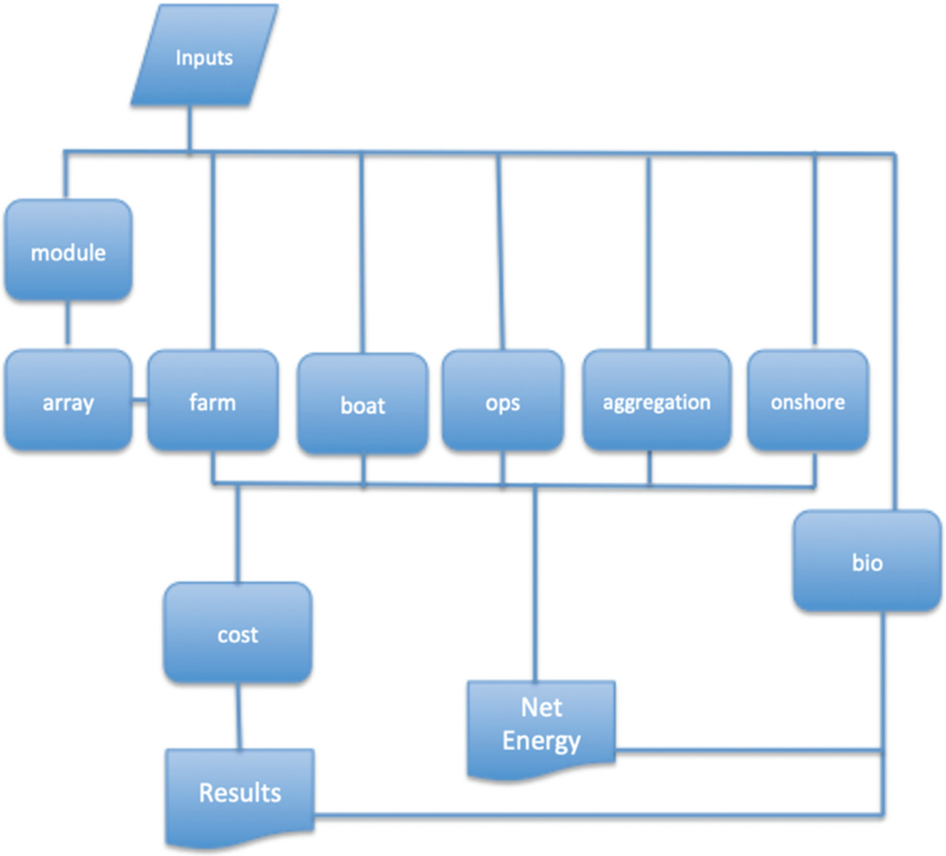

Figure 4. Techno-Economic analysis model process flow for seaweed farm.

The model algorithm computes the physical amount of all inputs required for a given farm scale (ha of farmed water area). This includes total length of grow ropes and other materials, number of boats, crew and other personnel, and expendable inputs such as fuel. It then computes the annualized cost of all inputs to the farming operation, based on farm scale, unit capital costs, and unit operating costs (see Input data section below). It also computes the net farm output, in terms of wet and dry biomass harvested.

The key output from the model is the total production cost in terms of $ per dry tonne biomass harvested (aggregated at the farm in "wet" condition, and not otherwise transported or processed). We draw the "boundary" of the analysis at the farm gate because we prefer not to make assumptions about how or where the biomass will be processed – at the biofuel scale, this may take place on floating facilities near the farm site.

Input data

Input values to the techno-economic analysis were developed by the authors in the course of work on DoE ARPA-E MARINER projects (US DoE, 2021). Unit costs are estimated in part from the cost of components on the MARINER project prototype farms and assumptions about how unit costs may scale with larger volumes. The full list of unit costs and other input assumptions is provided in the Appendix. Table 2 lists some of the key assumptions.

Farm gear input assumptions include the configuration and dimensions of modules, and unit capital cost and expected service life of module components (catenaries and grow lines), anchors, and moorings. They also include costs associated with deployment, annual maintenance requirements, and retrieval and retirement of the farm gear.

Farm boat input assumptions include capital cost, crew requirements, and operation cost of crewed vessels and drone tugs (tropical). They include boat capacity and time required for specific tasks, such as planting, crop maintenance, farm gear maintenance, and harvesting per metre of grow rope.

Input assumptions about the farm site include water depth, current, and weather conditions, all of which influence the cost of mooring the modules. They also include distance from the farm site to the shore base, which affects the cost of logistics for farm boats and crews, and supplies needed for farm operations.

Key biological input parameters include the wet biomass yield per metre for each growing season (temperate), and the daily biomass growth rate (tropical), which affects the length of the tropical farm harvest cycle. While temperate crops such as sugar kelp can sustain more than 20 kg m^{-1} wet weight on grow ropes, tropical seaweed biomass usually reaches a maximum yield around 5–6 kg m^{-1} wet weight before net growth decreases due to biological and structural reasons. Our baseline assumption of 15 kg m^{-1} for temperate farms is roughly the midpoint of yield values reported for kelp farms in the Gulf of Maine (Augyte, Yarish, Redmond, & Kim, 2017), southern New England (Kim, Kraemer, & Yarish, 2015; Yarish, Kim, Lindell, & Kite-Powell, 2017), and Alaska (Stekoll et al., 2021), and is consistent with the data summarized by Kim, Stekoll, & Yarish (2019). In these studies, yields of 10 to 20 kg m^{-1} were achieved without the benefit of selective breeding or strain optimization. We therefore consider 15 kg m^{-1} to be a conservative average baseline value for future farming operations.

There are important risk factors to consider in seaweed farming, including loss of biomass due to disease, grazing, and storm events. As described above, the farm structures are designed to be submerged below the wave

Table 2. Baseline input values.

Parameter	Units	Temperate	Tropical
Grow rope/net	$ per meter	0.20	0.30
Grow rope/net life	# of harvest cycles	10	24
Spacing of grow ropes	meters	0.75	1.0
Module dimensions	meters x meters	180 x 90	300 x 50
Farm boat capital cost	$	5 000 000*	1 000 000
Farm boat crew size	# of crew members	4	8
Boat crew labor rate	$ per hour	17	17
Boat capacity – planting	# grow lines x m s^{-1}	5 x 0.5	10 x 0.5
Boat capacity – harvesting	# grow lines x m s^{-1}	5 x 0.5	10 x 0.5
Drone tug capital cost	$	n/a	100,000
Weather days (no farm ops)	days per year	20	30
Nursery cost	$ per m grow rope	0.05	0.01
Harvest cycle	weeks	25	9
Net yield (wet weight)	kg m^{-1} per harvest	15.0	5.0
Water content of harvest	% of wet weight	85%	86%

*Portion of full cost allocated to kelp farm; boat is used for fishing during summer.

energy zone in the event of a major storm; in general, these farms must be designed to survive extreme events without structure losses, because the implications for social licence of large amounts of derelict farm gear on beaches or in coastal waters after a storm are likely to be severe. We do not model biological risks explicitly here, but treat the "net yield" value (see Table 2) as an average yield that takes into account expected losses from disease, grazing, etc. Variations in net yield in our sensitivity analysis (see below) therefore reflect different levels of risk and biological productivity at different sites.

Onshore input parameters include the cost of facilities to support farm boats, management overhead, insurance, and nursery operations. The cost estimates for nursery systems to support both temperate and tropical large-scale farming operations have been developed by the MARINER project team assuming a direct seeding approach for kelp (Stekoll et al., 2021) and a set of onshore nursery tanks to supply material for re-planting tropical seaweeds in the event of a farm shutdown or crop loss (Roberson et al., 2022). See supplementary materials for the full list of input assumptions.

Results and discussion

Sensitivity analysis suggests that production cost is affected strongly by assumptions about biological yield and by distance from the shore base. To illustrate the likely range of production costs for a wide range of locations across the US EEZ, we run the model for combinations of farm site distance from shore base up to 200 km. We consider harvest yield of 10 to 20 kg m^{-1} wet weight for sugar kelp (*Saccharina latissima*), based on the range reported in prior studies (Augyte, Yarish, Redmond, & Kim, 2017; Kim, Kraemer, & Yarish, 2015; Kim, Stekoll, & Yarish, 2019; Yarish, Kim, Lindell, & Kite-Powell, 2017) and observed in our prototype farms in Alaska (Stekoll et al., 2021), and growth rates of 3% to 5% per day for tropical seaweed (Glenn & Doty, 1990; Munawan, Kasim, & Ruslaini, 2021), which translates to harvest cycles ranging from 7 to 10 weeks. We also vary other cost parameters by ± 25%.

Using this range of input assumptions, the distribution of farmgate production cost for farms of 1000 ha (10 km^2) seaweed footprint are shown in Fig 5. Tropical production cost estimates are centred in the range of \$200 to \$250 per dry tonne; temperate production cost estimates between \$250 and \$300 per dry tonne. These estimates are remarkably close to those generated 35 years ago for large-scale open ocean kelp farms by Feinberg & Hock (1985); see Table 1.

The \$100 per dry tonne production cost is achieved in about 10% of the simulations of the tropical farm and 5% of simulations of the temperate farm. Those scenarios generally involve locations less than 50 km from the shore base and/or biological yield near the high end of the range (5% per day growth in the tropics, 20 kg m^{-1} wet yield for temperate kelp).

Major components of baseline production costs, assuming median biological yield (15 kg m^{-1} temperate, and 8 weeks' growth to 5 kg m^{-1} yield in the tropics) and

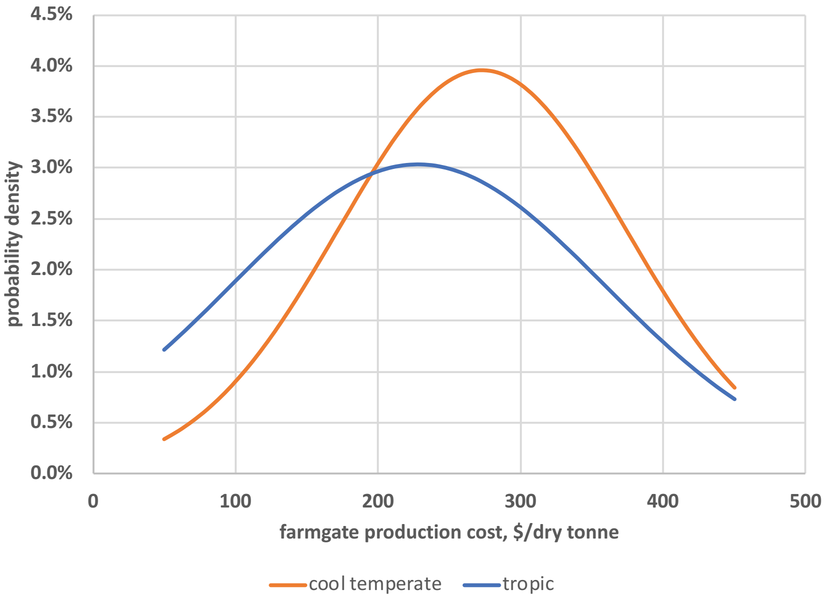

Figure 5. Distribution of farmgate production cost estimates, based on variations in distance from shore base (25 to 200 km), biomass yield for cool temperate (10 to 20 kg m^{-1} y^{-1}), and growth rate for tropical (7 to 10 weeks to reach 5 kg m^{-1}, starting from 0.5 kg m^{-1}).

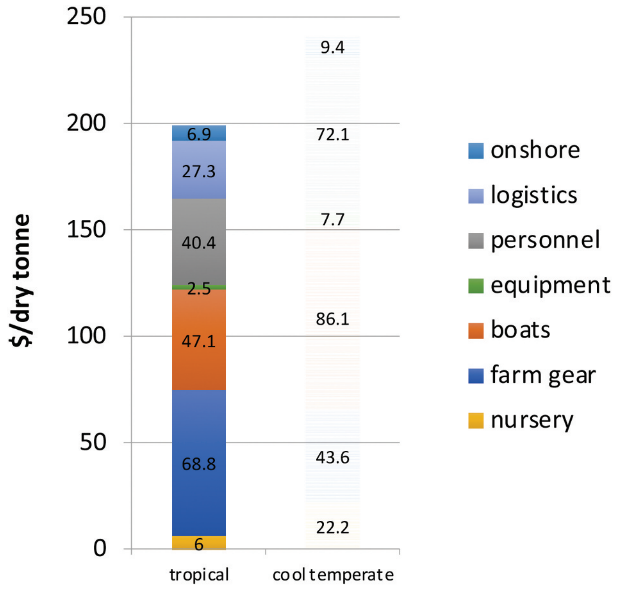

Figure 6. Production cost components.

75 km distance from the shore base in 50 m of water, are illustrated in Fig 6. The tropical farm relies largely on vegetative propagation and does not require as substantial a nursery operation as the temperate farm. Both farms have about 10 km of grow rope in the water per hectare of farmed surface, but the contribution of farm gear to total cost is greater for the tropical farm because the working life of grow ropes (and tube nets) is substantially less than that of the grow ropes for cool temperate kelp, which only see a single harvest cycle per year, and are not exposed to UV radiation year-round.

Boat costs are relatively larger for the temperate farm because the farm work is concentrated in relatively brief out planting and harvesting periods, and therefore requires a larger number of farm boats than the tropical farm, where work is spread evenly over the full year. The logistics costs for the tropical farm reflect the cost of ferrying crews and supplies to and from the farm site for continuous operation in multiple shifts per day. On the temperate farm, which employs larger boats, crews spend several days at a stretch at the farm site, and the larger capacity of the farm boats enables them to play a role in biomass aggregation, which is handled by drone tugs on the tropical farm.

The baseline farm operation for cool temperate kelp produces 32,800 dry tonnes of biomass per year on 10,900 km of grow ropes, and requires seven farm boats employing 42 crew members during the planting and harvest seasons. Capital investment is about $48 million, and annual operating cost about $4.7 million.

The baseline tropical farm operation produces 41 700 dry tonnes per year on 10 200 km of grow ropes, and requires three farm boats and 24 crew members working year-round. Capital investment for the tropical farm is about $31 million, and annual operating cost about $5.2 million.

Fig 7 illustrates the effect of farm scale on production cost. Our modelling suggests that while economies of scale are still significant up to the 1000 ha farm scale (production cost declines by about 40% as the farm grows from 100 to 1000 ha), for both the temperate and the tropical farm, scale economies diminish substantially above 1000 ha.

Assuming an energy content for dry seaweed biomass of 8 MJ kg^{-1} (90% of the higher heating value reported for another tropical seaweed, *Kappaphycus*, by Das, Mondal, & Maiti (2017)), the farming operations produce an estimated net energy return of 5:1 in the wet biomass at the farmgate. How that translates into reductions in CO_2 emissions when seaweed-based biofuel replaces fossil fuel depends on the details of the biomass conversion

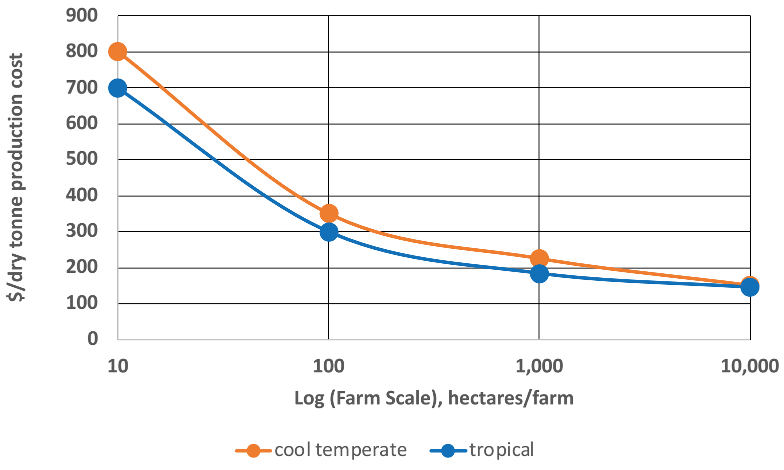

Figure 7. Effect of farm scale on production cost.

process, which is outside the scope of this analysis. A detailed life-cycle assessment of seaweed-based biofuel is being developed by a team at Argonne National Laboratory within the framework of the Argonne GREET Model (Argonne National Laboratory (ANL), 2021).

The results reported in this paper should be considered preliminary and are subject to refinement as more experience with large-scale seaweed farms is accumulated and incorporated into the techno-economic analysis. Our analysis includes implicit assumptions about the rate at which nutrients in surface waters are replaced as farmed seaweed crops draw them down that have not been measured or verified in many locations. Also, social licence for large-scale seaweed farming is likely only if it can be demonstrated that these farms do not have significant negative side-effects on ecosystem services, including primary production and food web effects, and effects on the natural biological carbon pump. Specific areas for refinement and extension of the analysis include:

- Potential multiple (partial) harvests of cool temperate kelp in one season.
- More detailed biological growth models linked to nutrient dynamics and environmental conditions at specific farm locations.
- Optimized planting and harvest schedules based on seasonal variations in growth.
- More detailed treatment of potential crop losses due to storms, disease, and grazing.
- Incorporation of data on yields that may be possible with selective breeding of seaweeds for optimal performance in specific locations/conditions.

Conclusions

At farm scales of 1000 hectares or more, our model suggests that farm gate production costs in waters up to 200 km from the shore base are likely to range between $200 and $300 per dry tonne. At farm sites close to shore support facilities and with optimal conditions for seaweed growth, production costs of $100 per dry tonne and less may be achievable, making seaweed economically competitive with land-based biofuel feedstocks. These cost estimates should be treated as preliminary until the assumptions on which they are based are further verified by data from larger farms operated over multiple seasons, and practical experience is gained with deployment, operation, and maintenance of large-scale seaweed farms in open-water locations.

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Disclosure statement

The authors have no conflicts of interest to declare. C.A. Goudey and Associates have a commercial interest in the drone tug technology and the catenary farm module design described in the paper (Goudey, 2019).

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