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Technological innovations promoting sustainable salmon *(Salmo salar)* aquaculture in Norway

Heidi Moe Føre [a,*], Trine Thorvaldsen [a], Tonje C. Osmundsen [b], Frank Asche [c,d], Ragnar Tveterås [e], Jan Tore Fagertun [a], Hans V. Bjelland [a]

[a] SINTEF Ocean, Postboks 4762 Torgarden, NO-7465 Trondheim, Norway
[b] NTNU Social Research, Dragvoll Allé 38b, Trondheim, Norway
[c] School of Forest, Fisheries and Geomatics Sciences and Food Systems Institute, University of Florida, Gainesville, FL 32611-0180, USA
[d] Department of Industrial Economics, University of Stavanger, Stavanger 4036, Norway
[e] University of Stavanger Business School, 4036 Stavanger, Norway

A R T I C L E I N F O

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A B S T R A C T

While highly successful in terms of profitable seafood production, salmon (*Salmo salar*) aquaculture may also be a source of potential negative environmental externalities. In an attempt to address these challenges through supporting the development of new technology, the Norwegian government has introduced a new class of aquaculture licenses labeled as development licenses. As a result, new technological solutions were proposed to reduce negative externalities through (1) expansion to open ocean areas not yet used for aquaculture and (2) reduced emissions from inshore production systems. This paper presents an analysis of the technological concepts proposed in applications for development licenses. The applications for development licenses provide a unique perspective on what technological directions existing marine aquaculture companies envisage that marine aquaculture may take in the future. The analysis indicates that units will become larger and stronger, as well as being specially designed to suit a variety of environments, creating a more heterogeneous industry. Large offshore structures such as semi-submersible platforms and other strong, rigid structures with permeable enclosures (nets) have been particularly successful in this application process, receiving relatively many development licenses. In sheltered fjord areas, many concepts involving closed enclosures (bags and tanks) have been suggested and awarded licenses.

1. Introduction

Globally, aquaculture has been the food production technology with the fastest growth rate in recent decades (Garlock et al., 2020), developing from a relatively marginal food production technology in the 1970s to representing a large part of global seafood production in the 2010s (Anderson et al., 2019). This growth has relied on several innovations that have reduced production costs and improved the competitiveness of aquaculture products (Asche, 2008; Kumar and Engle, 2016).

Aquatic farming is a relatively new way of interacting with the environment, creating a new set of environmental challenges such as pollution (e.g. feces and feed residues), habitat use and impacts on traditional wild fisheries, which makes the industry controversial and thus subject to a number of regulations (Belton et al., 2020; Anderson et al., 2019). The control over the production process in aquaculture also facilitates innovations to address such challenges, if the governance system provides the industry incentives to do so (Abate et al., 2016; Anderson et al., 2019). The need to achieve environmental sustainability is a strong driver for technological innovations, as well as an important factor in explaining regulatory innovations, such as the use of a wide range of environmental indicators in assessing the sustainability of aquaculture production systems (Osmundsen et al., 2020a, 2020b).

Atlantic salmon (*Salmo salar*) is one of the most successful aquaculture species in terms of production growth and the second most valuable species in global aquaculture after shrimp (Garlock et al., 2020). The production process is among the most knowledge- and technology-intensive in global aquaculture, and in several dimensions,

* Corresponding author.
E-mail addresses: Heidi.moe.fore@sintef.no (H. Moe Føre), Trine.thorvaldsen@sintef.no (T. Thorvaldsen), tonje.osmundsen@samforsk.no (T.C. Osmundsen), frank.asche@ufl.edu (F. Asche), Ragnar.tveteras@uis.no (R. Tveterås), jan.tore.fagertun@sintef.no (J.T. Fagertun), hans.bjelland@sintef.no (H.V. Bjelland).

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such as in technology use, feed formulation and nutrition, fish health and vaccines, breeding, and public policy and regulation, salmon aquaculture is regarded as globally leading (Asche and Smith, 2018; Kumar and Engle, 2016; Smith et al., 2010). Only five countries produce salmon in significant quantities, with Norway as the largest actor (55% production share[1]), followed by Chile (25%), United Kingdom (7.6%), Canada (6%) and Faroe Islands (3%).

In Norway, the dominant production technology today is net-enclosures supported by floating collars that are accessed by vessels (Moe et al., 2007). This basic concept was introduced in the 1970s, and research and development since then have mainly focused on gradual development rather than disruptive innovations, even though the scale of a farm has increased by many orders of magnitude (Asche et al., 2013). A combination of environmental challenges, public concerns and strict regulations has reduced production growth rates during the last decade (Iversen et al., 2020). A clear consequence of the low production growth and strong demand for salmon has been high prices and profitability (Asche et al., 2018, 2019; Dahl et al., 2021; Misund and Nygård, 2018), strongly signaling that the market wants more salmon. Another consequence is the development of new production concepts, such as fully or partially land-based farms (Bjørndal and Tusvik, 2019, 2020).

In aquaculture, most innovations appear to take place in a few countries and for a few species, and these spread to producers globally (Asche, 2008; Kumar et al., 2021), as with innovation processes in agriculture (Alston et al., 2009). The Norwegian salmon industry is one such innovation hub (Kumar and Engle, 2016; Smith et al., 2010; Bergesen and Tveterås, 2019). Increasing our knowledge about the incentives and structures for innovation in innovation hubs is also highly important for other regions that aim to develop their own aquaculture sectors, as well as other species.

1.1. Development licenses in Norwegian aquaculture

The challenge faced by the Norwegian regulator is a market that demands more salmon and an industry that is very willing to produce more if given licenses to do so, as well as several stakeholders that argue that the environmental impact of the industry is already too large to allow sustainable growth (Osmundsen et al., 2017). To address this twofold challenge, the Norwegian government launched “development licenses” in 2015, an innovative program that is unprecedented in design and scale within global aquaculture and, potentially, food production in general. The timeframe was limited, with a deadline for applications in 2017.

With these development licenses, the Norwegian government calls for considerable innovations and unique concepts, rather than marginal improvement of existing solutions. The development license program is encouraging innovation in new sustainable technologies that allow for (1) expansion to open ocean areas not yet used for aquaculture and (2) reduced emissions from inshore production systems. These two target areas are also recognized as the main challenges in an expanding global marine aquaculture production. Globally, the dominant mode of marine aquaculture production is open-cage farming in sheltered inshore areas. This production mode faces biosecurity, environmental and user conflict challenges. Low production growth rates, partly due to regulatory restrictions, are observed across countries and species (Abate et al., 2016; Osmundsen et al., 2017). If successful, the two main innovation avenues targeted in this innovation program may mitigate negative externalities and contribute to sustainable marine aquaculture growth beyond salmon aquaculture.

Development licenses are awarded in a process separate from the regular commercial production license system.[2] Applications that satisfy the criteria of the program are awarded free licenses, while a commercial license has, in recent years, had a cost on the order of 15–25 million US dollars (USD). Applicants are allowed to convert the development licenses into regular production licenses at a cost of 1.1 million USD (10 million) Norwegian kroner (NOK) when a project has been completed according to the criteria of the program, independent of outcome. The general rationale for such a subsidy for innovation is the market's perceived limiting of innovation due to the combination of high technological-biological risk and high initial investments, leading to insufficient private investments in risky innovation projects (Martin and Scott, 2000). The purpose of the development licenses is to facilitate the development of technology that can contribute to solving one or more of the environmental and area challenges that the aquaculture industry faces (Norwegian Directorate of Fisheries, 2016). The call requested that the innovations should promote sustainable aquaculture, contributing to solving one or several of the environmental and sea area utilization challenges in aquaculture. Environmental challenges included parasitic sea lice, escape of farmed fish and waste from fish production (e.g. feces and feed). Sea area challenges relates to limited available and suitable coastal locations for aquaculture. Development of fish farms that can be used further out into the ocean and into the fjords may contribute to the utilization of areas previously unsuitable for aquaculture. The increased utilization of both high-energy locations, with stronger currents and higher waves, and sheltered locations with limited water exchange requires technology development. Development licenses thus represent a strategy via which to increase sustainability through a reduction of environmental risk (especially regarding the escape of fish and the prevalence of salmon lice) due to technological innovation. New technology may also facilitate the production of new species because marine aquaculture may become feasible in areas that are not accessible with current technologies. Additionally, by awarding new licenses, this process also helps to increase overall production (Hersoug et al., 2021). The development licenses provide an interesting example of incentivized innovation, with some associated pitfalls because there is an implicit subsidy element which may cause applicants to inflate both costs and innovation potential (Hersoug et al., 2021). In addition, the innovation license applications represent an interesting assessment by the industry itself with respect to the direction of future production technologies.

By the end of 2017, 104 applications for development licenses had been received by the Directorate of Fisheries. Interest was high, and the 104 applications requested in total 884 development licenses in an industry that, at the start of 2021, operated 1540 production licenses for salmon and rainbow trout (*Oncorhynchus mykiss*) (Norwegian Directorate of Fisheries, 2021a). The scale of the associated projects determined how many production licenses the proposed production quantity required. These 104 applications provide a highly interesting insight into which directions the industry believes marine salmon production may take.

In several dimensions, the scope and scale of the development license innovation program is unique in the context of global aquaculture. The program has led to the development of several heterogeneous technological concepts, which will be described and analyzed further in this paper. Furthermore, it has contributed to the mobilization of highly skilled people and technology supplier companies not before employed in aquaculture, particularly design and engineering competencies from the offshore petroleum value chain (Tveterås et al., 2020). In a government-commissioned report, the market value of the 102 fish farming licenses that had been awarded through the call for development licenses by March 2021 was estimated at 1.1 billion USD (10 bn NOK, exchange rate 8.80 NOK/USD) (Grünfeld et al., 2021).

[1] Based on production numbers in 2015 (Iversen et al., 2020).

[2] Hersoug et al., (2019, 2021) provide good reviews of the ordinary regulatory system and the licenses. Osmundsen et al., 2022 provide a discussion of the development licenses as a regulatory instrument in Norwegian aquaculture.

Furthermore, the total investment costs of the 21 projects awarded was estimated at 1.7 billion USD (15 bn NOK) according to the same report. In comparison, the total R&D investment in Norwegian aquaculture in 2017 was 313 million USD (2.75 bn NOK). During the period from 2015 to 2020, development licenses represented almost 40% of the total new salmon aquaculture production capacity awarded. The total maximum allowed biomass (MAB) of 84,134 metric tons awarded thus far represents an annual production of 135 thousand tons (assuming a 1.6 ratio between production and MAB) and a potential farm gate production value of 765 million USD (6.7 bn NOK, assuming a sales price of 50 NOK/kg).

1.2. Objective

In this paper, we seek to answer the following question: **Which technological directions are prominent in development license applications and awarded licenses?** The paper presents an analysis of the various technological concepts suggested in the applications for development licenses and discusses the extent to which the awarded concepts differ from the total pool of applications. These findings provide information about the aquaculture industry's perceptions of potential future directions for marine aquaculture and are relevant for not only salmon but all species that are produced in net pens.

2. Materials and methods

A systematic content analysis was performed to establish a base for investigating the technological directions proposed in the development license applications. The main material applied in the content analysis was the response and decision letters from the Norwegian Directorate of Fisheries (NDF) and the Ministry of Trade, Industry and Fisheries (MTIF) to the 104 applications for in total 884 development licenses. Each licence involves a maximum allowed biomass, normally of 780 tons. The NDF performed the initial evaluation of applications, while the MTIF evaluated complaints issued by applicants not granted licenses in the initial evaluation. For some applicants, the complaints resulted in awarded licenses. All response letters, including responses following complaints from the applicants, are publicly available at the directorate's website (Norwegian Directorate of Fisheries, 2021b). The analysis provides the status per the 13th of September 2021. The NDF response letters contain descriptions of the proposed technological solutions and follow a fairly standardized structure, making them suitable for a systematic review.[3] Letters to applicants awarded licenses are, in general, more thorough than the letters to applicants who were rejected. For awarded licenses, there is also more information available at the directorate's website, as well as the companies' websites, which were sometimes checked for details regarding the technology.

It is important to note that the focus of the letters is on evaluating the suggested technologies based on the objective of the call, rather than reproducing all information from the applications. Consequently, not all information from the applications is found there. For instance, while descriptions of measures aimed at ensuring the personal safety for workers are rarely mentioned in the response letters, such measures may have been described in greater detail in the applications.

Based on a review of all response letters, categories describing the production technology (including farm concepts, floaters/platforms and fish enclosures), sustainability measures (prevention of sea lice infection and escapes, and promotion of fish welfare), and intended location/sea area of the proposed concepts, and causes for rejection, were established through an iterative process. Where available, information about investment costs were also drawn from the response letters. When the categories were established, each concept was analyzed and categorized. All applications were associated with only one farm concept and floater/platform material and shape. Two concepts involved floaters and enclosures of different size-categories (small + medium/large). These have been counted in both categories and weighed as half an application in each as results are given in percent. 11 concepts involved multi-material enclosures, and many applications claimed several different sustainability measures.

3. Results

3.1. Licenses

According to the response letters from the NDF, the call led to 104 registered applications, requesting in total 884 development licenses. Most applications were submitted by established farming companies, but newly established companies as well as supplier industry were also listed as applicants in some cases. The different concept developments often involved cooperation with a range of suppliers and research groups. By September 2021, 23 applications had been awarded, 78 had been rejected, and three applications had not received a final decision by the NDF. The awarded applications corresponded to 111 production licenses with a total maximum allowed biomass of 84,134 tons. All applicants had been given a response, but many had written formal complaints, both as a consequence of refusal and being awarded fewer licenses than requested. About twenty of the rejected applications were still awaiting a final decision by the MTIF following complaints at the time the analysis ended (Kyst.no, 2021). If the MTIF supports a complaint, the application will be considered again by the NDF, and additional applications may be awarded in the future. Most of the awarded licenses allow for a maximum biomass of 780 tons. However, five of the licenses awarded allow for a lower biomass (73–530 metric tons), all of which are associated with closed and semi-closed fish farming (see Section 3.4 for more details on the decision process).

3.2. Production technology

The prospect of significant innovations was the number-one priority during the evaluation of the applications. As many as 75 of the 104 applications claimed to involve innovative fish farm concepts, while the remainder (29) involved other production technology (many involved both). The latter included technologies for de-lousing, collection of waste, improved fish welfare and surveillance. Many of these were considered to be outside the scheme of the development licenses by the NDF because they were not directly associated with technological equipment for aquaculture production. Only one of the awarded applications did not involve an innovative fish farm physical structure concept, i.e., the iFarm by Cermaq Norway, involving a sensor system allowing for treatment of live salmon as individuals in cages, e.g. treating only infected individuals and not the whole group.

3.2.1. Farm concepts

The farm concepts reflect the main design features of the involved aquaculture structures. Fig. 1 provides illustrations of farm concepts that have been awarded development licenses. The following categories of farm concepts were established based on observations in the applications (listed by descending number of registered applications):

- *Closed:* Closed sea-based fish farms that involve impermeable fish enclosures that separate the enclosed water volume from the surroundings (Fig. 1a). This category also includes "semi-closed" facilities, which have impermeable enclosures but are not fully isolated from the surroundings, because they will release waste (Nofima, 2020). The enclosure is most often filled with seawater pumped up from deep water to prevent parasite infections.

[3] Application documents can be accessed at request and was considered as a possible data source. However, the response letters from the authorities were considered as a more updated and practical source, providing the sought information.

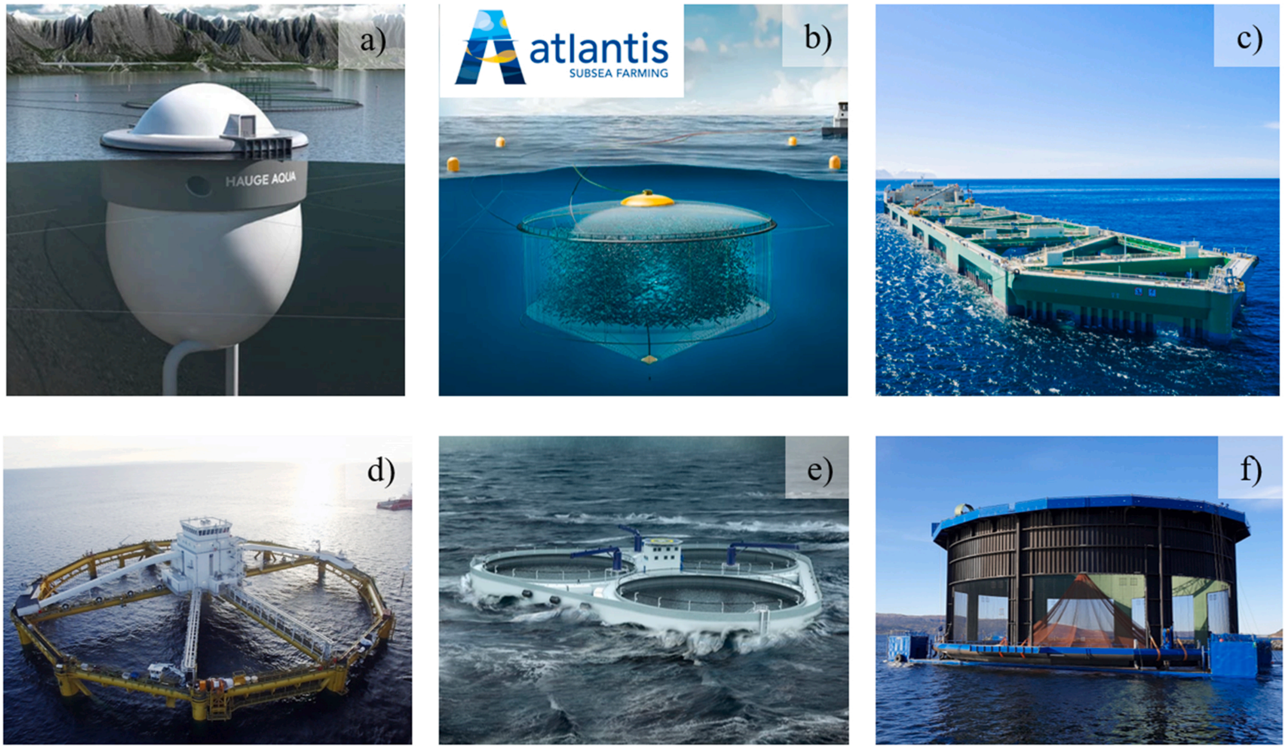

Fig. 1. Illustrations of farm concepts that have been awarded development licenses. a) closed farm called "The egg" (ill.: Hauge Aqua), b) submersible PE-rings called Atlantis (ill.: Atlantis Subsea Farming), c) semi-subs called Havfarm (photo: Nordlaks/Deadline Media), d) semi-subs called Ocean Farm (photo: Ocean Farming), e) rigid floater called Øymerd (ill.: Astafjord Ocean Salmon), f) partly closed farm called Aquatraz by Seafarming systems (photo: Steinar Johansen/MNH).

- *PE-rings:* Floating flexible cages with a circular floater made of HDPE (high-density polyethylene) pipes and permeable nets (Fig. 1b). This is the most widespread farm concept currently used in Norwegian salmon aquaculture.
- *Semi-submersible platforms (semi-subs)*: Rigid platforms with their buoyant elements below the water surface (Fig. 1c and d).
- *Rigid floaters:* Floating structures situated at the water surface holding a permeable net (Fig. 1e).
- *Partly closed farm:* A combination of impermeable and permeable enclosures or partly permeable enclosures, for instance, applying closed farming for smolt and nets for larger fish or enclosures with openings in the lower parts of the structure (with low parasite pressure) (Fig. 1f). At least 50% of the enclosure should be closed in this category; i.e., this does not include common lice skirts covering the upper part of the net.
- *Cage:* Permeable net cages enclosing a spherical or cylindrical (cigar-shaped) volume without a distinct floater or platform structure.
- *Other:* Concepts that do not fall under one of the above defined categories or in which the fish farm concept is not clearly defined or decided. This includes a trusswork structure fixed to the seabed and a wire structure.
- *N.A.:* The suggested innovation does not involve or depend on a certain type of fish farm.

Fig. 2 and Table 1 provide a quantitative overview of the different farm concepts involved in the applications generally and the awarded applications, as well as the corresponding number of licenses and allowed biomass. Closed farms and PE-rings were the most common concepts in the applications, representing more than half of the applications (31% and 25% respectively). As many as nine closed farms concepts were awarded (39% of total awards), but only two PE-rings (9%). In the closed category, half of the 32 applications involved circular floaters with impermeable fish enclosures, while barges and ship shaped structures with production tanks were included in ten of the

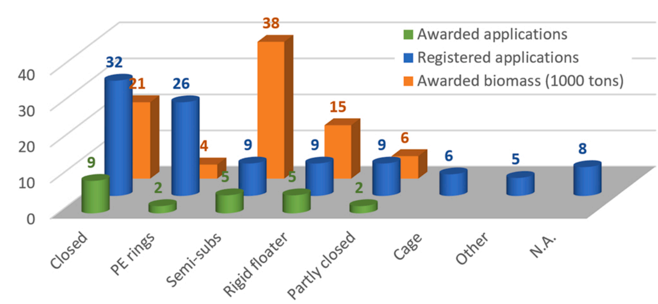

Fig. 2. Number of registered (blue) and awarded (green) fish farm concepts, as well as the biomass associated with awarded development licenses (orange). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

Table 1
Registered and awarded applications and awarded licenses and biomass for various farm concepts.

Farm concept	Registered applications	Awarded applications	Awarded licenses/ biomass [1000 kg]	Percentage of awarded biomass [%]
Closed	32	9	30/21,204	27
PE rings	26	2	5/3900	5
Semi-subs	9	5	49/37,940	44
Rigid floater	9	5	19/14,820	17
Partly closed	9	2	8/6240	7
Cage	6			
N.A.	8			
Other	5			
Total	104	23	111/84,103	100

applications in the closed category. Semi-submersible platforms and rigid floaters were the two concepts with the highest success rate in the allocation process: In both these categories, five of nine applications were awarded, representing 61% of the total allocated biomass (Table 1). Closed farm concepts were awarded 27% of the total allocated biomass, and the remaining 12% were divided between four applications involving partly closed concepts and conventional PE-rings.

Most awards allocated between one and four licenses for fish farming (16 of 23). The concepts with the highest number of awarded licenses were the semi-submersible platforms "Havfarm" (21 licenses, Fig. 1c), Ocean Farm (8, Fig. 1d), Arctic Offshore Farming (8), and Mariculture (8), the closed "Reset" (8), "the Egg" (6, Fig. 1a), and the rigid floater Fjordmax (6).

Eighteen of the 104 applications involved farm concepts that will be permanently or periodically submerged below the water surface to avoid parasite infections, large waves, algae blooms and other challenges that may occur in upper water layers. The farm concepts of all the above-mentioned categories are planned to be submerged, except for *closed* farms. The most commonly suggested submersible farm concepts were *PE-rings* (5) and *cages* (5[4]). These submerged concepts did not include so-called snorkel-cages, in which a submerged net roof will keep the fish several meters below the water surface, allowing the fish to swim up an impermeable snorkel to fill their swim bladder with air (snorkel-cages are a measure against salmon lice; see Section 3.3.1).

3.2.2. Floater and platform technology

The main function of moored floaters and platforms is to keep the fish farm in the required vertical and horizontal position. In addition, the floater will often serve as a working platform and facilitate storage (e.g., feed) and serve as a fundament for various equipment (Moe Føre and Thorvaldsen, 2020).

Most farm concepts associated with the development license applications involve a floater or floating platform with integrated buoyancy, which will be moored to the seabed through multiple conventional catenary mooring lines, similar to the technology applied at current Norwegian fish farming sites. Only 23 of the applications involved alternative positioning technology, including single-point mooring, bottom-fixed installation, tension mooring, mooring to another structure (e.g., bridge or pier) and dynamic positioning (DP). Five of these applications were awarded development licenses, including farms with single-point and tension mooring and DP.

An overview of the suggested materials and shapes of floaters and platforms (in all registered applications) is shown in Fig. 3. The content analysis shows that most concepts involved the use of steel or polymer structures, with concrete as the third most common choice. The awarded applications represented the same material use, except for a relatively higher share of concrete structures (ten steel, six polymer and six concrete). In comparison, most conventional Norwegian sea-based fish farms apply circular floaters of PE-pipes (polymer), a few use rectangular steel floaters, while concrete farms are uncommon. One half of the suggested concepts involved circular cages, but oblong structures and various polygon shapes were also frequently suggested (Fig. 3). *Other* shapes included two concepts with three circular net enclosures integrated into a flat surface platform (a triangle with rounded corners), as well as a curved platform. The awarded concepts included twelve circular floater concepts, six polygon-shaped floaters (one of them square), three oblong floaters and two triangular floaters with rounded corners. In 8% of the applications, the floater/platform was not of relevance to the suggested innovations (N.A.).

Floater size has been defined as the largest horizontal main dimension, e.g., the diameter of a circular floater or the length of a production ship. Three categories have been established:

- *Small* floater size: Less than 35 m.
- *Average* floater size: Between 35 and 60 m, corresponding to the Norwegian industry standard.
- *Large* floater size: More than 60 m.

Floater size was given in most applications. For some, the suitable category was determined based on information given in the application. For instance, applications involving standard PE-cages were categorized as *average* size. The analysis showed that 10% of the applications involved small floaters, 35% average-sized floaters, and 38% large floaters. The size was not given in 10% of the applications, and for 8% of applications, the floater was not a part of (or of relevance to) the innovations.[5] A relatively large fraction of the large floaters were awarded licenses because twelve of 23 awarded projects fell into this category (including the semi-submersible platforms mentioned in Section 3.2.1). Four small and seven average-sized floater concepts were awarded, of which all the small floaters were associated with closed fish farms. Some concepts involve several floaters, each supporting a single fish enclosure (e.g. PE-rings), others involve one floater with several fish enclosures (e.g. large ship hull shaped structures).

3.2.3. Fish enclosures

The main function of the fish enclosure is to keep the fish in a confined space that prevents escape but, at the same time, provides a high level of fish welfare and biomass growth (Moe Føre and Thorvaldsen, 2020). Enclosures, particularly closed containers, may facilitate optimal conditions for the fish, e.g., high oxygen levels, beneficial temperatures and low levels of parasites and pathogens.

Conventional fish enclosures are made of permeable polymer netting, reinforced by a rope structure (Moe et al., 2007). Of the development licence applications, 40% plan to apply common netting in the fish enclosures (Fig. 4). Eight of these will combine common netting with other materials, mostly tarpaulin. Overall, eleven concepts combine two enclosure materials. These include the awarded concepts iFarm (combining common and stronger netting in a double net) and the partly closed "production tank" by Hydro Salmon Company (combining a steel lice skirt with stronger netting below). Twenty-five percent of the 104 registered applications stated that they would apply double enclosures to provide a double barrier against escape of fish, as opposed to the conventional single barrier net enclosures. Such double barriers were rewarded as 52% of the awarded concepts involved double enclosures.

Nineteen concepts proposed steel enclosures, mostly in the form of stiffened steel plates (e.g., hull structures and tanks), in addition to a few steel mesh structures. Sixteen concepts plan to apply stronger polymer netting materials, i.e, produced from stronger materials such as UHMWPE (e.g., Dyneema®), or thicker filaments (e.g., EcoNet™). Several closed or partly closed concepts involved flexible tarpaulins (heavy-duty waterproof cloth), more rigid polymer structures or fully rigid concrete tanks. Two applications involved permeable brass mesh enclosures, while for twelve concepts, the net material was not given or not of relevance to the innovation.

The awarded concepts included a variety of enclosure materials. However, concepts involving other than common netting materials had a higher success rate, particularly stronger-than-normal netting materials. It is also known that some of the awarded concepts applied stronger netting materials (e.g., Havfarm), although this was not given in the source material (Section 2). In several cases, the choice of netting material has been a part of the development process after licenses were awarded.

Three categories for enclosure volume have been established as given

[4] In practice, the latter involved only three concepts because two cigar-shaped concepts were included in two applications each ("Gigante offshore" and "Beck Cage").

[5] All numbers have been rounded to the nearest integer. Two-decimal numbers are: 9.62%, 35.10%, 37.98%, 9.62%, 7.69%.

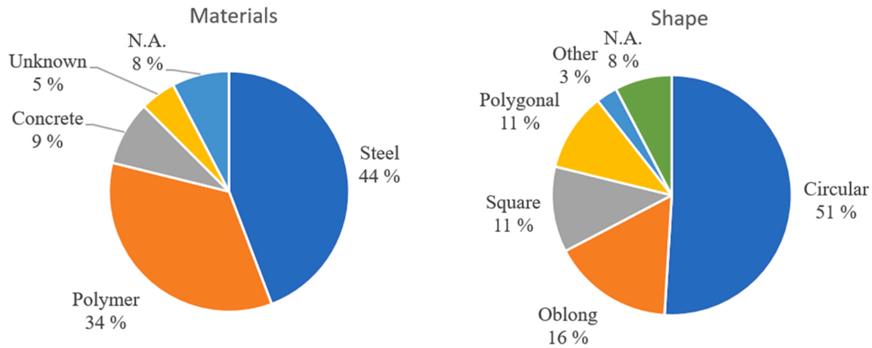

Fig. 3. Applied materials in floaters and platforms (left) and shape of floaters and platforms (right) associated with the 104 applications.

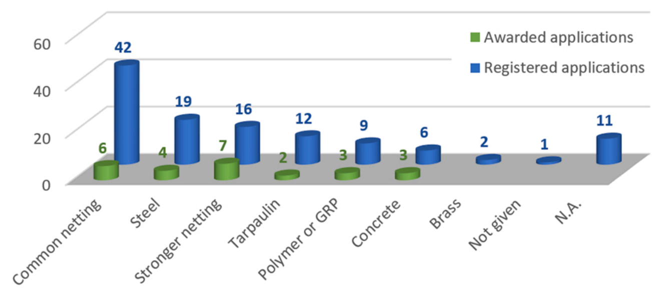

Fig. 4. Enclosure materials.

Table 2
Enclosure volumes in registered and awarded applications.

	Volume [m^3]	Registered applications	Awarded applications
Small	< 20.000	18	5
Medium	20–60.000	46.5[a]	10
Large	> 60.000	16.5[a]	8
Unknown		15	0
N.A.		8	0

[a] In two cases, enclosures of different size-categories have been applied (small + medium/large). These have been counted in both categories and weighed as half an application in each.

in Table 2 (small, medium and large). Medium-size enclosures, corresponding to the Norwegian industry standard, were proposed in almost half of the applications. Sixteen percent of the applications involved small volumes (all of which were closed), and another 16% involved large enclosure volumes. The large enclosures were all permeable, except "Aqua semi" (awarded four licenses), which is a semi-submersible partly closed steel enclosure that is closed down to 25 m, below which open steel mesh panels allow for exchange of water.

3.2.4. *Other technological aspects*

Some of the innovative concepts introduce new technology beyond the main structural components (floater, mooring system and enclosure), and an overview is given in Table 3. Several concepts, particularly submersible designs and large enclosures, are planning for underwater feeding instead of or in addition to the traditional method of distributing feed onto the surface. Currently, most farms use diesel generators to produce the needed electricity. Eighteen percent of the applications plan for an alternative power supply, either by connecting to the land network or the facilities' own power production (wind, wave, biogas, and solar energy). This is outside the scheme of the development licenses and did not affect the authorities' evaluation process.

Conventional fish farms have separate barges for storage of feed and facilities for personnel. For 25% of the applications, traditional barge functions were integrated into the floater, while 10% planned for an innovative barge design. The latter were not awarded licenses, because they were often outside the scheme of the development licenses, while almost half of the awarded projects had traditional barge functions integrated in the floater.

Table 3
Other technological aspects in registered and awarded applications.

	Registered applications	Awarded applications
Feeding technology		
Under water feeding	25	8
Power supply		
Electricity from land network	9	3
Own power production	12	2
Barge		
Integrated in floater/platform	27	11
Innovative barge	10	0

3.3. *Technological measures for enhanced sustainability*

The applications addressed the sustainability issues (parasitic sea lice, escape of farmed fish, disposal of waste and increased utilization of sea areas) differently depending on location. In sheltered locations, collection of waste may be a success criterion. By contrast, open ocean sites require farms that are able to withstand high environmental loads. At all locations, the fish farm technology must provide a healthy environment for the fish.

Categories reflecting technological measures aimed at increased sustainability were established during the content analysis, as shown in Table 4. Most suggested innovations were concerned with the prevention of sea lice infections, and all awarded concepts had measures against sea lice. According to the response letters, 70% of the

Table 4
Sustainability measures based on descriptions provided by the applicants, given per cent for the number of main categories and number of applications for sub-categories.

Sustainability measures	Applications	Awarded applications
Prevent sea lice infection	**92%**	**100%**
Shielding	66	17
Inlet water	37	10
Treatment	26	1
Submersion	22	4
Infection pressure	16	4
Prevent escape	**70%**	**91%**
Stronger enclosures	56	20
Operations	18	6
Structural integrity	17	8
Collect waste	**39%**	**43%**
Promote fish welfare	**60%**	**70%**
Aquatic environment	38	14
Handling	22	4
Surveillance	21	4

applications and 87% of the awarded concepts involved specific measures against escape. Thirty-nine percent of the applications involved collection of waste. This mainly included concepts for sheltered locations, where waste may accumulate and affect the surroundings (Hargrave et al., 1997) due to limited exchange of water. Approximately two of three applications and awarded concepts claimed measures to promote fish welfare. Measures for improved welfare were not requested in the call, but the applicants had to ensure that welfare requirements were met. The sustainability measures in Table 4 are described further in the following sections.

3.3.1. Sea lice

Measures to prevent or treat parasitic sea lice infections were included in most applications (96), and an overview is provided in Fig. 5. The measures have been categorized as follows:

- Shielding: Upper water layers or the entire enclosure volume is separated from surrounding water to reduce or avoid sea lice and larvae in the water.
- Inlet water: Inlet water is filtered and/or pumped from deeper water.
- Treatment: Parasitic sea lice are removed from the fish, most often by applying freshwater.
- Submergence: The fish are submerged to avoid upper water levels known to contain a higher level of sea lice. This can include snorkel nets, in which the net is equipped with a submerged roof and a closed snorkel, giving access to the water surface for air (in addition to the 18 submerged platform concepts, see Section 3.2.1).
- Infection pressure: Choice of location expected to have a reduced sea lice infection pressure (offshore) or the removal of sea lice in the water column via, e.g., electricity or ultrasound.

Fig. 5 shows that more than half of the applications and awarded concepts involved shielding and that many of the applications involved several measures against sea lice. Furthermore, most closed concepts and a few others will add clean water (with no or very few parasites) into the production system. Several concepts suggested treatment of the fish, but only one of these concepts was awarded (iFarm, providing treatment of infected individuals). Most of the concepts with the treatment of sea lice infections as their main focus were not considered significant innovations by the authorities. Some have been assessed to be out of scope, and the associated technology was often considered "existing technology". In addition, freshwater treatment was in general not supported, because sea lice may develop a tolerance for freshwater (Norwegian Veterinary Institute, 2016). Submergence and reduced infection pressure in open oceans were each applied in four awarded concepts. These data thus reflect the measures described by the applicants and mentioned in the letters from the authorities.

3.3.2. Escape of fish

The content analysis showed that 30% of the applications did not present any particular measures against escape. However, 87% of the awarded concepts included extra measures against escape.

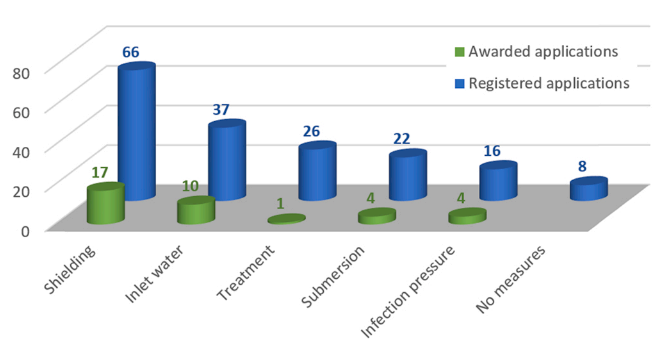

Fig. 5. Measures against sea lice, given as number of concepts including or describing the individual measures.

Three categories of measures against escape have been established:

- Stronger enclosures: This includes enclosures made of stronger materials than the current industry standard, and/or double enclosures.
- Operations: The innovation includes fewer operations or safer operations.
- Structural integrity: The fish farm is considered to have a generally higher structural integrity than conventional farms.

Half of the applications involved the use of stronger enclosures (Table 4), and 20 of 23 awarded concepts involved stronger enclosures (see Section 3.2.3 for details). A few applications involved measures concerning operations and structural integrity, representing a high success rate because eleven awarded applications included one or both such measures.

3.3.3. Fish welfare

- Sixty percent of the applications involved one or several measures to promote fish welfare and health (Table 4). Based on this, we categorized welfare measures into three categories: Aquatic environment: The innovation promotes a beneficial aquatic environment for the fish. This includes adding oxygen, fewer parasites and pathogens, temperature control and shielding against high environmental loads.
- Handling: Gentle and/or less handling of fish.
- Surveillance: Surveillance of aquatic environment and/or fish response.

One in three applications involved innovations that claim to provide a beneficial aquatic environment for the fish, and most of these included closed concepts. A few applications involved measures for the handling and/or surveillance of fish, and the same fraction was found among awarded concepts.

3.3.4. Utilization of sea areas for fish farming

Through the development licenses, the NDF intends to support technology that can expand the areas suitable for marine aquaculture (Norwegian Directorate of Fisheries, 2016). In the content analysis, concepts have been categorized according to the intended localization from a technological point of view:

- *Sheltered* areas represent locations with limited exposure to environmental loads from current and waves, with a maximum expected significant wave height of less than 2 m.
- *Coastal* areas represent locations currently used in aquaculture. Maximum expected significant wave height is 2–4 m.
- *Open ocean* areas are found outside the fjords further out into the ocean. Open ocean locations are more exposed to large waves and have, in this context, been defined through an expected significant wave height above 4 m.

Fig. 6 shows the distribution of intended locations associated with all applications (left) and awarded applications (right). Open-ocean locations were the most frequent in both applications and awards. Although the difference in the number of awarded applications between the different areas was small, 51% of the allowed biomass was associated with open-ocean locations, 33% was associated with coastal areas and only 16% was associated with sheltered areas.

The potential for the increased utilization of sea areas has mainly been assessed by NDF for the awarded concepts, and 20 out of 23 were considered to contribute to the use of previously unsuitable locations (*sheltered* and *open ocean*) or the increased sustainable utilization of existing areas for aquaculture (*coastal*). These included new use of sheltered and open ocean areas, mainly through collection of waste and

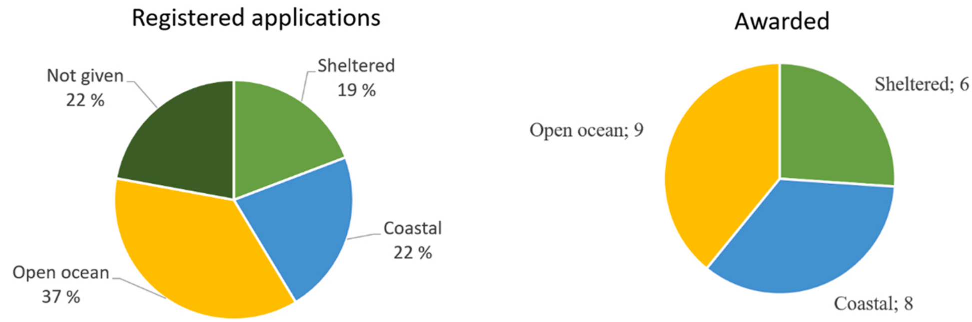

Fig. 6. Area for fish farming (location), given in registered applications as a percent share of total applications (left) and number of applications awarded (right).

strategies to endure large waves, respectively, and increased use of coastal areas through strategies for sea lice prevention and collection of waste. Forty-three applications involved collection of waste, of which ten were awarded.

The nine awarded open-ocean concepts included four semi-sub platforms, five rigid floaters and one PE-ring (three of the nine were submersible), while in sheltered areas, only closed concepts were awarded. Five applications involved closed farms in open ocean, mainly production ships. These were not considered to involve significant innovation by the NDF but, rather, existing technology (see Section 3.4). In coastal areas, concepts with various level of shielding against sea lice (lice skirts, semi-closed and closed concepts) were awarded. For open oceans, awarded concepts included various strategies to avoid excessive loads from waves: Semi-subs have a limited volume in the wave zone, utilizing a strong and slender truss-work structure; rigid floaters applied shielding, wave dampers and heave-compensation; and others will submerge the structures to avoid large wave loads close to the water surface. A variant of the semi-sub, *Havfarm*, will, in addition, be able to move to more sheltered areas and thus avoid large waves.

3.4. Innovation and costs

The NDF first considered whether the application involved significant innovations. If that was not the case, further evaluation of the application has typically not been performed, and the application was declined.

As part of the content analysis, the causes given for “insignificant innovation” in the response letters of concepts that were rejected were identified and categorized. In the response letters, one or several reasons for the refusal was given, and an overview of the categories can be seen in Table 5. Half of the applications did not include sufficient documentation. In other words, the applicant has not provided sufficient evidence that the project can be realized as described (according to the response letters). Regulations (Norwegian Directorate of Fisheries, 2016) stated that the development work must differ significantly from common commercial use today. One-third of the applications were considered to include existing technology or a natural continuation in product development. Twenty-one applications were considered to not represent any improvement to existing fish farms and could even be associated with increased risks. Fourteen were rejected by the NDF because they were “out of scheme”.

Of the 25 applications that were considered to involve significant innovations, 23 were awarded licenses, one is awaiting a final decision, and one was rejected because it was considered to not involve significant investments. If the application was considered a significant innovation, the assessment process proceeded with the estimation of investment costs to determine whether they could be considered significant. Significant investments were thus another criterion because the licenses were intended for large projects that would not be realized without such support. The budgeted investment costs were most often required to be higher than the commercial value of the awarded licenses, while in some cases, investment costs were compared to the total investment costs for Norwegian fish farming companies. The estimated investment costs applied in the evaluation of the awarded concepts varied from 80 million (Atlantis Subsea Farming) to 1900 million NOK ("Havfarm"). Of the 23 awarded projects, twelve had an estimated cost above 400 million NOKs (Fig. 7). Budget estimates of investment costs were provided by the applicants, and in some cases, they were adjusted by the NDF because not all costs were accepted as investments (e.g., operational costs).

Table 5
Cause of rejection due to “insignificant innovation.”.

	Applications
Insufficient documentation	50
Existing technology	35
No improvement	21
Out of scheme	14
Similar to previous concept	8

4. Discussion

Using the oceans to produce food on such a scale as modern aquaculture has provided generally healthy seafood in large quantities to consumers but also caused several negative environmental externalities, such as escapees, as well as an increase in prevalence of parasites, diseases, waste underneath the pens and competition with other users in access to coastal areas. In an attempt to address these challenges with new technology, the Norwegian government introduced a new class of license known as development licenses. The applications for development licenses and the awarded farm concepts represent a unique glimpse into a potential future of marine aquaculture technology, one that can address these environmental challenges and, at the same time, allow for increased production. While the specific solutions are proposed for the production of salmon, the applicability of these concepts to

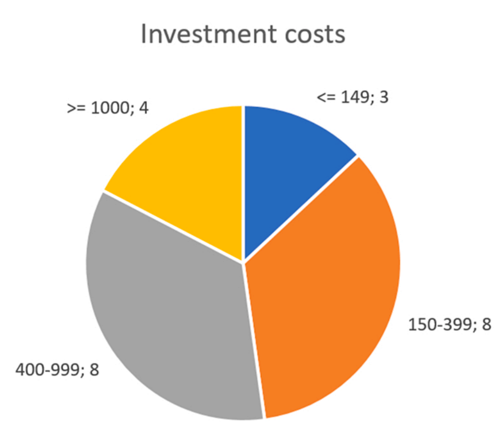

Fig. 7. Estimated investment costs in million NOK for awarded concepts.

other species and other geographical areas outside of Norway is high and may well mark a shift in the development of aquaculture globally.

The systematic analysis of the proposed applications and awarded concepts reveals that some technological solutions are considered more favorable by both applicants and the evaluation panel. However, there are important differences between successful groups of proposals, particularly with regard to the main components of the technology and where farms are to be located. The results show that technologies that were awarded licenses are designed for three main locations: sheltered, coastal and open ocean. Closed farms and PE-rings were the most popular concept among the applications, and represent half of the awarded concepts. PE-rings represent the production concept most widely used today and are in the proposals developed to facilitate production in the open ocean. These applications appear to be an evolution of current technology to suit a new production environment, enabled by stronger materials and enclosure structures, sometimes in combination with cage submersion opportunities. All of the concepts awarded for sheltered coastal areas were closed farms, thus containing what the applicants claim are effective barriers against sea lice, escapees, pathogens and pollution (e.g. feces and feed residues). These closed farm concepts provide a higher degree of control with respect to the production environment (e.g. water quality control) than open cage systems and, as such, represent an innovation toward biological manufacturing, as implied by higher control and production processes more similar to manufacturing plants in other sectors. Concepts designed for open ocean locations are designed to withstand increased loads from waves and currents. More than half of the applications proposing semi-submersible platforms or rigid floaters (and permeable nets) were awarded licenses and, as such, appear to have been regarded as the most innovative concepts by the evaluation panel. Such concepts were awarded 61% of the biomass allocated, indicating the capital intensity and financial risk of such technologies.

More than half of the awarded concepts involve structures larger than conventional PE-rings, and there were a few applications for smaller concepts that can be regarded as prototypes. A few small, closed facilities for sheltered locations were awarded. Also, when considering enclosure volumes, larger production systems were more successful in the award process. Large enclosures represented only 16% of the applications but 38% of the awarded concepts. In contrast, only 19% of the awarded concepts had small enclosure volumes. The main components are moving in two separate directions: More robust open ocean units and closed production units farthest into the fjords. These concepts also require other technological solutions, such as under-water feeding and integrated feed barges. Coupled with the tree main strands of production technology, designed for sheltered, coastal and open ocean locations, regulation of the industry is currently being designed and adapted to the particularities of situating production in different zones of the seascape. While it remains to be seen, this will result in greater variety in the type and cost of production permits, the control and follow-up by authorities as well as the requirements producers must comply with.

Most of the awarded concepts are still under development and testing and will continue to be so for several years. However, based on the extensive material that both applications and awarded concepts represent, we see the contours of a marine aquaculture industry that is more diverse in terms of production technology. Because environmental and economic sustainability is technology dependent, this may expand the marine areas that are suitable for aquaculture relative to what is reported by Gentry et al. (2019). Moreover, and possibly more importantly in a global context, more diverse technologies may also facilitate the production of new species.

What will marine fish farming look like in the future? Even though the development licenses were designed to promote technological innovation for sustainable salmon aquaculture in Norway, these developments may also shape salmon aquaculture production in other regions. Depending on the existence of favorable institutional frameworks and financial means for investments (Gentry et al., 2019), innovations allowing for increased control with production are highly sought after as salmon prices continues to be high, and the industry is scrutinized by stakeholders to improve fish welfare and environmental sustainability. The immediate result of the development licenses in Norway is a strengthened and diversified supplier sector highly skilled in aquaculture related topics, which is keen to offer its knowledge and solutions to a global market.

Judging by the technological designs proposed and awarded, the units will become larger, stronger and specially designed to suit a variety of environments. Increased variety and adaptability in production technologies are likely to move the future of marine aquaculture toward both farming in new areas of the ocean and new species. However, such developments will depend on the economic profitability of these new concepts, together with the demands and limitations imposed by the institutional and regulatory contexts in different regions.

A common feature of the awarded concepts is less integration with the external environment through shielding from parasites, barriers against escapes and collection of waste while improving the welfare of the farmed fish in more controlled internal environments. For the fish farmer, this entails a larger distance between him/herself and the fish and a stronger reliance on technology, such as sensors, to gain an understanding of the fish's welfare and living conditions. For the fish, hopefully, there will be a less stressful life, with less physical handling.

CRediT authorship contribution statement

Heidi Moe Føre: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Trine Thorvaldsen**: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Funding acquisition, Project administration. **Tonje Osmundsen**: Conceptualization, Validation, Investigation, Writing – original draft, Writing – review & editing, Funding acquisition. **Frank Asche**: Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Funding acquisition. **Ragnar Tveterås**: Conceptualization, Investigation, Writing – review & editing, Funding acquisition. **Jan Tore Fagertun**: Investigation, Writing – review & editing. **Hans V. Bjelland**: Conceptualization, Investigation, Writing – review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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