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VALIDATION OF PROJECT PILOTS & SCENARIO DEVELOPMENT FOR FUTURE RAS USE IN THE BALTIC SEA REGION

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Executive Summary

This report integrates global Recirculating Aquaculture System (RAS) experiences with Baltic Sea Region (BSR) regulatory, environmental, and infrastructural realities to inform the validation of RAS pilots and the development of credible future scenarios. Across all examined cases from New Zealand, Norway, Canada and Australia to large-scale U.S. ventures, the analysis demonstrates that RAS can play a pivotal role in the BSR's food system, but only under conditions of disciplined scaling, rigorous biological validation, stable governance, and resilient energy and infrastructure planning.

The Baltic Sea's fragile ecosystem, strict nutrient caps, and limited scope for expanding open-water aquaculture create a structural imperative for land-based production. RAS offers controlled, year-round output with minimal discharge, aligning with the region's environmental requirements while addressing dependency on seafood imports and increasing demand for locally produced, traceable fish. Industrial-energy clusters such as Ida-Viru further position the region to leverage waste heat, renewable energy, and circular-resource integration to enhance RAS competitiveness.

International case studies highlight both enabling conditions and common pitfalls relevant to future RAS deployment in the Baltic Sea Region. New Zealand's NIWA Northland Aquaculture Centre demonstrates the value of long-term research foundations, modular design testing and consistent government support, resulting in reliable commercial-scale performance. In contrast, U.S. mega-projects such as Atlantic Sapphire, Nordic Aquafarms and Pure Salmon reveal the risks of premature scaling, engineering complexity, capital strain, regulatory disputes and insufficient community engagement. Australian experiences reinforce these insights: Huon Aquaculture's Forest Home facility shows how medium-scale, juvenile-stage RAS can stabilise supply with manageable risk, while Project Sea Dragon illustrates how overextended ambition and inadequate governance can undermine large-scale ventures.

These global lessons resonate strongly with conditions in Estonia, where aquaculture remains dominated by freshwater species primarily rainbow trout, and domestic production meets less than half of national consumption. Although Estonia has a stable base of licensed farms and suitable conditions for species such as rainbow trout and Arctic charr, commercial RAS use remains limited. Successful RAS operation in Estonia hinges on efficient water treatment, environmental control, biosecurity and operational skill—factors closely aligned with the challenges observed internationally.

Recent Arctic charr developments in Canada and the wider BSR demonstrate additional opportunities for species diversification. Canada's large-scale Sapphire Springs project shows the potential of Arctic charr in industrial RAS settings, while smaller Quebec farms highlight the viability of urban, niche-focused production. Baltic examples including Latvia's SIA Blue Circle, Finland's Polar Fish and Lithuania's expanding Noras LT facility, confirm the species' suitability for cold-water RAS and growing market potential. Estonia's small-scale Arctic charr trials indicate emerging interest and feasibility, suggesting that the species could form part of future RAS pilot validations and scenario pathways. These lessons align closely with BSR-specific conditions. Regional initiatives, such as Baltic Interreg TETRAS pilots, Estonia's agropark concepts, and emerging industrial symbiosis models, underline growing interest in integrated food–energy–resource systems. However, recent delays in flagship projects also highlight the need for clear governance, coordinated stakeholder leadership, predictable permitting processes, and financing models suited to 10–15-year development horizons.

Drawing from global evidence and BSR structures, three strategic pathways emerge for future RAS development in the region. A phased innovation pathway emphasises pilot-scale systems co-developed with universities and industry to generate robust biological and technical data before expansion. A circular bioeconomy pathway embeds RAS within industrial clusters that utilise waste heat, renewable energy, and nutrient recovery, aligning with Green Deal objectives. A selective specialisation pathway focuses on niche species or high-value juvenile production, enabling countries such as Estonia, Finland and Poland to build competitive strengths without undertaking full grow-out operations prematurely.

Validating future RAS pilots requires stress-testing against realistic regional conditions, including energy price volatility, water access regulations, cold-chain reliability, labour availability, feed supply dependencies, community acceptance, and long-term capital requirements. RAS must be treated as an interconnected system spanning technology, biology, logistics, governance, and finance not merely an engineering installation.

The business-model implications reflect this systemic nature. Market opportunities lie in sustainability, consistency, and traceability, attributes increasingly demanded by EU retailers and consumers. While capital expenditure remains high, revenue resilience improves when ventures combine fish production with training, consulting, data services, and tourism. Successful projects will require patient capital, strong public–private research partnerships, and proactive community engagement.

Overall, RAS holds strategic importance for the Baltic Sea Region's food security, decarbonisation ambitions, and blue-economy growth. The region is well positioned to develop globally competitive RAS systems, provided that development proceeds incrementally, is anchored in biological evidence, leverages energy-secure locations, and is supported by cohesive governance and realistic scenario planning. When these conditions are met, RAS can become a foundational element of the Baltic Sea Region's sustainable and resilient aquaculture future.

1. Introduction

The expansion of Recirculating Aquaculture Systems (RAS) across the Baltic Sea Region (BSR) has become a strategic priority for the European Union as it aims to strengthen food-system resilience, reduce environmental pressures on marine ecosystems, and accelerate the transition toward climate-neutral, resource-efficient and circular aquaculture production. In a region where nutrient loads, biodiversity concerns and spatial constraints limit the growth of traditional marine farming, RAS offers one of the few viable pathways for scaling aquaculture while fully aligning with EU Green Deal, Farm to Fork and Sustainable Blue Economy objectives.

This document provides a comprehensive framework for validating RAS project pilots and developing scenarios for future deployment in the Baltic Sea Region. It integrates global evidence, Baltic-specific data and regulatory insights, and business-model development tools to support policymakers, investors and industry stakeholders in shaping the next phase of RAS growth. The analysis is organised into twelve chapters, each contributing essential components to a holistic understanding of RAS feasibility, risk factors and strategic opportunities.

Chapter 2 examines the current state of fish farming in Estonia, where freshwater aquaculture, particularly rainbow trout dominates national production. Despite steady growth and a well-established base of 45 licensed farms, domestic production meets less than half of consumption, indicating significant room for expansion. The chapter also highlights Estonia's early-stage trials with Arctic charr and the technical, operational and energy-efficiency conditions that determine RAS success in the local context.

Chapters 3 to 6 present international case studies spanning Norway's Havlandet project, New Zealand's NIWA Northland Aquaculture Centre, major U.S. RAS ventures and the contrasting Australian experiences of Huon Aquaculture and Project Sea Dragon. Together, these cases demonstrate the enabling conditions that support successful RAS deployment such as strong research foundations, modular scaling, robust governance and stable capital structures as well as the pitfalls associated with premature scaling, engineering complexity, weak biosecurity, regulatory disputes and governance failures.

Chapter 7 expands the species diversification perspective by analysing Arctic charr RAS projects in Canada and across the BSR. Large-scale initiatives such as Manitoba's Sapphire

Springs project demonstrate industrial-scale potential supported by government backing, while smaller urban RAS farms in Quebec illustrate agile, niche-market viability. Baltic examples including Latvia's SIA Blue Circle, Finland's Polar Fish and Lithuania's Noras LT confirm Arctic charr as a technically suitable and commercially emerging species for cold-water RAS systems. These insights offer valuable direction for Estonia's ongoing small-scale trials and future pilot development.

Chapter 8 focuses on the halted EISAP Auvere Agropark project, providing a detailed analysis of the governance, financing and organisational challenges that led to development delays. This case serves as a practical lesson on the importance of clear leadership, coherent project management structures and well-coordinated stakeholder engagement in large integrated RAS-based industrial concepts.

Chapters 9 and 10 consolidate findings from the LOT B Technical Report and provide a structured assessment of how RAS pilots should be designed, validated and stress-tested in the BSR. The emphasis is placed on energy stability, water access, labour supply, community acceptance, regulatory compliance and the need for long-term capital resilience in order to strengthen the robustness of future RAS scenarios.

Chapters 11 and 12 translate the strategic and technical insights into actionable business development tools. Chapter 11 outlines core criteria for business-model creation based on the TETRAS project findings, while Chapter 12 presents a tailored RAS Business Model Canvas for the BSR, enabling alignment between value propositions, partner networks, revenue structures and regional infrastructure realities.

Taken together, the chapters in this document position RAS not simply as a technological solution but as a strategic infrastructure pillar for the Baltic Sea Region's transition toward sustainable, resilient and innovation-driven aquaculture. By linking global lessons with Baltic-specific opportunities that includes species diversification into Arctic charr and the expansion potential identified in Estonia's State of the Art assessment, this report provides a coherent roadmap for EU-aligned, low-impact and future-ready RAS development across the region.

2. Fish farming in Estonia – State of the Art

Estonian aquaculture is dominated by freshwater fish farming, with rainbow trout (*Oncorhynchus mykiss*) representing the cornerstone of national production. According to the latest data (Table 1), total aquaculture production reached 963 tonnes in 2024, valued at €7.8 million, representing a remarkable 36.8% increase in value compared to 2023 (Kotta et al., 2020; European Commission, 2024). This growth trajectory demonstrates the sector's resilience and adaptation to market demands despite various operational challenges.

Table 1 Market consumption and trade analysis

Product Category	**Domestic Production 2024 (tonnes)**	**Imports 2024 (tonnes)**	**Exports 2024 (tonnes)**	**Domestic Consumption (tonnes)**	**Self-sufficiency Rate (%)**	**Average Price Domestic (€/kg)**	**Average Price Export (€/kg)**
Fresh Fish	963	2100	789	2274	42,3	8,10	6,85
Processed Fish	2850	8500	7200	4150	68,7	12,50	11,20
Smoked Products	1200	450	980	670	179,1	24,80	22,40
Frozen Fish	3200	12500	8900	6800	47,1	4,20	3,95
Fish Roe	21	5	18	8	262,5	285,00	320,00
Canned Products	850	6200	1200	5850	14,50	3,80	3,45
Total	9084	29755	19087	19752			

The market consumption and trade analysis shows, that around half of the consumer demands are fulfilled by domestic production, which shows a potential of increasing the domestic production. Rainbow trout maintains its dominant position (Figure 1), accounting for 86.7% of total production in 2024, with 835 tonnes produced. Fish roe production has emerged as a particularly lucrative specialty segment, reaching a record 21 tonnes in 2024, commanding premium prices of approximately €285 per kilogram in domestic markets.

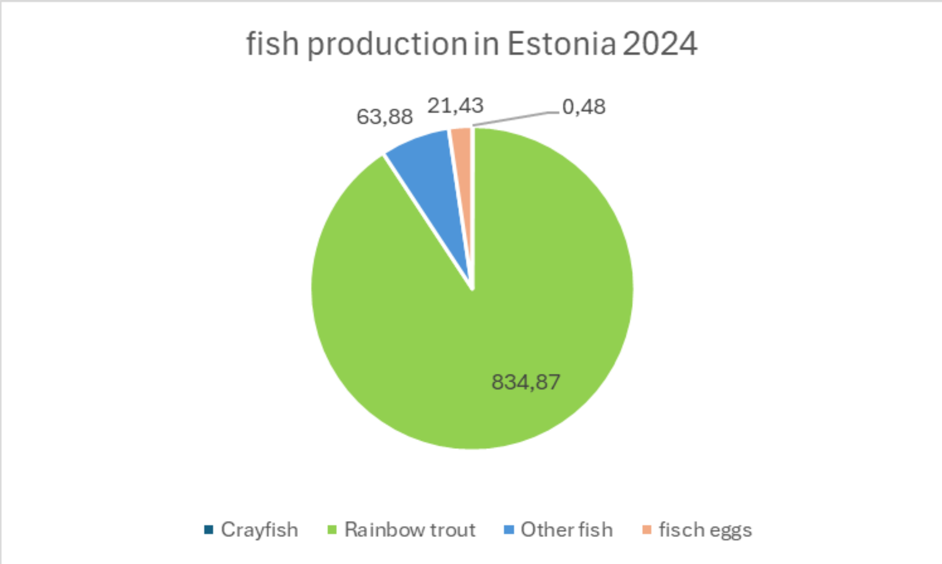

Figure 1: *Share of Fish Production in Estonia in 2024*

Development of the fish production shows a stable development of average 925 tonnes per year (± 10%) (Table 2), with average share of trout by 90% and a stable number of licenced companies (45). This confirms the focus of trout in the fresh fish production, but there is still possibilities for development as the Self-sufficiency Rate in fresh fish is about 42%.

Table 2: *Estonian aquaculture production analysis 2018-2024*

Year	Total Production (tonnes)	Production Value (million eur)	Rainbow Trout (tonnes)	Rainbow Trout Share (%)	Fish Roe (tonnes)	Licensed Companies	Average Price (eur per kg)
2018	832	2,8	720	86,5	8	42	3,37
2019	1062	3,7	927	87,3	12	45	3,48
2020	927	3,2	835	90	15	43	3,45
2021	862	4,1	798	92,6	18	44	4,76
2022	915	5,2	842	92	20	45	5,68
2023	918	5,7	827	90,1	19	45	6,21
2024	963	7,8	835	86,7	21	45	8,1

Other fish are small scall production of arctic charr, carp, catfish, river trout, eel, tench, perch, pike and sturgeon. The industry structure comprises 45 licensed aquaculture companies, ranging from small-scale family operations to larger commercial enterprises T.e potential production capacity of Estonian aquaculture facilities is estimated at over 4,000 tonnes annually, indicating substantial room for expansion under current licensing frameworks.

The fish species most suitable for raising in Recirculating Aquaculture Systems (RAS) in Estonia, based on biological compatibility, stress tolerance, growth rates, and market demand, include Rainbow Trout, Artic Charr and Tilapia.

The recommended fish species for RAS are represented in Estonia as small-scale production. The success factors of a good Recirculating Aquaculture System (RAS) in Estonia include several critical technical, environmental, and operational aspects:

a. *Water treatment and recirculation efficiency:* A core success factor is the effective mechanical and biological filtration that continuously removes solid wastes, ammonia, carbon dioxide, and other toxins while maintaining optimal water quality. Systems with high water recycling ratios (above 90%) greatly reduce water consumption, which is vital in Estonia due to environmental regulations and water resource considerations.
b. *Species-specific tank design:* Tank size, shape, and water flow rate must be tailored to the cultured species' needs. For example, flatfish require shallow tanks with low flow, whereas salmonids need larger volumes and stronger currents. Proper tank design promotes fish welfare, reduces stress, and optimizes growth.
c. *Temperature and pH control:* Temperature regulation is crucial since fish metabolism and microbial biofilter activity depend on it. pH needs continuous buffering as biofiltration generates acids that lower pH. Precise environmental control ensures fish health and biofilter efficiency.
d. *Oxygenation and aeration:* Supplying pure oxygen and maintaining dissolved oxygen at ideal levels prevents hypoxia and supports high stocking densities. Effective aeration systems also remove excess carbon dioxide.
e. *Energy efficiency and sustainability:* Although RAS is resource intensive, optimizing energy use, integrating renewable energy, and minimizing emissions are essential to ensure long-term economic and environmental sustainability in Estonia’s climate and regulatory landscape.
f. *Skilled operation and automation:* Continuous monitoring with sensors, automated feedback systems, and skilled staff are imperative to promptly detect issues, adjust parameters, and maintain stable operations. Proactive management prevents disease outbreaks and system failures.

g. *Fish welfare and biosecurity:* RAS offers improved disease control due to closed environments limiting parasite and pathogen entry, essential for maintaining fish health in Estonia's aquaculture industry.
h. *Economic viability and market integration:* Success also depends on matching scale and production costs to market demand, investing in marketing, and leveraging regional infrastructure for distribution.

3. Norwegian Project Havlandet

Havlandet's RAS pilot in Florø is one of the more instructive Norwegian examples of how a land-based salmon project can move from idea, via piloting, towards industrial scale. The project centres on a relatively small land-based recirculating aquaculture system (RAS) for salmon and later cod, built at Fjord Base in Florø, Norway's westernmost city. It has been used not just as a production unit but as a full-scale testbed for technology, biology, operations and business models in land-based grow-out.

Regulatory and funding milestones show how the pilot evolved from concept to operation. Havlandet Havbruk received permission in 2017 to establish a land-based pilot plant for production of harvest-size salmon on land. In 2018 the dedicated company Havlandet RAS Pilot AS was created, and Innovation Norway granted approximately NOK 15 million under its environmental technology scheme to support a pilot project to test land-based salmon production with RAS technology in Florø._Early communications from regional authorities describe a total cost frame of around NOK 50 million, to be financed by the grant, equity from shareholders and loans from regional banks. Construction at Fjord Base began in late 2019, after roughly two years of planning, with ScaleAQ chosen as RAS supplier. A presentation from Havlandet's management later noted that the pilot represented an investment of about NOK 65 million and was completed towards the end of 2020, suggesting that final capital costs overshot early estimates, as is common in first-of-kind facilities. The plant itself was physically established in 2020 and entered its first production cycle shortly thereafter. For the publicly co-funded "pilot project" as defined by Innovation Norway, a final project report dated 1 December 2021 marks the formal end of that support period. Taken together, these sources indicate a project timeline that runs from regulatory approval in 2017, through financing and detailed planning in 2018–2019, construction in 2019–2020, and a funded pilot phase that effectively concludes in late 2021, even though the facility continues operating as a commercial and R&D site beyond that date.

Technically, the Havlandet RAS pilot is designed as a relatively compact grow-out facility licensed for an annual production of about 200 tonnes of salmon. RAS system was supplied by ScaleAQ and is intended to take fish all the way from post-smolt to harvest weight on land, which differentiates it from many other land-based systems designed only for smolt or post-smolt production. The plant value has been estimated in media reports at between EUR 3.7 million and 6.5 million, while a single 500 m³ tank was valued around EUR 0.2 million. These estimates, together with Norwegian presentations mentioning a NOK 65 million investment, place the specific investment in a range broadly consistent with other small to medium RAS pilot plants. Academic and industry reviews of RAS economics frequently use Havlandet as one of several case examples when comparing capital intensity per tonne and cost structure across different land-based salmon projects.

One of the most useful features of the Havlandet case for other projects is the way the pilot is embedded in a broader regional industrial ecosystem. The facility is located on Fjord Base, a large oil and maritime supply base in Florø, where the owners, INC Gruppen, are major players. The long-term concept couples large-scale land-based salmon production with a planned hydrogen plant, where hydrogen is produced primarily for the maritime sector, while oxygen and waste heat are delivered to the fish farm. The concept also foresees close integration with a local slaughterhouse, using pipelines rather than road transport for fish, and collaboration with a nearby feed producer and laboratory for feed and quality analyses. This demonstrates how a RAS pilot can be designed not only as an isolated fish farm but as a node in a circular, multi-industry system that leverages industrial waste streams, logistics and infrastructure, which is highly relevant for other land-based initiatives trying to anchor themselves in regional clusters.

Biologically and operationally, the pilot has provided a controlled test environment for salmon grow-out. Havlandet entered salmon with long experience from land-based production of cod, ballan wrasse and other species, which gave it a head start on husbandry and water quality management. One of the clearest performance snapshots comes from a presentation at the GATH conference, where Havlandet reported that salmon placed in the pilot plant reached an average weight of about 330 grams in 2021 and were sold in October of the same year at around 4.2 kilograms after eight months of production, with mortality around 3.5 percent. is a biologically strong performance for a new RAS grow-out facility and suggests that the combination of water quality control, feed strategy and environmental management met key biological benchmarks. The company and its research partners have emphasised that the pilot allowed them to reduce the grow-out time from around four years in earlier cod programmes to roughly 18 months to harvest for land-based salmon, indicating learning effects across species and systems.

A distinctive aspect of the Havlandet pilot, and one that has been documented in both trade press and manufacturer case studies, is the deliberate use of LED lighting as a management tool in RAS. Philips/Signify and related brands have installed specialised aquaculture LED systems tailored to tank depth, water clarity and salmon biology in the pilot facility. Reports from these collaborations state that carefully tuned light spectra and photoperiod regimes reduced unwanted sexual maturation and improved fish welfare, while supporting higher growth rates and reducing reliance on parasite treatments compared with conventional systems. For other RAS projects, Havlandet's experience highlights that lighting is not just an add-on but a core part of the production system design in closed, land-based environments, influencing biological performance, behaviour and ultimately cost per kilo.

Not all experiences have been positive, and this is precisely what makes the pilot so instructive. In December 2020, a 500 m³ tank at the facility failed and emptied, just days before fish were scheduled to be stocked, though no people were injured and there was no major pollution. Media reports at the time noted that the tank failure affected a pilot plant valued at several million euros and forced a reevaluation of technical risk, supplier follow-up and contingency planning. Later, in December 2022, Havlandet suffered a serious hydrogen sulphide incident at the same RAS site, this time in cod production, leading to mortality of about 32,000 cod with an average weight of 1.5 kilograms. These setbacks underline that even experienced land-based operators can face sudden technical-biological interactions in RAS, and they reinforce the need for robust H_2S monitoring, emergency degassing, redundancy in aeration and water treatment, and clear operational protocols. For other projects, the key lesson is that pilot plants must be treated as genuine experimental environments, with systems in place to learn quickly from failures and feed that learning into design revisions and standard operating procedures.

The pilot has also been a platform for broader research collaboration, particularly around cod and feed innovation. Havlandet RAS Pilot is frequently listed as an industrial partner or site in Norwegian research projects, including work on new feed ingredients for cod where the facility is used for trials on shellfish meal and other alternative protein sources. This reinforces the idea that a RAS pilot can double as both commercial unit and experimental facility, which in turn can attract public R&D funding and academic partners. For other project developers, positioning a pilot as a shared research infrastructure rather than a purely private production unit can help diversify income streams and increase knowledge output.

On the economic side, publicly available financial and corporate data paint a picture common to many pioneering RAS projects: multiple years of negative results before any sign of profitability. Havlandet RAS Pilot AS was incorporated in 2017, with only a handful of employees. Revenue data cited in Swedish planning documents show that the company had a turnover of about NOK 17.0 million in 2021 and NOK 19.3 million in 2022, while recording losses before tax of roughly NOK 10.2 million and NOK 8.4 million respectively. Proff.no data suggest that by 2024 the company reported operating revenues of about NOK 1.9 million with a positive result before tax and an EBITDA of around NOK 1.4 million, indicating at least a temporary shift towards positive operating margins in that year, though longer-term performance remains to be seen. Media summaries have noted that the company recorded negative results for six and then seven consecutive years, emphasising how long it can take for a land-based pilot to reach economic stability. For other projects, the implication is clear: even with strong technical performance and public support, capital-intensive RAS pilots can require many years of losses before the technology, operations and market are sufficiently optimised to generate acceptable returns.

Strategically, Havlandet has always presented the pilot as a stepping stone towards large-scale production. Early communications from INC Invest spoke of a EUR 4 million pilot followed by a much larger grow-out facility with an investment requirement of about EUR 87.4 million on the island of Florø. Later, lighting and technology suppliers described the pilot as a 200-tonnes-per-year plant that would inform a planned land-based facility targeting 20,000–25,000 tonnes of salmon annually from around 2026. Regional strategy documents also point to a broader Havlandet plan to establish land-based production not only of salmon but of cod and other species, including broodstock, fry and cleaner fish, positioning Florø as a diversified aquaculture cluster. For other developers, this highlights the role of a pilot plant as a proof-of-concept for investors and regulators: it is less about scale efficiency and more about showing that biology, technology, energy integration and logistics can work together in a specific location before hundreds of millions are committed.

When all of this is synthesised, the Havlandet RAS pilot can be seen as a compact but information-rich case of land-based salmon development. Formally, the Innovation Norway–supported pilot project runs roughly from 2018 to late 2021, with construction starting in 2019, completion in late 2020 and first harvests in 2021. It involves an investment on the order of NOK 50–65 million for a 200-tonnes-per-year facility whose main purpose is to generate operational and biological knowledge to de-risk a much larger planned expansion. Biologically, the pilot has demonstrated that harvest-size salmon can be produced on land with competitive growth rates and low mortality using RAS, advanced environmental control and optimised lighting, while also revealing the severity of risks such as tank failures and hydrogen sulphide events. Economically, it illustrates that even a technically successful RAS pilot is likely to operate at a loss for several years and must therefore be embedded in a financing structure that combines grants, bank loans, equity and, ideally, research income, Havlandet uses the pilot as a platform for scaling plans, regional industrial integration and species diversification, connecting salmon and cod grow-out with hydrogen production, feed, slaughtering and laboratory services in a circular system.

For other land-based RAS projects, the main lessons from Havlandet's pilot are that a clearly bounded pilot period with defined funding and reporting can accelerate learning; that technical and biological risks are real and must be actively managed through design and monitoring rather than assumed away; that integration with local industry, energy systems and logistics can strengthen the overall business model; and that patience and robust capitalisation are required because the road from pilot to profitable full-scale operation is typically longer and more volatile than original business plans suggest.

4. New Zealand Project NIWA Northland Aquaculture Centre

The NIWA Northland Aquaculture Centre (NAC) at Ruakākā is one of the most instructive examples globally of how a research hatchery can be turned into a fully-fledged, land-based recirculating aquaculture system (RAS) for high-value marine finfish. For other projects, it is useful to see it not just as a farm, but as a long, staged innovation programme combining basic biology, engineering development, regional economic policy and market testing. The site itself has been active since 2002, when NIWA established what was then commonly referred to as the Northland Marine Research Centre to investigate the aquaculture potential of high-value species such as yellowtail kingfish and hāpuku.

Over roughly two decades the team refined broodstock management, larval rearing and grow-out protocols under controlled conditions, building a substantial body of knowledge and a large broodstock base. A recent poster summarising the project notes that NAC's research on fish life cycles dates from 2002, and that by 2024 NIWA could look back on 22 years of work on yellowtail kingfish biology and production at the site.

The RAS pilot is framed as a commercial-scale prototype farm for yellowtail kingfish. In March 2020 the New Zealand Government's Provincial Growth Fund (PGF) announced a NZD 6 million loan to NIWA to build and operate a 600-tonne-per-year RAS unit at Ruakākā, explicitly described as a pilot to test the technical and economic feasibility of land-based kingfish farming. Total project cost was put at NZD 19.8 million, with NIWA contributing NZD 7.84 million, Northland Regional Council up to NZD 6 million in buildings and infrastructure, and the PGF providing the NZD 6 million loan. A later technical poster rounds this to a total investment of about NZD 20 million and stresses that the government loan is intended as "further (and final) government investment for this stage", with any expansion to 3,000 tonnes expected to be privately financed. Construction of the farm infrastructure is reported as starting in 2021 and being completed in 2022, with the first commercial harvest occurring in 2024. The commercial-scale RAS facility itself was officially opened on 13 August 2024 by the local MP, marking the formal transition from project build to operational phase. There is no published "finish date" in the sense of a project ending; the capital project phase is complete, but the farm is intended as an ongoing commercial and research platform.

The physical configuration of the Northland Aquaculture Centre is an important part of its replicable design. The site covers about 35,000 m² (3.5 hectares) within a larger NIWA freehold block of roughly 8 hectares, with ready access to the open coast at Bream Bay. High-quality seawater is delivered via pipelines originally built to cool a former power station, a classic example of industrial reuse that significantly reduces intake capital costs for the aquaculture project and is explicitly highlighted in technical summaries as a key site advantage. Inside the farm building, the commercial RAS grow-out is based on eight circular tanks of about 350 m³ each, arranged in two rows within a tunnel-like superstructure. These tanks are fed by a sophisticated RAS treatment train that allows between 95 and 99 per cent of the water to be cleaned and recycled, with only a small fraction discharged after treatment back to the ocean.

Upstream of the grow-out farm, NAC operates a large hatchery and nursery which is central to de-risking supply for both the pilot and potential future farms. NIWA reports that the hatchery at NAC can consistently produce around 500,000 kingfish fingerlings per year, scalable to one million, from multiple broodstocks staggered to provide eggs year-round. These juveniles transition through nursery systems before being stocked into the RAS grow-out tanks, where they are raised from a 1 mm egg to a 3 kg market fish in less than 12 months under tightly controlled conditions. The integrated design—broodstock, hatchery, nursery and farm on one site—gives strong biosecurity control and allows continuous feedback between research and production.

The production target for the current pilot module is 600 tonnes of yellowtail kingfish per year. Government and NIWA documents consistently frame this as a demonstrator for a subsequent 3,000-tonne full-scale operation, with modelling suggesting farm-gate revenue on the order of NZD 45 million per year at the 3,000-tonne scale and the creation of around 75 full-time jobs in the region. Initially the RAS pilot was expected to generate about 18 jobs in Northland, with downstream benefits to processing, logistics and services. The farm supplies premium domestic food-service customers and, according to a 2024 technical poster, also exported product in its first harvest year, signalling the move from purely domestic niche markets to participation in global high-end seafood chains.

From a technology and sustainability standpoint, the project is explicitly positioned as a climate-resilient alternative to sea-cage farming. NIWA and Northland Regional Council chose land-based RAS partly to avoid risks from marine heatwaves, storms, and disease interactions with wild fish, and government assessments of the project emphasise that RAS production can have a significantly lower carbon footprint per kilogram of protein than some terrestrial livestock systems. The system uses intensive water treatment and recirculation, with flow rates on the order of 300 litres per second and a footprint “about half a football field” for the 600-tonne farm, according to a New Zealand Geographic feature, which contrasts this favourably with the thousands of hectares required to produce equivalent protein from lamb. Backup power systems and redundancy are built into the design, and accounts of operations during events such as Cyclone Gabrielle describe automatic switching to diesel generation to maintain oxygenation and pumping, underscoring the engineering focus on risk management.

Economically and institutionally, the Northland project is a good example of blended finance and staged risk reduction. The capital structure spreads risk across NIWA, a regional council landlord-partner, and central government via a loan, with the expectation that once the 600-tonne module proves its performance, private investors and lenders will fund subsequent expansion. The project is framed as contributing to New Zealand's national aquaculture strategy, which aims for NZD 3 billion in annual aquaculture sales by 2035, and specifically as a pathfinder for land-based finfish farming that coastal iwi and private investors could adopt on suitable sites around the country. For other projects, this shows how aligning a pilot facility with national strategy and regional development goals can unlock concessional finance and political support, while still keeping an eye on eventual commercial independence.

Scientifically, NAC functions as a hybrid between a commercial farm and a research campus, and this dual identity has produced a substantial academic literature. Experiments on kingfish physiology, ocean acidification, and temperature tolerance have been conducted using NAC broodstock and systems, including controlled-environment studies of elevated CO_2 impacts on growth and condition, and work on how climate-change-like conditions affect fish hearing and behaviour. Theses and articles on snapper and hāpuku reproduction, growth and reproductive endocrinology also list the Northland Marine Research Centre as their experimental site, demonstrating that the facility's tanks and life-support systems are suitable for a wide range of species beyond kingfish. The 2024 poster on the RAS prototype goes further, presenting a coherent roadmap for future research: ongoing genetic improvement of kingfish through selective breeding, development of RAS-specific feeds with lower carbon footprints, and circular economy approaches to waste capture and reuse. For other projects this integration of active, publication-driven science with commercial operations is a key lesson, because it allows the facility to continuously refine husbandry, welfare and efficiency while generating peer-reviewed evidence that can de-risk investment elsewhere.

Day-to-day, the farm operation is organised around very tight control of environmental parameters and welfare, which again is well documented in both popular and technical accounts. The RAS design allows stable temperature and oxygen regimes, and the circular tanks match the natural schooling behaviour of kingfish, which are fed frequently with formulated feeds sourced from certified suppliers such as BioMar in Tasmania. Feed development, including trials to reduce fish-meal content and improve feed conversion ratios, is an ongoing research frontier. Wastewater is stripped of solids, passed through biofilters where microbial communities convert ammonia to nitrate, and then re-oxygenated and reused, with only a small bleed-off volume discharged after treatment. The emphasis on animal welfare, product quality and post-harvest handling is strong: maintaining sashimi-grade flesh quality for premium restaurant markets has driven refinement of harvest, stunning and chilling protocols, something NIWA emphasised even in pre-pilot market-testing phases when it was sending only a few hundred kilograms per week to select restaurants.

Several overarching lessons emerge from the Northland Aquaculture Centre experience. First, the project underscores the value of a long research runway before scaling, particularly for new species. NAC's 20-plus years of biology and production work on kingfish meant that by the time the 600-tonne pilot was funded, uncertainty around broodstock, larval survival and grow-out performance was relatively low; the pilot's focus could shift to engineering scale-up, economics and markets rather than basic life-cycle feasibility. Second, the project highlights the importance of site selection and infrastructure reuse: building on an existing NIWA coastal site with established seawater intake and discharge pipelines dramatically reduced permitting and civil-works risk, something many emerging projects underestimate. Third, the way funding, governance and national strategy are linked at Northland shows an effective pattern: a publicly funded research agency anchors the project; a regional authority co-invests in buildings; central government provides a time-limited development loan; and the whole endeavour is explicitly tied to broader aquaculture-growth and regional-development objectives, making later private-sector participation more plausible.

In a nut shell, the Northland project demonstrates that a RAS pilot can be designed as a modular, exportable concept rather than a one-off. NIWA and its partners describe the 600-tonne module as the first in a series that could be replicated at NAC and other sites, using hatchery fingerlings, refined feed regimes, and a proven combination of tank sizes and treatment systems. Because the farm is embedded in an active research environment, it can also generate data on energy use, feed conversion, welfare and product quality that directly inform the design of second-generation facilities. In that sense, the "project" is ongoing: the capital build phase from 2021 to 2022 and the first harvest in 2024 are milestones in a longer process of creating a template for climate-resilient, land-based, high-value finfish aquaculture that others can adapt to their own contexts.

5. RAS Projects in the USA

Major USA RAS projects include among others the “Atlantic Sapphire's facility in Florida”, “Nordic Aquafarms' projects in Maine and California”, and “Pure Salmon's facility in Virginia”. These large-scale salmon farms are a response to growing demand for US-raised seafood and challenges in traditional salmon farming.

5.1. Atlantic Sapphire’s Bluehouse, Florida

Atlantic Sapphire’s land-based salmon project in Homestead, Florida is by far the most advanced, largest, and most publicly scrutinised RAS development in the United States. The company first established itself through RAS trials in Denmark in the early 2010s, later choosing South Florida as the site for an industrial-scale commercial build-out. Planning activity began around 2013, with construction commencing in 2017. The first fish were stocked in 2018, and the initial commercial harvest occurred in late 2020. This multi-year timeline illustrates the long development arc required for pioneering RAS projects, particularly at large scale and in new climatic and regulatory environments.

The “Bluehouse,” as Atlantic Sapphire brands its facility, was envisioned as a multi-phase development ultimately capable of producing tens of thousands of tonnes of Atlantic salmon annually. Phase 1 was designed for roughly 9,500 to 10,000 tonnes head-on gutted output, while Phase 2 was planned to increase capacity toward 25,000 tonnes. The company has at different times communicated even higher long-term ambitions, although financial realities have tempered these projections. Capital expenditures for Phase 1 alone reached several hundred million dollars, and combined investments for the ongoing development have exceeded half a billion dollars. This makes the Bluehouse one of the most capital-intensive aquaculture projects ever attempted on land.

A major strategic choice was the site’s geology, which allows access to both fresh and saline water from different aquifers. Water can be withdrawn and treated before being injected back into deep wells, thereby reducing surface discharge and some associated environmental hurdles. The facility also features massive reinforced-concrete grow-out tanks, advanced filtration systems, oxygenation, energy-intensive chillers, and high levels of automation. These engineering decisions were intended to create the conditions for stable, controlled-environment salmon farming in a subtropical climate vastly different from the species’ native range.

Operationally, Atlantic Sapphire has demonstrated both the promise and fragility of large-scale RAS. On the one hand, the company has succeeded in bringing domestically raised, antibiotic-free salmon to the U.S. market, supplying major retailers and earning internationally recognised certifications. It has shown that land-based systems can deliver premium-quality fish with predictable logistics and without the environmental risks associated with open-net pens, such as sea lice or escape interactions with wild stocks. On the other hand, the company has experienced significant setbacks, including fish mortality events, water-quality disturbances, and mechanical failures. These incidents have repeatedly disrupted production plans, reduced biomass, and required costly corrective measures.

Financially, Atlantic Sapphire has faced ongoing capital needs as it navigates both technical refinement and scale-up challenges. Periodic losses and liquidity pressures have shaped the company's trajectory, with equity raises, debt restructuring, and attempts to access public financing tools all featuring prominently in its recent history. Investors and analysts now view the Bluehouse as a real-world test of RAS economics at industrial scale.

The Florida example highlights several key lessons. First, scaling RAS technology from a few hundred tonnes to many thousands introduces new biological, engineering, and operational risks. Problems do not simply become larger; they become fundamentally different in their dynamics and consequences. Second, extremely large RAS farms require stable long-term financing, patient investors, and realistic performance expectations. Third, no matter how advanced the engineering, unforeseen biological and mechanical failures must be anticipated as part of the operational reality, not exceptions to it. Finally, the extended timeline from planning to operational maturity emphasises the importance of transparent community engagement and robust capital planning.

5.2. Nordic Aquafarms in Maine and California

Nordic Aquafarms' U.S. efforts represent a different but equally instructive pathway for RAS development, one defined less by technical challenge and more by regulatory, legal, social, and political friction. The company first announced plans to build a large salmon RAS facility in Belfast, Maine in 2018. The vision was ambitious: a multi-phase, approximately 33,000-tonne-per-year salmon farm covering more than 50 acres. The proposed design included hatchery, smolt, grow-out, processing, and wastewater treatment infrastructure, with capital investment expectations near half a billion dollars.

The project initially made steady progress. Nordic secured key state environmental approvals, and local officials viewed the proposal as a long-term economic anchor. The facility was projected to provide significant employment, expand the tax base, and stimulate supporting services in the region. Technical documentation submitted to regulators described a sophisticated RAS employing extensive recirculation, advanced filtration, and precisely modelled discharge treatment. Based on this, the project seemed poised for success.

The true bottleneck, however, was neither technology nor environmental compliance but property rights related to a narrow strip of intertidal land needed for seawater intake and discharge pipelines. Competing claims from local landowners led to prolonged litigation, community conflict, and ultimately the unravelling of the entire project. After years of courtroom battles and multiple appeals, a ruling went against Nordic's ownership claim. Local government efforts to use eminent domain to secure the land were also withdrawn under public pressure. By early 2025, after seven years of planning, Nordic Aquafarms formally abandoned the Belfast project, having spent substantial sums without ever commencing major construction.

The Maine setback became a case study in the importance of early, definitive site control. No amount of environmental modelling, engineering design, community outreach, or regulatory compliance could overcome the absence of a clear legal pathway to essential coastal infrastructure. RAS developers elsewhere can draw a clear conclusion: legal due diligence on land access must be complete and uncontested before major expenditures begin.

Meanwhile, Nordic Aquafarms also pursued a West Coast project on the Samoa Peninsula in Humboldt County, California. Initially envisioned as another large salmon RAS similar to Maine, the project later shifted toward producing yellowtail kingfish and scaled down to around 10,000 tonnes per year. The Samoa site seemed more favourable because it was located within a former industrial zone where public agencies were already redeveloping the area for marine research and aquaculture. Nordic secured several key permits, and the project benefitted from state and federal investments in shared intake and discharge infrastructure.

However, despite regulatory progress, the California project has in recent years experienced significant delays, limited visible progress, and signs of corporate retrenchment. While not formally cancelled, the project appears stalled, with local entities reporting little recent engagement from Nordic and no forward movement on construction. The combination of rising construction costs, shifting corporate priorities, and financial pressure after the Maine failure has left the project in a state of uncertainty.

Together, Nordic's Maine and California experiences demonstrate how large-scale RAS investment hinges on more than technical capability. Social licence, political stability, property rights, and investor confidence, all external to the biology and engineering of RAS, can determine success or failure. For other projects, these cases emphasise the need for meaningful, early, and continuous engagement with affected communities, ironclad site- and water-rights verification, and realistic assessments of local political dynamics before committing to large capital investments.

5.3. Pure Salmon Virginia (Project Jonah)

Pure Salmon's Virginia project, often referred to as Project Jonah, offers a third type of RAS development narrative, one characterized by long gestation, repeated delays, and adaptation under changing economic conditions rather than outright failure. Planning began in the early 2010s when regional officials sought new industries to replace declining coal-related employment in Southwest Virginia. The vision was to build a fully integrated land-based salmon RAS capable of producing around 20,000 tonnes per year, with hatchery, grow-out, and processing facilities included on-site.

In 2019, Pure Salmon announced a funding package that included state and regional support commitments. Reported total investment requirements ranged from around 200 to 300 million dollars, depending on the phase and equipment configuration. The project promised to create hundreds of jobs, making it one of the largest single industrial investments in the region in decades. Local and state authorities made infrastructure commitments, including improvements to roads, utilities, inspections, and environmental safeguards, signalling strong institutional support.

Despite this promising setup, progress slowed considerably. Site development proceeded more slowly than expected, and global economic shifts—including construction cost inflation, supply-chain disruptions, and rising interest rates—put pressure on the feasibility of the original salmon-focused concept. By 2024, more than a decade after initial discussions, the project had not yet transitioned into active construction of its main production modules. Local media referred to the initiative as "long awaited," reflecting a growing scepticism among community members who had anticipated earlier job creation and operational activity.

In 2025, the company announced a strategic pivot away from Atlantic salmon toward steelhead or rainbow trout, citing cost pressures and the need for a species better suited to the prevailing economic and technical conditions. Trout have lower oxygen, temperature, and water-quality demands compared to salmon, potentially reducing system energy loads and capital intensity. They also face fewer marketing barriers in the U.S., which may improve commercial viability. This shift demonstrates adaptability, but it also reflects the project's exposure to macroeconomic volatility and the difficulty of committing to a fixed design in a long and uncertain construction cycle.

The Virginia case is therefore most instructive in illustrating how RAS projects must remain flexible over long timeframes. Although the facility retains strong institutional support and remains in development, it now looks different from what was originally proposed. The lesson for other ventures is clear: large RAS projects must incorporate strategic flexibility at the design stage to allow for species changes, phasing adjustments, and cost-management strategies as economic conditions evolve. Long timelines demand this adaptability, as conditions at the point of concept often differ dramatically from those at the point of construction.

5.4. Synthesis and Cross-Project Insights

When considered together, the three projects represent three distinct stress tests of RAS development in the United States. Atlantic Sapphire shows what happens when a technologically advanced project pushes the limits of scale. Its journey reveals the biological and engineering challenges that arise only at very high production volumes, as well as the financial demands of sustaining a multi-year learning curve. Nordic Aquafarms illustrates how even well-designed systems can fail if regulatory and social licence foundations are not secure. The Maine case, in particular, demonstrates the decisive power of local politics, litigation, and contested land access. Pure Salmon Virginia demonstrates the vulnerability of long-duration projects to shifting economic conditions and the need to retain flexibility in species selection, infrastructure phasing, and financing structure.

Across all three projects, certain themes emerge. Large RAS facilities require exceptionally robust financing frameworks capable of absorbing delays, setbacks, and redesigns. Community engagement must begin early, with particular attention to land access, water rights, and local perceptions of industrialisation. Technical design must incorporate redundancy, emergency response capability, and energy-efficient systems. And critically, developers must expect timelines measured in many years, not months, with multiple points where political, financial, or biological factors may require strategic recalibration.

5.5. Comparative Note on the Three Projects

Looking at the three projects in the USA, there clear distinction in both similarities and differences shown in Table 3. This became visible after placing key information side-by-side, to reveal patterns that may not be immediately visible in narrative form, such as how regulatory challenges differ from technical ones, why some projects advance while others stall, and how financial and operational risks evolve across regions and species.

Table 3: *Comparative Table of the U.S.A RAS Projects*

Category	Atlantic Sapphire – Florida	Nordic Aquafarms – Maine & California	Pure Salmon – Virginia
Project Type	Large-scale Atlantic salmon RAS ("Bluehouse")	Two large RAS projects: salmon (Maine) and kingfish/salmon hybrid concept (California)	Large-scale RAS initially for salmon, later shifted to trout
Location	Homestead, South Florida	Belfast, Maine & Samoa Peninsula, California	Southwest Virginia (Tazewell region)
Start of Development	Denmark trials ~2010; US site work from 2013; construction from 2017	Maine announced 2018; California announced ~2019	Conceptual planning ~2013; announced publicly in 2019
First Stocking / Operations	First fish stocked 2018; first harvest 2020	Neither site reached operational farming; Maine cancelled; California stalled	No full operations yet; facility still pre-construction
Current Status (2025)	Operating but below design capacity; ongoing Phase 2 expansion with technical and financial challenges	Maine officially abandoned (2025); California stalled with no active construction	Project continues with redesign; pivot to rainbow trout announced
Planned Capacity	Phase 1 ~9,500–10,000 tonnes; Phase 2 ~25,000 tonnes; aspirational long-term 90,000+ tonnes	Maine: 33,000 tonnes; California initially ~33,000 then reduced to ~10,000 tonnes	Planned ~20,000 tonnes; final capacity may change due to species shift
Capital Cost (Estimate)	Phase 1 $300–400M; total investment to date >$600M	Maine ~ $500M full build; California initially similar (later reduced)	$200–300M depending on phase and redesign
Key Strengths	First industrial-scale commercial salmon RAS in the U.S.; strong market access; advanced engineering; ASC certification achieved	Strong engineering proposals; well-developed permit dossiers; access to coastal intake/discharge; supportive local agencies (California earlier on)	Strong regional support; large available land base; potential to revitalise coal region economy; flexible design
Major Challenges	Multiple mortality events; high operational costs; scale-up complexity; ongoing need for capital; energy intensity	Severe permitting and legal disputes in Maine; land access failure; community opposition; California affected by slow progress and financial strain	Long project delays; cost inflation; species pivot; investor caution due to decade-long gestation
Reason for Delays/Failure	Technical failures at scale; biological instability; energy and cost pressures	Maine: legal loss over intertidal access; California: unclear financing and corporate strain	Inflation; shifting market conditions; long permitting and development arc
Primary Lessons for Other RAS Projects	Scaling RAS introduces entirely new risk modes; plan for a decade-long ramp-up; ensure redundancy in all systems; secure large capital buffers	Secure site rights early; underestimate social licence risk at your peril; legal clarity is essential; engage deeply with local communities	Build flexibility into species choice and design; avoid overpromising timelines; ensure funding matches long development horizons
Overall Outcome	Operational but unstable; a global test case for whether mega-RAS salmon farming can succeed	Maine a complete shutdown; California drifting but not officially closed	Still alive, but evolving; now pursuing a more modest and biologically easier species (trout)

6. The Huon Aquaculture Forest Home Atlantic salmon facility and Project Sea Dragon, Australia

The Huon Aquaculture Forest Home Atlantic salmon facility and the large-scale land-based prawn development known as Project Sea Dragon represent two of Australia's most significant and ambitious RAS-based aquaculture projects.

Taken as a pair, these two projects provide valuable insights for successful RAS projects. Successful RAS development depends on scale-appropriate design, strong biological validation, realistic staging, solid governance and careful alignment of finance, science and infrastructure. Projects that match these conditions can thrive. Those that outpace their own risk-management capacity, however well-intentioned, may falter long before reaching their intended production targets.

6.1. Huon Aquaculture's Forest Home Atlantic Salmon Facility (Tasmania)

Huon Aquaculture's Forest Home Hatchery, located in the Huon Valley of Tasmania, is one of Australia's most prominent examples of a land-based recirculating aquaculture system used to support a major salmon-farming industry. Although it is primarily a freshwater RAS hatchery rather than a full grow-out land-based farm, it demonstrates many of the design, environmental and operational principles that other aquaculture projects can draw from when planning to expand the land-based portions of production.

The origins of Forest Home lie in Huon's strategic decision during the early 2010s to increase the size and robustness of smolt before transfer to marine cages. This "controlled growth" approach aimed to reduce time at sea, improve survival rates, and smooth the supply of fish to downstream processing facilities. Construction of the Forest Home facility began in 2014, water flowed through the systems in 2015, and the first smolt entered the ocean phase in 2016. The facility was formally opened shortly thereafter, representing the culmination of capital works and the beginning of its operational integration into Huon's production cycle. The total capital cost was approximately AUD 35 million, reflecting the company's commitment to highly controlled hatchery technology.

Forest Home is a sophisticated multipurpose RAS facility that houses egg incubation, fry systems and smolt production under one roof. The hatchery is divided into several independently operated systems to enhance biosecurity and support multiple cohorts of fish simultaneously. Incoming water is sourced from the nearby Huon River and on-site bores and is then subjected to advanced filtration, ozone treatment and ultraviolet disinfection before entering the recirculating loops. These loops enable extremely precise control of temperature, dissolved oxygen, ammonia, pH and other parameters that influence the quality of smolt.

The facility is designed to produce more than two million smolt annually, alongside several million-fry destined for Huon's separate land-based nursery. At full capacity, the hatchery produces around 580 tonnes of juvenile biomass each year, which later translates into an estimated 17,000 tonnes of harvest-weight salmon from sea cages. Water recirculation rates at Forest Home are extremely high, generally around 95 percent and in some systems approaching 99 percent. Wastewater is treated and used for agricultural irrigation on neighbouring farmland, reducing both environmental impact and operating cost.

Forest Home is managed by a relatively small but specialised workforce that provides 24-hour coverage through rotating shifts. The facility includes automated feeding, water-quality monitoring, alarm systems and backup power generation to ensure stability. This combination of automation and skilled staffing creates a highly reliable production environment that ensures consistency in smolt size and quality.

The strategic benefit of Forest Home lies in its ability to shorten the marine phase of production, thereby reducing fish exposure to the environmental risks associated with offshore grow-out in Tasmania, such as episodic warming events and storm systems. Producing larger and more uniform smolt also improves feed efficiency, reduces overall mortality in sea cages and supports year-round planning for marine operations. The success of Forest Home later influenced Huon's decision to invest in expanded RAS infrastructure elsewhere, reinforcing the idea that robust on-land juvenile production is a stabilising anchor for larger aquaculture companies.

Scientific findings from Australian research institutions have further validated the biological soundness of Forest Home's approach. Studies on smoltification, osmoregulation and seawater performance under controlled RAS conditions show that properly managed recirculating systems can produce smolt that adapt to seawater as effectively as, or better than, those reared in traditional flow-through systems. These findings underscore the biological feasibility of shifting more early-life production on land.

Forest Home offers several instructive lessons. First, targeted RAS investment at the smolt stage may offer a more manageable, lower-risk entry point into land-based aquaculture compared to full grow-out systems. Second, success depends on the degree to which the hatchery is integrated with the rest of the production chain; Forest Home works because it is part of a larger, established industry. Third, environmental and community benefits—such as high-water reuse, controlled waste management and reduced impacts on local rivers—can strengthen a project's public and regulatory acceptance. The facility demonstrates that RAS does not need to replace marine farming outright; instead, it can reduce marine risk and enhance overall productivity.

6.2. Project Sea Dragon (Northern Australia)

Project Sea Dragon was one of the most ambitious aquaculture proposals ever developed in Australia. Envisioned as a fully integrated, large-scale prawn-farming enterprise producing black tiger prawns for export markets, it aimed to transform northern Australia into a major global centre for prawn aquaculture. The project provides a rich source of insight into both the potential and the challenges associated with mega-scale aquaculture development.

Project planning began in the early 2010s with scientific work focusing on breeding and genetic improvement of black tiger prawns. Over several years, state and federal governments granted the project major status, recognising its projected economic impact. The intended structure of Project Sea Dragon was sprawling: a founder-stock and quarantine facility in Western Australia, a breeding and maturation centre near Darwin, a hatchery at Gunn Point, an enormous grow-out complex at Legune Station spanning more than 1,000 hectares in Stage 1, and a processing plant in Kununurra. At full build-out the project envisioned approximately 10,000 hectares of ponds and production of more than 100,000 tonnes of prawns annually.

Capital costs were estimated at between AUD 1.4 and 2.0 billion for the full project, with an initial Stage 1a cost of around AUD 280 million. Considerable government funding went into enabling infrastructure, including roads and supporting utilities, to help position the project for construction. By the late 2010s, the project was widely publicised as "shovel-ready," with significant investments already spent on planning and early civil works.

The scientific foundation of the project was robust. Australia had become a leader in black tiger prawn genetics, developing broodstock with dramatically improved growth rates and disease resistance. Small and medium-scale trials in Queensland demonstrated the viability of high-performance prawn strains, with yields far exceeding historical averages. Project Sea Dragon's developers intended to apply this breeding advantage in a new region, using very large pond modules to deliver efficient, industrial-scale production.

Regulatory approvals across multiple jurisdictions progressed steadily. Environmental reviews, Indigenous land agreements, water-use assessments and cross-border approvals were completed over several years. All major permissions necessary for construction of Stage 1a were ultimately granted, and early works, including trial ponds and worker facilities, began at both the breeding and grow-out sites. However, despite its political support and technical promise, Project Sea Dragon encountered severe difficulties beginning in 2022. A comprehensive internal review concluded that the project had not adequately de-risked key elements and that moving immediately into full-scale construction posed unacceptable financial and operational risks. Among the concerns were the remoteness of Legune Station, the untested nature of extremely large pond modules in that environment, the extensive logistics required, and the escalating costs of construction materials.

As delays mounted, financial pressures intensified. Disputes with construction contractors further strained the project's viability. The development entity responsible for Project Sea Dragon eventually entered voluntary administration, and a court ruling in 2024 determined that the company had been insolvent for several years. The project was ordered to be wound up, ending active development of the original concept. Although substantial planning work and initial on-site construction were completed, the project never reached commercial production.

In late 2025, signs emerged that parts of the project might be revived under new ownership and with a more incremental, phased approach. This suggests that although the original structure of Project Sea Dragon proved unsustainable, the underlying vision of large-scale Australian prawn farming, supported by advanced genetics and strong market demand, may still have a future, albeit on a more cautious basis.

For developers of other aquaculture projects, Project Sea Dragon offers several critical lessons. The first is the importance of scaling responsibly. Even when science supports high productivity in smaller trials, transferring that performance to a remote, mega-scale operation presents new risks that need to be validated through intermediate-scale pilots. The second lesson concerns financial and governance structures: large capital projects require strong contingency planning, professional project governance and the ability to withstand delays or external shocks. The third lesson is that political support, while helpful, cannot compensate for operational uncertainty or structural financial weaknesses. Finally, Project Sea Dragon illustrates the danger of overly optimistic public expectations; when timelines slip and planned outputs fail to materialise, investors and community stakeholders may lose confidence.

6.3. Comparative Note on the Two Projects

Together, Huon Aquaculture's Forest Home Hatchery and Project Sea Dragon represent opposite ends of the aquaculture development spectrum in Australia. Forest Home demonstrates a contained, technically successful and economically integrated use of RAS technology that strengthens an existing production system. Project Sea Dragon represents an ambitious attempt to create an entirely new aquaculture industry at unprecedented scale, one that ultimately struggled under the weight of its financial and operational risks. Below a comparative Table (4) shows what makes both projects distinct. It highlights purpose, scale, investment, timelines, progress, risks, and lessons. Even though both are large scale project only the Huon Aquaculture's Forest Home Atlantic Salmon Facility (Tasmania) became very successful.

Table 4: *Comparative Table of the Australian RAS Projects*

Category	Huon Aquaculture – Forest Home Facility (Tasmania)	Project Sea Dragon – Black Tiger Prawn Megaproject (Northern Australia)
Project Type	Freshwater recirculating aquaculture system (RAS) hatchery for Atlantic salmon smolt production	Large, integrated land-based prawn-farming project involving hatchery, breeding centres, ponds and processing
Primary Species	Atlantic salmon (smolt production)	Black tiger prawns (Penaeus monodon)
Location	Judbury, Huon Valley, Tasmania	Northern Territory/Western Australia border region (Legune Station, Bynoe Harbour, Exmouth, Kununurra)
Purpose	Produce larger, robust smolt to reduce marine risk and improve survival and growth in sea cages	Create an export-scale prawn industry producing up to 100,000+ tonnes per year at full build-out
Start of Development	Construction began in 2014	Concept formulated early 2010s; planning and approvals progressed 2014–2020
Operational Start	First smolt to sea in 2016; fully operational shortly afterward	Trial ponds and partial works built, but no commercial production ever commenced
Estimated Capital Cost	Approx. AUD 35 million	AUD 1.4–2.0 billion for full project; Stage 1a approx. AUD 280 million
Scale of Facility	Produces ~2 million smolt annually; ~580 tonnes of juvenile biomass; supports ~17,000 tonnes harvest from marine sites	Planned up to 10,000 hectares of ponds; initial 1,116 ha Stage 1; envisioned 100,000+ tonnes prawn output per year
RAS Level / Technology	High-density recirculating systems; 95–99% water reuse; advanced filtration (ozone/UV)	Not RAS in grow-out phase; instead huge pond-based systems; RAS used at hatchery and broodstock facilities
Environmental Strategy	High water reuse; treated effluent used for irrigation; strong biosecurity; reduced pressure on river systems	Designed for controlled breeding and biosecure production; large land and water footprint; complex environmental assessments
Operational Performance	Successful, stable, integrated into larger Huon marine production cycle; strong smolt quality	Project halted due to financial, logistical and execution challenges; development entity liquidated in 2024
Key Strengths	Proven commercial performance; integrated with established salmon farming; manageable scale; strong engineering	Ambitious national-scale aquaculture vision; advanced prawn genetics; extensive government support and approvals
Key Challenges	Standard hatchery risks such as water treatment, biosecurity, energy consumption	Remote location, massive scale, high capital cost, unproved mega-pond model, cost inflation, contractor disputes

Category	Huon Aquaculture – Forest Home Facility (Tasmania)	Project Sea Dragon – Black Tiger Prawn Megaproject (Northern Australia)
Outcome (2025)	Fully operational and a core asset for Huon Aquaculture	Project collapsed financially before commercial operation; potential future revival at smaller scale
Lessons	Start with targeted RAS (smolt/juvenile); ensure integration with existing operations; prioritise water quality and recirculation; scale gradually	Avoid over-ambitious scale without pilot validation; ensure realistic costings; phase development; manage remote logistics; maintain strong governance and financial discipline
Overall Assessment	A successful, pragmatic application of RAS that enhances marine farming performance	A visionary but overextended project illustrating the risks of large-scale aquaculture without proven intermediate steps

7. Arctic Charr Projects in Canada and BSR

Comparable studies of arctic charr as fish species suitable for considering in Estonia and partly realized in Estonia, can be found in Canada. The planned project of Sapphire Springs represents industrial-scale ambition with global impact potential but faces execution risks, while Opercule excels in agile, low-impact urban viability. Both leverage Canada's cold climate and RAS for Arctic Charr's optimal growth (7-13°C), emphasizing water efficiency and sustainability, key for export-oriented production.

7.1. The Sapphire Springs Artic Char

The Sapphire Springs Arctic Char (Manitoba, Canada) is a set to become Canada's largest Arctic char RAS facility, with government backing and an investment of around $145 million CAD. It expects to produce 5,000 metric tons annually, potentially increasing global Arctic char supply by up to 50%. The farm will use a state-of-the-art recirculating aquaculture system on a site with ideal water quality and temperature for Arctic char.

Urban RAS farms in Quebec: Quebec's first urban RAS facility is actively growing Arctic char from eggs, focusing on controlled urban aquaculture and local supply chains. This facility demonstrates the feasibility of Arctic char farming in smaller-scale or urban environments using RAS technology.

Other Canadian Projects: British Columbia hosts RAS Arctic char facilities dating back to the 1990s, including pioneering greenfield farms and research centers cultivating broodstock and juvenile fish to support commercial operations.

These Canadian farms highlight the global expansion and commercial viability of Arctic char production through RAS technology, supported by favorable climates, advanced technology, and growing market demand for sustainable fish protein. Lessons for Estonia: Scale to market demand; integrate urban/large models for diversification

7.2. Small-scale Farming in Quebec

A notable example is a small-scale commercial farmer in Quebec, Canada, who successfully produces approximately 30 tonnes per year of Arctic Charr in a RAS facility. This farm emphasizes the high value of Arctic Charr, its suitability for urban RAS farming, and the premium prices achievable. They also focus on reusing fish waste and exploring secondary products from smaller fish, showcasing a sustainable and value-focused business approach.

a. Comprehensive guides and business plans for Arctic Charr farming stress the importance of careful site selection, water quality management, disease prevention, and tailored feeding regimes to maximize growth and maintain fish health. Economic feasibility depends on scaling production appropriately, technology selection, and strong marketing aligned to premium market segments.
b. The Innovasea RAS Investor's Handbook discusses the investment considerations for RAS farms, including Arctic Charr, highlighting environmental benefits, control over production parameters, year-round growing, and proximity to markets that reduce distribution costs. It models different farm sizes and explores capital and operational costs relevant to planning.

These resources collectively provide practical and financial insight for developing Arctic Charr RAS projects, emphasizing sustainable practices, technological rigor, and market alignment critical for commercial success.

Table 5: *The Sapphire Springs Artic Char*

Category	**Sapphire Springs Arctic Char RAS (Manitoba)**	**Opercule Urban RAS (Quebec)**
Project Type	Large-scale commercial land-based RAS facility on former government hatchery site	Small-scale urban commercial RAS in building basement
Primary Species	Arctic Charr (Salvelinus alpinus) .	Arctic Charr
Location	Rockwood, north of Winnipeg, Manitoba, Canada (140-acre site with glacial aquifer)	Ahuntsic-Cartierville borough, Montreal, Quebec, Canada
Purpose	Commercial production to meet global demand for sustainable, high-quality Arctic Charr; increase global supply by ~50%	Local fresh supply to restaurants; reduce imports/carbon footprint via urban farming
Start of Development	2020 (company founded; site acquired from DFO) .	~2017 (pilot in garage); commercial scale post-2020
Operational Start	Planned for 2026	Pilot 2019-2020; first commercial batch Dec 2022
Estimated Capital Cost	CAD 145 million (USD 107 million)	Not publicly detailed (startup scale) .
Scale of Facility	5,000 metric tonnes/year	25-30 tonnes/year; 50,000 fish in 12 basins
RAS Level / Technology	State-of-the-art RAS with innovative tech for water quality, animal welfare, and processing	High recirculation (99.5% water reuse); controlled basins for growth stages
Environmental Strategy	Uses pristine glacial aquifer; sustainable practices with high water recirculation and low discharge	100-200x less water than traditional farms; electric bike deliveries
Operational Performance	Not yet operational (pre-2026)	Successful pilots with restaurants; high fish quality praised by chefs
Key Strengths	Massive scale, government support (CAD 10.75M loan), prime location, vertical integration via Icy Waters acquisition	Ultra-local (farm-to-plate same day), low carbon, proven taste/market fit

Category	Sapphire Springs Arctic Char RAS (Manitoba)	Opercule Urban RAS (Quebec)
Key Challenges	High capital cost, construction delays, market scaling for increased supply	Limited scale, urban space constraints, initial lack of expertise
Outcome (2025)	Under construction; on track for 2026 opening with secured funding	Operational and scaling; established urban model
Lessons	Leverage government backing and existing research sites; prioritize genetics/broodstock early	Start small (garage pilots); focus on local markets and sustainability for niche success
Overall Assessment	Ambitious flagship project with high potential to transform global Arctic Charr supply	Innovative proof-of-concept for urban RAS; complements large-scale projects

7.3. Artic Charr farming in the Baltic Sea Region

Examples of fish farms producing Arctic Charr in RAS facilities include:

1. SIA Blue Circle (Latvia): Operates a RAS farm at Jaunciedras producing Arctic char. The farm has a capacity of up to 110 tons annually and uses advanced biofiltration technologies to maintain water quality. The site draws water from deep bores and supports juveniles and on-growing halls. This farm exemplifies a working model of Arctic char production in a northern European climate, targeting regional markets.
2. Polar Fish (Finland): Converted a traditional farm to a RAS system around 2010, producing 50-100 tons of Arctic char. It represents an example of retrofitting existing aquaculture farms to modern RAS technology for enhanced control and year-round production.
3. Estonian small-scale trials: Estonia has small-scale RAS farms conducting trials with Arctic char alongside other salmonids like Atlantic salmon and brook trout. While commercial production volumes are still limited, these trials indicate growing interest and development.[230]. Arctic charr: Production is emerging but remains small compared to rainbow trout. It is cultivated in some RAS farms due to its climate adaptability.

These examples demonstrate the feasibility and growing adoption of RAS for Arctic char in the Baltic and Nordic regions, supporting sustainable, controlled production aligned with climate and market conditions.

Current Arctic char farming in Estonia is conducted on a smaller scale compared to rainbow trout, primarily in land-based recirculating aquaculture system (RAS) farms. Specific farm locations are not extensively published, but available sources indicate that the main sites tend to be situated in regions with access to clean fresh water and appropriate infrastructure typical for northern Estonia’s aquaculture activity zones.

One company closely linked to Arctic char RAS farming in the Baltic region is NORAS LT, operating a successful land-based farm in Klaipeda, Lithuania, with Baltic-wide distribution including Estonia. This reflects the interconnected nature of Baltic aquaculture efforts, with farms in neighbouring countries supplying regional demand.

Estonian aquaculture reports mention small-scale trials and production demonstrating growing interest in Arctic char, with farms generally located around the key aquaculture hubs in northern and western Estonia where water quality supports salmonid farming.

Table 6: *Artic Charr farming in the Baltic Sea Region*

Category	SIA Blue Circle (Latvia) - Jaunciedras RAS Farm	Noras LT (Lithuania) - Klaipėda RAS Farm
Project Type	Pilot-to-commercial land-based RAS facility	Commercial land-based RAS (phased expansion)
Primary Species	Arctic Charr (Salvelinus alpinus)	Arctic Charr (egg to >4kg)
Location	Jaunciedras, Latvia (Baltic Sea region)	Klaipėda region, Lithuania (largest Baltic farm)
Purpose	Demonstrate RAS viability for local/export markets (Nordics, Central Europe, Russia); cold-water species production	Large-scale sustainable production for Baltic/export markets
Start of Development	~2014 (initial planning)	Pre-2020 (initial 75 tonnes); ongoing phases
Operational Start	December 2019 (pilot); scaling to full production post-2020	Initial operations ~2020; Phase 2 (300 tonnes) completed recently
Estimated Capital Cost	Not publicly detailed (medium-scale pilot)	Not detailed; significant for 1500-tonne target
Scale of Facility	110 tonnes/year full production (pilot: 40 tonnes)	Phase 1: 75 tonnes; Phase 2: 300 tonnes; Target: 1,500 tonnes/year
RAS Level / Technology	Advanced RAS with Rotating Bed Bioreactors (RBBR), solids removal, low-head oxygenation, UV, ozonation; deep bore water (100m)	Energy-efficient RAS: no mechanical pumps, vacuum degassing (degas/protein skim/circulation), nanobubble oxygenation, honeycomb bio-media, intelligent controls
Environmental Strategy	High water recirculation; balanced treatment minimizes discharge; maintenance-free bioreactors	Pump-less design for energy savings; optimized solids/oxygen; low production cost target (<€3/kg salmonids)
Operational Performance	>300,000 fish on-site; good water quality and fish wellbeing in pilot	Phase 2 complete; R&D pilots optimizing costs
Key Strengths	Market proximity (24h to Nordics); flexible for other salmonids; reliable tech partner (Clewer Aquaculture Oy)	Energy efficiency; full lifecycle (egg-to-market); largest Baltic producer
Key Challenges	Pilot scaling; COVID-related on-site support limits; local RAS failure precedents	Phased scaling risks; cost optimization in R&D
Outcome (2025)	Operational pilot; expansion planned based on markets	Phase 3 grow-out imminent; operational at 300+ tonnes
Lessons	Partner with proven tech providers; prioritize solids removal and self-cleaning systems; location for logistics key	Integrate multi-function units (e.g., vacuum degassers); focus on energy/cost reduction for competitiveness
Overall Assessment	Successful Baltic RAS pioneer; scalable model for regional cold-water aquaculture	Leading Baltic scaler; tech innovation drives regional leadership

8. EISAP Auvere Agropark Project: Explanation for the Development Halt

The hold on Estonian Industrial Symbiosis Agropark (EISAP) is linked to Estonia's stringent environmental and construction permitting regime, judicial review outcomes emphasizing thorough impact assessments at all project stages, and the need to ensure full regulatory compliance before resuming construction or operations. According to the Nordregio report. the reason for setting the project on hold were multifaceted. Because of the close proximity to the Estonian-Russian border increased geopolitical tensions and security risks, has diminished the attractiveness to investors. Furthermore, rising energy prices and the loss of the St. Petersburg market, a key export target for the park's greenhouse produces, have significantly impacted the project's economic viability.

Conflicting political goals and land use interests have also jeopardised the project, with Estonia's plan to phase out oil shale by 2040 creating further uncertainty in energy use. Investors' growing demands for 100% renewable energy are not met by the proposed 70% biomass and 30% oil shale mix, and national defence needs restrict renewable energy expansion, such as wind and solar, in this area. Recent regulatory and tax changes have further strained finances, with potential land tax increases and stringent land use requirements driving up costs. Especially additional requirements connected to building construction, which are based on the political decision of change of energy sources in the region, creates additional challenges.

Although there is no direct information about the estimated production and export quantities to St. Peterburg, it could be estimated the quantity based on the Lifecycle Impact calculation of trout, comparative life cycle assessment (LCA) of raising rainbow trout (Oncorhynchus mykiss) in different production systems 2013 and the figures in the master plan of the EISAP project (2021). The production quantity could be estimated by using the LCI with 22.000 tonnes per year, which is a significant exceeding of the production and export plans for Estonia (4000 tons per year) and above the real quantity produced in Estonia 2024 (around 900 tonnes in 2024).

Regarding fish production quantity in Estonia in general, in 2024, fish and crayfish farms sold about 963 tonnes of commercial fish and crayfish, valued at 7.8 million euros. This represents a 5% increase compared to 2023. Rainbow trout is the most farmed species, accounting for around 87% of the total farmed fish quantity, approximately 835 tonnes sold in 2024. Fish roe sales reached a record 21 tonnes in 2024 as well. These figures reflect the national scale of aquaculture production, which EISAP likely contributes to but does not specify individually.

8.1. Requirement Connected to Building Construction

In the last time there were popping up legal and regulatory challenges related to construction permits and environmental assessments. Specifically, recent experiences in Estonia show that:

I. The Supreme Court annulled construction permits for some large-scale projects after determining that potential environmental impacts must be assessed during the building permit proceedings, not just during initial planning. This precedent affected ongoing projects, requiring reassessment and halting construction until proper procedures are completed.
II. While direct public sources on EISAP's specific legal status are limited, it is likely that similar regulatory scrutiny and procedures related to environmental impact assessments and permit challenges have contributed to the project's pause or delay.
III. Broader funding uncertainties, administrative reviews, or requirements to meet all environmental and construction regulations could also have influenced the decision to hold the project until compliance and risk concerns are fully addressed.
IV. The major challenge for the EISAP is linked to Estonia's stringent environmental and construction permitting regime, judicial review outcomes emphasizing thorough impact assessments at all project stages, and the need to ensure full regulatory compliance before resuming construction or operations. This reflects a cautious and legally rigorous approach to large-scale industrial and aquaculture developments in Estonia, prioritizing environmental safeguards and procedural correctness.

This reflects a cautious and legally rigorous approach to large-scale industrial and aquaculture developments in Estonia, prioritizing environmental safeguards and procedural correctness.

I. The Supreme Court ruling in Estonia set a precedent requiring comprehensive environmental impact assessments (EIA) to be conducted and considered not only during the initial project planning but also as an integral part of the building permit process. This has led to annulments of permits for ongoing large-scale projects until the EIA procedures are fully respected.

II. EISAP, being a large-scale industrial and aquaculture development, has been impacted by this precedent, likely requiring reassessment or additional environmental impact studies before construction can proceed.
III. Other potential influences include the need to comply strictly with environmental and construction regulations, as well as possible funding or administrative reviews related to project viability and risk.
IV. The approach taken reflects Estonia's commitment to environmental protection, regulatory transparency, and due legal process in managing complex development projects.

This cautious regulatory environment, while leading to project delays, ultimately aims to ensure sustainable and responsible development aligning with national and EU environmental policies.

8.2. Summation on the Juridical Challenge

Below is detailed and specific information regarding the regulatory and legal framework affecting large-scale projects like EISAP in Estonia, which sheds light on reasons for project delays and holds, with references to relevant regulations and case law:

A. According to a legal analysis of recent large construction projects in Estonia, the Supreme Court annulled certain construction permits due to inadequate environmental assessment during building permit stages, not just at initial planning. This has set a precedent requiring projects like EISAP to conduct thorough environmental impact assessments (EIA) integrated into the building permit process—failing which construction may be suspended or halted
B. The Estonian Building Code enforces that potential environmental impacts of construction must be assessed at the building permit phase. Two major projects were delayed for 2-3 years under this regime. The lesson bears directly on large aquaculture projects subject to environmental scrutiny
C. Estonia's Regulation No 5 of February 4, 2025 governs support for large-scale investments, requiring detailed project plans, eligibility criteria, compliance with state aid rules, and monitoring by the Estonian Business and Innovation Agency (EIS). Projects must demonstrate creation of local jobs, adherence to environmental regulation, and justified expenses. Non-compliance or incomplete documentation leads to support rejection or suspension

D. The regulation also empowers EIS to suspend or recover support if a project fails to meet obligations, including environmental and construction permits, emphasizing strict compliance requirement [eis.ee Regulation No 5].
E. This comprehensive legal and administrative framework reflects Estonia’s cautious approach emphasizing sustainability, job creation, proper environmental evaluation, and regulatory compliance. Large projects like EISAP face rigorous oversight resulting in procedural delays designed to ensure environmental protection and legal correctness.

The specific Supreme Court decision related to construction permit annulments due to inadequate environmental impact assessments in Estonia concerns a shale oil plant project. The Supreme Court annulled the construction permit for this plant in late 2023 because it found that potential environmental impacts must be assessed not only during the initial project planning but again as part of the building permit process, as required by the Estonian Building Code.

Key details:

a. The ruling means construction cannot continue until proper environmental impact assessment procedures are completed during the building permit stage.
b. The case set a precedent emphasizing comprehensive environmental review beyond initial planning, leading to reassessment of major projects.
c. The Council's safety period for preserving incomplete construction was set for two months to manage ongoing risks.
d. This legal framework impacts large-scale projects like EISAP, which may be subject to similar procedural requirements and delays.
e. similar procedural requirements and delays.

8.3. Status of the Architecture Planning of the Project

In the area a detailed plan and Strategic environmental assessment (SEA) were initiated on 25 July 2020 for Auvere Agropark and its surrounding area in Mustanina village, Narva-Jõesuu. According to EELIS (Eesti looduse infosüsteem, english: Estonian Nature Information System) data, the detailed plan area and its vicinity contain protected species, and expert assessments have been commissioned to evaluate the potential impact on them. The potential impact on protected natural objects will be determined during the SEA of the detailed plan of the area (project EISAP area). Because of this situation the comprehensive plan (planning started in 2018) does not consider anymore (with decision from 30.09.2025) the area as a perspective development as foreseen in the detailed plan, but it could be considered in the future when all requirements of the detailed plan will be fulfilled. Additionally, major part of the area (in Figure 2 marked as REV1 area in black) was defined as restricted area of the Sirgala training ground of the Defence Forces (marked as red line in Figure 2), which has direct impact on the potential usage of the area (Vabariigi Valitsus korraldus nr 301, 21.12.2023: Kaitseväe Sirgala harjutusvälja laiendamine). Restrictions based on the national defence requirements (radar functionality) which limit the expansion of local wind and solar energy sources, and therefore the achieving of the planned energy mix and sure to meet the investor demands for 100% green energy.

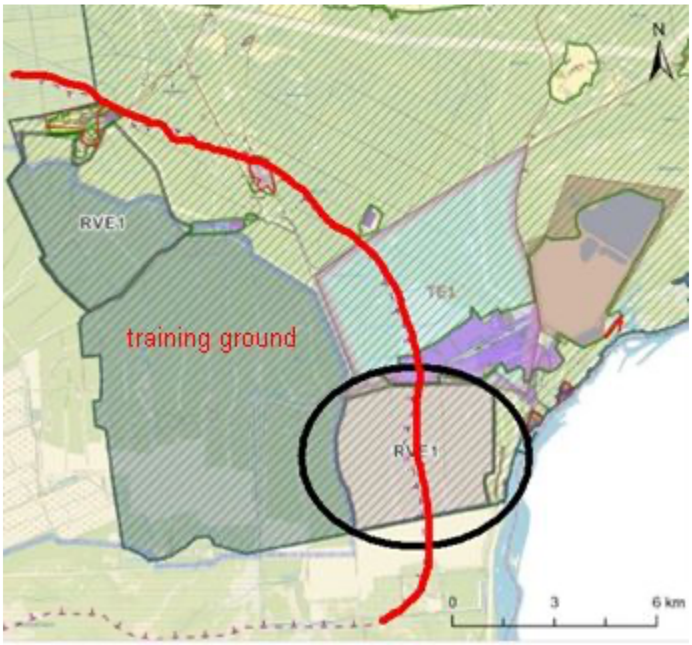

Figure 2: *EISAP geographical area and its surroundings*

8.4. Other Constraints

The production quantity of 22.000 tonnes per year of trout has impact on the volumes of investments and required energy production. Based on the assumed of 20 €/kg fish. *Current status of recirculation aquaculture systems (RAS) and their profitability and competitiveness in the Baltic Sea area. Natural Resources Institute Finland (Luke). http://urn.fi/URN:ISBN:978-952-380-504-0)* the estimated investment volume is min €400 million. Estimated funding from the transition fund is approximately maximum €15 million, which is less than 5% of the investment amount. Significant contribution of the investors is required.

In the Masterplan was estimated energy consumption of electricity 465.000MWh and heat used 1.120.000MWh. Compare with the renewable anergy production in Estonia by 2024 means, that 13-17% of the electricity and 33% heat produced should be used for the Auvere RAS complex. Additional power stations of significant size should be built to fulfil these demands. The masterplan did not show the full pictures of this aspect, and it is suggested to reevaluate, as a detailed analysis, the energy consumption and investment demand of the Auvere project taking into account the assessment of risks and limitations.

Additionally, a constrain factor is the skill deficit: there is a shortage of qualified personnel, including specialized RAS managers, operators, and aquaculture veterinarians, compromising operational stability. Based on the masterplan it was estimated that around 1000 employees should work in the area. Considering that 40% are technical specialists (RAS engineers, biologists) are 60% trained operators, means establishing additional staff capabilities especially for the project. Development of knowledge and skills is a long-term and complex process, and if it is not supported by the national bodies, then it should be considered to establish a cooperation with educational institute to develop the capability like the Cleveron model in Estonia.

9. Summary of LOT B Technical Report

The LOT B technical report presents a deeply integrated evaluation of how Recirculating Aquaculture Systems (RAS) can function as a sustainable, resilient and strategically meaningful component of Estonia's and the wider Baltic Sea Region's aquaculture and food-security architecture. Its central concern is not simply the performance of RAS technology itself, but how technological choices interact with energy systems, cold-chain logistics, supply-chain dependencies, policy contexts and regional industrial structures. Through this multi-layered approach, the report validates the feasibility of future RAS pilots and develops forward-looking scenarios that reveal both opportunities and constraints for implementing advanced land-based aquaculture across the Baltic Sea Region.

9.1. Why Estonia and the Baltic Sea Region Need RAS

The report begins by identifying the structural fragilities of Estonia's current fresh-fish supply model. Domestic aquaculture output is minimal and focused on freshwater species with relatively low commercial value. Meanwhile, consumer demand for high-value salmonids continues to grow, which keeps Estonia heavily dependent on imports. These imports arrive through highly sensitive cold-chain logistics that are easily disrupted by weather, geopolitical tensions, market instability or broader supply-chain failures.

Because the Baltic Sea is ecologically fragile, further expansion of marine aquaculture is highly constrained. The enclosed sea basin has slow water turnover and elevated eutrophication sensitivity, making additional nutrient loads ecologically unacceptable. For this reason, traditional, open-water cage systems are largely unsuitable for Estonia. Land-based RAS represents the only viable pathway for scaling aquaculture in an environmentally compliant manner. RAS can be operated anywhere with access to energy and water, and it prevents nutrient release through advanced filtration and recirculation.

Nevertheless, RAS is profoundly dependent on energy, automation and uninterrupted supply flows. The report stresses that technological sophistication alone does not guarantee resilience. Instead, resilience emerges from the broader system in which RAS must operate, energy systems, industrial infrastructures, cold-chains, regulatory environments and the international supply chains that feed RAS operations. Only by understanding these interdependencies can Estonia plan RAS pilots that are scalable and sustainable in the Baltic Sea Region context.

9.2. Regional and Environmental Conditions Shaping RAS Feasibility

The report places particular emphasis on Ida-Viru County, and especially the Auvere industrial area. This region offers unique advantages for RAS deployment: reclaimed industrial land, powerful electrical infrastructure, waste heat sources, pre-existing water networks and opportunities for industrial symbiosis. These create a rare alignment between ecological constraints and industrial capability. At the same time, the region remains exposed to geopolitical risks, energy transitions and logistics dependencies.

Environmental regulation is a key structuring factor. Estonia enforces strict rules for water abstraction and discharge, requiring RAS systems to employ efficient water recirculation and advanced nutrient-removal technologies. The Baltic Sea's ecological fragility reinforces the need for tightly controlled effluent and high-performance filtration. The report shows that RAS, when properly designed, is inherently suited to compliance with these environmental demands, but only through robust water-treatment engineering and continuous monitoring.

9.3. Technology and Infrastructure: Operational Demands of RAS in a Northern Climate

The technical assessment highlights the complexity of RAS as an integrated infrastructure system rather than a standalone technology. Culture tanks, mechanical filters, biological filtration, oxygenation, degassing, temperature control and digital automation must work continuously and redundantly for fish to remain healthy. Estonia's northern climate amplifies the importance of energy provision. RAS facilities require stable heat regimes year-round, otherwise fish metabolism, water chemistry and treatment efficiency become unstable.

Waste-heat integration is described as especially promising. Industrial processes in Ida-Viru produce substantial heat flows that could be redirected into RAS to reduce operational costs and energy demand. Similarly, the region's water systems and CO_2 streams present opportunities for creating circular, industrial-ecology loops. Such integrations would strengthen both resource efficiency and system resilience, making future pilots more competitive and sustainable.

9.4. Sustainability and Resilience Analysis: What Determines Long-Term Viability

The sustainability assessment concludes that RAS can be highly environmentally efficient when designed to minimise water discharge, recover nutrients, use energy effectively and integrate with industrial partners. RAS sludge, once stabilized, can support fertiliser production or greenhouse cultivation, making nutrient recycling a central part of a circular aquaculture-industrial ecosystem.

However, sustainability does not guarantee resilience. The system's resilience depends on continuity: continuous power, continuous oxygen, continuous feed, continuous automation, continuous supply of juveniles and spare parts. The report therefore evaluates resilience across internal and external layers. Internal resilience concerns mechanical redundancy, digital reliability, biosecurity and emergency systems. External resilience concerns energy security, supply-chain vulnerabilities, climate impacts, regulatory shifts and logistics stability.

The analysis makes clear that RAS is only as resilient as the least stable element of the system. Weakness in any supporting infrastructure can cascade into biological loss, financial instability or operational shutdown.

9.5. RAS Logistics Chain: From Inputs to Market Delivery

The report provides a dynamic mapping of the entire value chain. It shows how RAS operations depend on globally sourced feed, imported juveniles, specialised equipment, oxygen supply, packaging, technical maintenance and trained labour. These dependencies are particularly acute in the Baltic Sea Region, where certain inputs are sourced from Nordic suppliers who themselves face climate, disease and geopolitical risks.

On the outbound side, RAS facilities rely on cold-chain distribution networks. Disruptions in transport corridors, border delays, winter road closures or maritime uncertainty quickly translate into financial losses, reduced product quality or forced processing at lower margins. This recognition reinforces the need to design RAS pilots that either build local cold-chain capacity or integrate RAS with nearby processing hubs.

9.6. Scenario Development: Stress-Testing Future RAS Use in the Baltic Sea Region

A core contribution of the report is its scenario modelling. Several categories of disruptions are explored to reveal the thresholds at which RAS systems fail or adapt. Energy shocks are the most decisive. Sharp price spikes or temporary grid outages can compromise oxygenation, circulation and thermal control, making energy diversification, waste-heat integration and backup generation crucial for pilot success.

Feed-supply disruption is identified as another major vulnerability. Because feed is the largest recurring input and sourced through international markets, any shipping delay, commodity shock or supplier instability can threaten production continuity. Juvenile supply is equally critical; Estonia lacks its own hatchery capacity, making cross-border imports essential yet unstable.

Equipment failure and digital malfunction expose internal vulnerabilities that can be mitigated only through redundancy, rigorous maintenance and cybersecurity. Logistics and cold-chain disruptions challenge outbound deliveries and inbound input flows. Environmental and climatic extremes impose additional stress on thermal systems and water infrastructure. Regulatory shifts such as tightening discharge limits or new carbon-pricing frameworks can reshape cost structures or infrastructure requirements.

The scenarios collectively show that RAS systems can withstand moderate stress but become fragile when multiple shocks coincide. The report therefore validates the necessity of designing pilots with layered resilience measures and strong integration into regional infrastructure networks.

9.7. Learning from Reference Models: Cold-Chain Complexity in Germany and Data-Driven Adaptation in Norway

To strengthen the analytical basis for Baltic Sea Region RAS pilots, the report draws on two external reference models. Germany's advanced cold-chain logistics illustrate how complex distribution systems can be stabilised through redundancy, infrastructure diversification and regional coordination. Norway's salmon industry demonstrates how big-data analytics, real-time monitoring and predictive modelling enable rapid market adaptation, risk reduction and biological optimisation.

These examples help contextualise what Estonia and other Baltic Sea countries must develop to enable technologically sophisticated, resilient RAS industries: advanced logistics systems, integrated data architectures, coordinated governance structures and workforce competencies.

The final chapters translate the technical and scenario insights into strategic guidance for pilot implementation. The report emphasises strengthening water-treatment and effluent-management systems, expanding energy-resilient configurations, enhancing automation reliability, developing domestic hatchery and broodstock capacity, improving waste valorisation, coordinating regulatory processes and treating RAS as strategic food-security infrastructure.

On the non-technical side, the report encourages industrial symbiosis partnerships, workforce training, supplier diversification and integration of RAS into regional food-security strategies. This approach reflects the understanding that RAS is not merely a technological intervention but an infrastructural one requiring coordinated action across sectors.

9.8. Conditions for Successful Future RAS Pilots

The report concludes that RAS can become a central pillar of sustainable, resilient aquaculture in Estonia and the broader Baltic Sea Region, but only under conditions of strategic alignment. RAS must be embedded within energy-secure, digitally robust, supply-chain-diversified and circular-economy-oriented frameworks. Ida-Viru County offers one of the most favourable environments for pilot implementation due to its industrial capabilities and potential for thermal and resource symbiosis.

Future scenarios validate that RAS is feasible, but its success depends on anticipating system thresholds, investing in redundancy, strengthening local capacities and integrating operations with regional infrastructures. When these conditions are met, RAS becomes more than a technology: it becomes a resilient food-production asset, a contributor to circular industrial ecosystems and a stabilising force within the Baltic Sea Region's food and environmental landscape.

10. Project Pilots and Scenario Development – Lessons for the BSR

Key lessons from successful RAS projects in the USA, Norway, New Zealand, Canada and Australia that Baltic Sea Region (BSR) can adapt to increase production capacity include the following:

Technical expertise and skilled management: All successful projects emphasize the need for highly trained staff experienced in water quality management, biofiltration, mechanical maintenance, and system troubleshooting. Investing in staff training and technical expertise is crucial to operating complex RAS systems effectively and avoiding costly failures.

Modular and scalable system design: Successful farms use modular RAS units allowing stepwise capacity expansion with standardized components. This shortens installation times, reduces engineering costs, and enables flexible scaling as market demand grows. Such modularity also simplifies operator training and maintenance.

Water quality optimization: The heart of RAS success lies in advanced mechanical and biofiltration, maintaining low ammonia and nitrate levels, stable pH, and optimal oxygenation. This sustains fish health, reduces disease outbreaks, and improves feed conversion. Lessons stress continuous real-time water quality monitoring integrated with automated response systems.

Species selection and system customization: While freshwater species thrive in RAS, saltwater species require customized water treatments and system engineering. Estonian projects must focus on species suited to RAS (e.g., trout, sturgeon) and design systems tailored to species biology, reflecting adaptation models from successful global farms.

Energy efficiency and sustainability: Examples from Norway and Australia highlight integrating renewable energy solutions, heat recovery, and energy-efficient pumps to reduce operational costs. Sustainable practices, including biosecure waste management and water reuse, are crucial for regulatory acceptance and long-term viability.

Risk management and biosecurity: Closed RAS farms minimize exposure to pathogens and invasive species, improving biosecurity. Regular disease monitoring, quarantine protocols, and effective disinfection contribute to risk reduction.

Market alignment and economic planning: Successful projects integrate RAS production with local market demands, logistics, and value-added processing. Strong business planning and investment in marketing improve profitability and system resilience.

The BSR stands to gain a lot by learning how to develop technically advanced, modular, and energetically sustainable RAS farms operated by skilled teams, combined with tailored species choice and environmental control. These lessons from international leaders will guide scaling aquaculture production effectively while maintaining high fish welfare and environmental standards.

10.1. Suitable RAS fish farming possibilities in BSR

The fish species most suitable for raising in RAS in BSR, based on biological compatibility, stress tolerance, growth rates, and market demand, include:

- **Rainbow Trout:** Highly adaptable to RAS, rainbow trout thrive in controlled cold-water environments typical of Estonia. They have excellent feed conversion ratios, tolerate high stocking densities, and are well accepted in the market. RAS technology for trout enables efficient water use and disease control, making them a sustainable choice.

- **Arctic Charr:** Naturally adapted to cold, confined environments, Arctic charr perform well in RAS at temperatures of 7–13°C, aligning with Estonia's climate. They are fast-growing, manage stress effectively in tank systems, and generate premium product quality suitable for high-value markets.

- **Tilapia:** Though a warm-water species, tilapia is widely recognized for its hardiness, rapid growth, and efficient feed use in RAS. It demands temperature control to maintain optimal growth but offers economic advantages through short production cycles and strong market demand globally. Tilapia could be an option for heated or climate-controlled farms.

- **Other considerations:** Depending on technological capabilities, species like sturgeon, barramundi, catfish, and some marine species may be considered, but ramping up rainbow trout and Arctic charr production aligns best with Estonia's environmental conditions and market context.

Rainbow trout and Arctic charr emerge as the best species choices for RAS in Estonia for example due to their alignment with local water temperatures, growth efficiency, and market acceptance. Tilapia and other species require more specialized conditions but remain feasible with appropriate climate control and technology. Whereas tilapia shows in different geographical areas as a considerable fish species for establishing in Estonia and BSR.

This recommendation synthesizes recent global RAS species selection insights with BSR temperate climate and aquaculture industry trends. The size of the fish farms is considered by a production capacity of about 100 tonnes per year. The impact on the environment is limited, consider a low financial risk than bigger farms, and ensure a better solving the workforce shortage. This supports the growth of the sector in a smooth way.

10.2 Norwegian Project Havlandet

The Norwegian project Havlandet, producing around 20,000 tons of salmon annually, primarily uses **specialized vessels called well boats** for transporting live fish to customers. Well boats are equipped with large tanks ("wells") that hold water with controlled conditions to ensure fish welfare during transport.

Key points about their live fish transport:

- Well boats transport salmon between aquaculture sites or to slaughterhouses.
- Tanks can be open or closed systems depending on pathogen risk and fish health status to prevent spread of infections.
- The well boats maintain water quality parameters such as oxygenation, temperature, and cleanliness throughout the journey.
- This method reduces fish stress, mortality, and improves product quality upon arrival.
- Well boats enable long-distance and bulk transport of live salmon efficiently and safely under the regulatory oversight of the Norwegian Food Safety Authority.

In addition, processed salmon is cooled and packed with ice for transport by road, rail, and air to markets globally, ensuring temperature-controlled conditions to maintain freshness and quality.

Thus, Havlandet’s live fish transport success relies heavily on advanced well boat technology for on-board life support, combined with precise biosecurity and animal welfare protocols. This approach could serve as a best-practice model for similar large-scale RAS production and live transfer logistics in Estonia or elsewhere.

10.3 New Zealand project NIWA Northland Aquaculture Centre

The NIWA Northland Aquaculture Centre (NAC) in Ruakākā, New Zealand, is a successful land-based recirculating aquaculture system (RAS) facility producing up to 600 tonnes of kingfish per year. Key experiences and lessons from this project include:

- The facility demonstrates commercial viability of on-land aquaculture using RAS, offering superior environmental and economic performance with full control over production parameters.
- Kingfish were chosen for their rapid growth and efficient feed conversion, growing from 1 mm egg to 3 kg market size in less than 12 months—a key factor supporting fast production cycles.
- Extensive research identified optimal conditions to maximize fish health and welfare, including water quality management, nutrition, and disease control. This tailored approach contributes to high fish quality praised by chefs and suppliers.
- The NAC benefits from strong collaboration between NIWA and the Northland Regional Council, combining scientific research capability with regional economic development goals, boosting local job creation and investment confidence.
- The project acts as a proof-of-concept, sparking interest in larger-scale RAS farms in New Zealand and showcasing the potential for sustainable, environmentally-friendly aquaculture growth through controlled land-based systems.[140]
- The site houses 200 research tanks of various sizes and laboratories for general research, hatchery work, algae production, and pathology, supporting innovations and continuous system improvement.
- NIWA's expertise spans system design, environmental interactions, species development, disease prevention, and nutrition, helping integrate scientific knowledge with commercial production.

The NIWA Northland Aquaculture Centre demonstrates that success in expanding RAS production capacity relies on species selection suited to rapid growth, rigorous scientific management of fish welfare, strong multi-stakeholder partnerships, and a focus on environmental sustainability. Its experience offers a valuable model for Estonia to develop scalable, high-quality land-based aquaculture operations leveraging RAS technology.

10.4 RAS Projects in the USA

The three U.S. case studies offer not only cautionary lessons but also valuable insights into what is required for the successful scale-up of land-based aquaculture. The field remains promising, with strong sustainability credentials, growing demand for predictable supply, and regulatory pressures on traditional sea-based farms increasing globally. But the lessons from Florida, Maine, California, and Virginia make clear that the pathway to commercially stable, large-scale RAS is complex and highly dependent on aligning technology, economics, politics, and community support over extended periods of time.

From the U.S. cases, the BSR can extract a clear roadmap: secure land rights and community trust before investing; align biological designs with local energy and climate; build capital structures scaled to multi-year uncertainty; prepare for slow, iterative ramp-up phases; and incorporate both technical and strategic flexibility from the outset. With these lessons integrated, the BSR can avoid the costliest failures observed in the U.S. and build a more durable, regionally appropriate model for land-based aquaculture.

1. *Scaling RAS Is Not Linear—It Is a Phase Shift in Biological and Financial Risk*

The Atlantic Sapphire experience shows that once RAS projects move beyond a few thousand tonnes into industrial scale, they undergo a transformation in the nature of their risk profile. Biological systems behave differently at large volumes; engineering redundancies that are optional at small scale become existential at large scale; and operational failures propagate more quickly and with more expensive consequences. For the BSR, this underscores the importance of cautious scaling, phased development, and the expectation that the early years of operation will be volatile. Mega-scale RAS should therefore be pursued only when there is a robust financing structure, high management sophistication, and deep engineering capacity. Countries or regions in the BSR with constrained energy systems, limited technical labour pools, or fragmented permitting landscapes should prioritise medium-scale and modular systems before attempting large flagship facilities.

2. *Capital Strength and Financing Architecture Determine Survival More Than Technology Does*

Across all three U.S. cases, the decisive factor in durability is access to capital that is patient, flexible, and capable of absorbing shocks. RAS development timelines in the U.S. consistently stretched beyond original expectations, often by many years. Atlantic Sapphire repeatedly required refinancing; Pure Salmon faced escalating costs during long development; and

Nordic Aquafarms' legal entanglements depleted funds without ever breaking ground. In the BSR, where energy transformations, inflation risks, and global supply chain volatility are similarly pronounced, investors must anticipate multi-year gaps between concept, construction, operational maturity, and stable output. Financing must be structured to endure redesigns, technical learning curves, regulatory reviews, and macroeconomic swings. This favours public–private financing models, risk-sharing partnerships, and the use of industrial-symbiosis sites where infrastructure costs can be reduced.

3. "Site Control First" Is a Non-Negotiable Principle

The Maine case is perhaps the most powerful warning. Despite strong engineering designs, obtained permits, and favourable economic projections, Nordic Aquafarms' project was undone not by technology but by the absence of clear, uncontested legal control over a narrow strip of intertidal land. This single constraint made the entire multimillion-dollar project impossible. For the BSR, where coastal access is heavily regulated, land-use planning is complex, and community sensitivities are high, absolute clarity in property rights, water intake/discharge rights, and zoning permissions must be secured before any significant capital is committed. The BSR's own history of contested shorelines, Natura 2000 protections, and municipal autonomy makes this lesson especially relevant.

4. Social Licence Shapes Project Fate as Much as Regulation Does

Nordic Aquafarms' experience also demonstrates that community acceptance is not a box to tick but an ongoing strategic engagement. In Maine, local resistance evolved into an organised political and legal force capable of blocking the project entirely. By contrast, the Virginia project illustrates how political support and institutional partnerships can keep a decade-long initiative alive despite delays and redesigns. For the BSR—where public attitudes toward industrial development vary widely between urbanised zones, rural coastal communities, and ecologically sensitive regions—meaningful participation, transparency, and early trust-building must be integral to project design. In regions already home to industrial activity (Ida-Viru, for instance), support will differ significantly from areas where aquaculture is culturally sensitive or tourism-dependent.

5. Climate, Energy, and Infrastructure Compatibility Must Be Assessed with Hard Realism

Florida's subtropical climate forced Atlantic Sapphire to engineer extremely energy-intensive recirculation and temperature-control systems. While the BSR does not face heat stress, it faces cold stress, high energy prices, and growing pressure to decarbonise. The lesson is that RAS does not exist independently of regional energy systems. Secure, predictable access to electricity and heat, preferably through industrial symbiosis, waste heat, district energy networks, or renewable baseload is essential. The Bluehouse model demonstrates that mismatches between biological demands and energy realities convert into recurring operational crises. BSR planners should therefore prioritise regions with stable grids, surplus heat sources, and proximity to large industrial utilities that can buffer RAS energy loads. Studying U.S. failures clarifies that inconsistent or fragile energy systems will render RAS economically and biologically unviable.

6. Regulatory Complexity Is Manageable but Legal Ambiguity Is Fatal

Regulatory approval did not stop Atlantic Sapphire or Pure Salmon; it also did not stop Nordic's California project, which actually achieved several permits. What broke Nordic Aquafarms was not regulation itself but litigation, land disputes, and political fracturing. The BSR includes jurisdictions with significantly different regulatory cultures, ranging from highly predictable Nordics to more administratively fragmented Baltic states. The lesson is that developers must distinguish between regulatory compliance, which can be planned and engineered toward, and legal uncertainty, which can destabilise even the strongest financing plan. RAS projects in the BSR should avoid jurisdictions with unclear or untested aquaculture permitting frameworks unless they have explicit state-level guarantees.

7. Flexibility in Species, Phasing, and Design Is a Strategic Asset

Pure Salmon Virginia's pivot from salmon to trout reveals an essential insight: RAS projects that require long construction timelines must not lock themselves into rigid biological and technological commitments. Species with lower oxygen demand, lower temperature requirements, or broader market acceptance can significantly reduce energy intensity and operational fragility. For BSR developers, where cold climates, energy constraints, and nutrient regulations are significant factors, alternative species models, trout, char, whitefish, perch, or even hybrid systems, may offer more stable margins than salmon-focused mega-RAS. Design modularity also allows projects to begin generating revenue earlier while reducing exposure to cost inflation.

8. Market Proximity Helps, but It Does Not Offset Internal Fragility

All three U.S. projects targeted large domestic markets seeking high-quality, locally grown fish. Atlantic Sapphire had direct access to the huge U.S. seafood market; Pure Salmon targeted East Coast distribution channels; Nordic Aquafarms intended to supply New England and California. This proximity reduced transport risks and strengthened sustainability narratives. For the BSR, proximity to Northern European markets is similarly advantageous. But the U.S. cases show that market access cannot compensate for system failures, financing gaps, or legal obstacles. BSR planners should therefore view market adjacency as a necessary but insufficient condition for RAS success.

9. Expect Timelines Measured in Decades, Not Years

Every U.S. case extended well beyond initial projections. Atlantic Sapphire's Danish trials date to 2010, with major construction from 2017 and operational optimisation still ongoing in 2025. Nordic Aquafarms' Maine project consumed seven years and was ultimately abandoned. Pure Salmon's Virginia initiative has been active for more than a decade without core construction completed. The BSR must therefore adjust expectations: RAS is not a fast industry. Serious projects require ten- to fifteen-year visions, not three- to five-year investment horizons. Governments, investors, and developers need to align their expectations with these long maturation cycles, particularly in regions where institutional or infrastructural environments may slow progress.

10. What the BSR Should Take Forward

The overarching lesson from the American projects is that RAS is not just a technological system, it is a convergence of engineering, ecology, politics, finance, community relations, energy systems, and legal structures. The BSR is uniquely positioned to learn from these high-cost U.S. experiments. The region benefits from a more predictable regulatory culture than the U.S., greater acceptance of industrial clustering, and strong institutional capacity for long-term planning. However, it also faces higher energy prices, environmental sensitivity in the Baltic Sea basin, and relatively small domestic markets.

10.5 The Huon Aquaculture Forest Home Atlantic salmon facility, Australia

The Australian RAS developments illustrate a divide between RAS systems that succeed because they are purpose-built, integrated, and biologically validated, and those that struggle because they scale faster than their own organisational, financial, or governance systems can support. This contrast offers exceptionally relevant lessons for the Baltic Sea Region, where interest in RAS is rising but the structural constraints, energy prices, ecological regulations, supply-chain gaps, and public scrutiny require disciplined planning.

1. *RAS Works Best When It Is Integrated into an Existing Production Chain*

Huon's Forest Home facility succeeds because it is rooted inside a mature aquaculture industry with established marine farming, processing, logistics, and market access. RAS here is not expected to carry the full economic weight of the business; instead, it stabilises the early-life stages, reduces marine risk, and enhances the productivity of an existing system. This stands in contrast to many failed or stalled global mega-RAS projects that attempted to build a complete value chain from scratch.

For the BSR where salmon grow-out at sea is ecologically limited but early-stage rearing is feasible, the clear insight is that RAS may be most impactful as a strategic component, not necessarily as a standalone replacement. The region can use RAS to reinforce its existing aquaculture production and supply chains, rather than expecting it to immediately substitute for marine farming at commercial scale.

2. *Targeted RAS Deployment (Smolt and Juvenile Stages) Can Deliver High Impact at Lower Risk*

Forest Home demonstrates that smolt-stage RAS offers a sweet spot of technical manageability, biological feasibility, and commercial impact. Producing robust, uniform smolt on land stabilises downstream operations, shortens higher-risk marine phases, and improves survival and feed efficiency. This model allows companies to reap the benefits of RAS without assuming the full financial and biological exposure of land-based grow-out.

For the BSR, where capital costs are high and energy prices volatile, early-life RAS modules provide a strategically low-risk entry point. This approach also aligns with regional policy goals: protecting the Baltic Sea from nutrient loads while supporting domestic fish production.

3. *RAS Success Depends on Biological Proof, Not Just Engineering Ambition*

Forest Home's operational reliability stems from strong biological validation demonstrated smolt quality, seawater performance and well-researched smoltification under RAS conditions. In contrast, Project Sea Dragon shows that ambitious engineering means little if the biological, logistical, or organisational elements are not equally validated.

The BSR can draw a key conclusion: every RAS project must prove its biological concept at a meaningful scale before expanding. Premature scale-up without biological certainty magnifies failure.

4. Scale Must Be Proportionate to Governance, Risk Management and Workforce Capability

Forest Home operates successfully because its scale matches the company's organisational maturity, supply-chain sophistication and labour competence. By contrast, ultra-large, capital-intensive land-based projects like Project Sea Dragon falter when scale exceeds the organisation's ability to manage biological risk, supply-chain complexity or financing consistency.

For the BSR, this means that RAS scale should be governed by institutional readiness energy systems, technical labour pools, supply-chain stability and governance clarity not by aspirational production targets. The region should favour modular, stepwise expansion rather than attempting to leap directly to tens of thousands of tonnes.

5. Strong Local Environmental Integration Strengthens Public Acceptance

Forest Home incorporates high water-reuse rates, advanced treatment and environmentally responsible effluent management, including irrigation reuse on nearby farmland. These features strengthen local social licence by showing tangible environmental safeguards.

In the BSR where public and regulatory scrutiny of aquaculture is high and the Baltic Sea is ecologically fragile, this lesson is decisive: RAS projects must visibly demonstrate environmental responsibility to earn and keep their legitimacy. High water recirculation, nutrient capture, circular-use partnerships and transparent reporting will be crucial.

6. Projects Must Be Embedded in Reliable Water, Energy and Infrastructure Systems

Huon's success is partly enabled by access to reliable freshwater, stable electricity, redundancy systems and skilled labour conditions that ensure biological stability. The implicit lesson is that infrastructure reliability is a precondition for biological reliability. Even advanced RAS technologies falter when their environmental, resource or infrastructure foundations are weak.

For the BSR where industrial regions like Ida-Viru offer strong utilities and symbiosis potential, the insight is that RAS should be clustered with reliable industrial infrastructure, not deployed in isolated or fragile localities.

7. Governance, Planning and Operational Discipline Matter More Than Technological Novelty

Forest Home is not defined by groundbreaking innovation but by reliable execution, redundancy, disciplined biosecurity and integration with broader strategic planning. This stands in contrast to aspirational mega-projects that collapse under organisational or governance weaknesses.

The BSR should therefore prioritise governance quality realistic timelines, operational discipline, experienced management, and risk-aware planning, over technological spectacle or “race to scale”.

8. RAS Is Most Effective When It Reduces Risk, Not When It Concentrates It

Huon uses RAS to reduce uncertainty in the marine environment, minimise mortality, stabilise supply, and increase predictability. Project Sea Dragon, however, shows that when RAS is scaled so aggressively that financing, logistics, workforce, and biology are all placed under maximum strain, the system becomes brittle.

For BSR decision-makers, the lesson is that RAS should be a tool for de-risking, not a vehicle for taking on more risk than the system can bear.

9. What These Lessons Mean for the BSR Going Forward

Collectively, the Australian cases reinforce that successful RAS in the BSR will require:

a. Phased and proportionate scaling matched to technical capacity and market size.
b. Deep biological validation before commercial expansion.

c. Integration into existing aquaculture or food-system value chains, rather than greenfield mega-RAS.
d. Strong governance, consistent operational discipline and reliable infrastructure as cornerstones of viability.
e. Environmental performance that exceeds regulatory minimums, promoting trust and social licence.
f. RAS used strategically to stabilise the wider production system especially early-life stages and reduce risk exposure.

These insights point toward a BSR RAS model that is modular, biologically validated, energy-efficient, circular, and institutionally anchored, avoiding the pitfalls of hyper-scale projects while capturing the benefits of controlled, land-based production.

11. Criteria for Business Model development - TETRAS Report on Practice of BSR RAS

Together with all information gather in reported projects in previous chapters this study will proceed to lay precedent for the proposal of an holistic RAS Business Model suitable for the BSR. An overview of the TETRAS Report on Practice of BSR RAS shows that RAS BSR focuses on their economic, environmental, and technical feasibility. This particular document explores key parameters that determine the sustainability of RAS farms, including water management, discharge control, energy use, infrastructure, and digitalization. Additionally, the report evaluates industrial symbiosis models for integrating RAS with other industries and provides insights into the current challenges and future prospects of land-based fish and shrimp farming.

The most business-relevant insights that can enhance the development of an Industrial Symbiosis Agro-Park with an RAS farm within the BSR are presented below. These are critical success factors identified for designing and operating a RAS-based agro-park within a circular economy framework, making it an ideal reference for business model development.

Industrial Symbiosis & Circular Economy Potential

- Waste heat and CO_2 utilization: RAS systems can integrate with power plants and industrial operations to reuse waste heat for fish tanks and CO_2 for greenhouse agriculture, improving energy efficiency.
- Resource recovery & by-product management: Fish sludge, nutrients, and organic waste can be repurposed for biogas production, fertilizers, or hydroponic systems.
- Water conservation and treatment: High-recirculation RAS systems (>90%) minimize water use and comply with EU environmental policies.

Technical and Operational Requirements

- Water management & treatment: Highly efficient filtration, biofiltration, and denitrification systems are required to meet Baltic Sea environmental regulations.
- Energy consumption & efficiency: RAS operations are energy-intensive, but integration with renewable energy sources (solar, geothermal, biogas) can reduce costs.

- Digitalization & automation: Real-time monitoring and AI-driven control systems are critical for water quality, oxygenation, and disease prevention.

Economic Viability and Market Demand

- Growing market demand: Sustainable, locally produced salmon and shrimp are in high demand across Europe hereby reducing reliance on imports.
- Investment requirements: High CAPEX is offset by lower OPEX due to water recycling, energy efficiency, and government incentives.
- EU funding & incentives: The Just Transition Fund, EU Green Deal, and Common Fisheries Policy (CFP) that offer substantial financial support for sustainable aquaculture projects.

11.4. Key Business Model Components for the Agro-Park

Value Proposition

- Sustainable, traceable seafood production i.e., local, eco-friendly fish and shrimp farming using RAS technology.
- Integrated industrial symbiosis model that maximizes resource efficiency by reusing CO_2, nutrients, and wastewater from surrounding industries.
- Regulatory compliance & environmental sustainability that meets the strict EU discharge regulations while maintaining profitability.

Revenue Streams

- Sale of farmed fish & shrimp through direct sales to supermarkets, HoReCa (hotels, restaurants, and catering), and seafood processors.
- Industrial symbiosis services selling CO_2 for greenhouse use, waste for biogas/fertilizers, and treated water for irrigation.
- Technology licensing & consulting with expertise on RAS digitalization, AI-driven water management, and waste heat utilization.
- Government grants & subsidies that can be obtained and applied through EU sustainability grants, aquaculture incentives, and carbon credit programs.

Cost Structure (sources)

1. **Capital Expenditures (CAPEX)**

- RAS system infrastructure (depending on the scale applied)
- Water treatment & biofiltration
- Renewable energy integration
- Licensing & regulatory compliance

2. **Operational Expenditures (OPEX)**

- Labour & staffing
- Energy & water costs
- Fish feed & shrimp feed
- Maintenance & regulatory compliance

Risk Management and Regulatory Compliance

1. **Major RAS risks include**
   - Licensing & permitting delays because of the complex Environmental Impact Assessment (EIA) process that sometimes can take up to 2 years.
   - Water quality challenges to ensure optimal biosecurity to prevent pathogen outbreaks.
   - High initial investment costs: Requires EU grants, green bonds, and private investment to offset CAPEX.

2. **Possible Mitigation**
   - Engage licensing consultants early to streamline regulatory approval.
   - Adopt advanced digital monitoring & automation to optimize production.
   - Diversify revenue streams to reduce financial risks.

Key Considerations for BM Development

The Best Business Practice report provides valuable benchmarks and case studies to leverage on for BM. These are

- Prioritizing high-recirculation RAS (>90%) to minimize water use and comply with environmental laws.

- Partnering with industrial actors for waste heat and CO_2 exchange.
- Incorporating renewable energy sources to reduce operating costs.
- Pursuing EU and Estonian government funding for green aquaculture development.
- Developing a strong brand identity focused on eco-friendly, sustainable seafood

12. RAS Aquaculture Business Model Canvas for BSR

The following Business Model Canvas synthesises the operational, economic, regulatory and market considerations required to establish viable RAS enterprises in the BSR. It integrates lessons from regional pilots, global case studies, and the specific infrastructural and ecological conditions of the Baltic environment.

12. 1 Business Model Canvas for BSR

The model provides a structured framework for understanding how value is created, delivered, and captured in RAS operations supporting informed decision-making for investors, policymakers, and industry stakeholders.

1. Value Proposition

The value proposition of RAS in the BSR is rooted in its environmental performance, particularly its exceptionally low nutrient discharge and high water-reuse capabilities, which directly support Baltic Sea protection goals and align with the EU Green Deal and Farm to Fork commitments. The system ensures year-round production unaffected by climatic variability and delivers high traceability, food safety, and predictability which is a key value for retailers and consumers. Species diversification, particularly into Arctic charr, enhances resilience and market competitiveness. RAS have emerged as a strategic production technology for the BSR, where ecological constraints, climate conditions, and EU policy priorities increasingly favour land-based, low-emission aquaculture models. RAS facilities also offer consistent, high-quality production throughout the year, overcoming the seasonality, pathogen exposure and climate variability typical of open-water systems. This enables the region to reduce its reliance on imported fish and provide stable, traceable supply chains for premium markets. In brief the value proposition would include the following:

- Sustainability: Environmentally friendly farming with reduced water use.
- High Fish Quality: Consistent production of healthy, pathogen-free fish.
- Year-Round Production: Controlled environments support continuous growth cycles.
- Traceability: Full tracking from farm to consumer, increasing trust and transparency.

2. Customer Segments

In addition to environmental alignment, RAS provides significant market advantages for cold-water species such as rainbow trout and Arctic charr. These species perform well in controlled environments and command higher prices in Nordic and Central European markets. Estonia's current aquaculture profile that is largely dominated by freshwater rainbow trout demonstrates both the strengths and limitations of existing production. Although the country has achieved stable annual output around 900–1,000 tonnes, domestic production meets less than half of national consumption. This gap signals a clear market opportunity, especially when paired with the rising demand for sustainable, locally sourced fish protein. Species diversification through RAS, particularly into Arctic charr, is supported by evidence from Canada and Baltic neighbours such as Latvia, Finland and Lithuania, where successful RAS operations demonstrate the species' suitability, premium value and potential for regional scaling.

The primary markets include Baltic and Nordic retail chains, premium restaurants, wholesalers, smokehouses, and sustainability-driven consumers. Export demand is especially strong for Arctic charr and premium-quality trout. Institutional buyers such as hospitals and schools offer additional opportunities under green procurement frameworks. Customer Segments are listed below:

- Retail Fish Markets
- Restaurants (mid-range to high-end)
- Wholesalers and distributors
- Environmentally conscious consumers

3. Channels

Distribution occurs through supermarket contracts, restaurant partnerships, regional logistics hubs, and online subscription models. Export markets are accessed via Tallinn, Riga, and Klaipėda. Reaching these customer groups requires a multi-channel strategy. Many successful Baltic and Canadian RAS operations have demonstrated the importance of long-term supply contracts with retailers, direct partnerships with the HoReCa sector, and the use of online platforms and subscription models for household consumers. Export logistics, particularly through hubs such as Tallinn, Riga and Klaipėda, enable rapid distribution to Nordic markets, where freshness and reliability are highly valued. RAS operations also benefit from strong branding built around sustainability stories, transparency, and regional identity elements that align closely with evolving EU food-marketing and eco-label frameworks using the following:

- Direct sales to restaurants and local businesses
- Online sales platforms
- Farmers' markets
- Wholesale distribution partners

4. Customer Relationships

RAS operations build trust through transparency, offering facility tours, educational outreach, and sustainability reporting. Stability in supply and quality fosters long-term retail and HoReCa partnerships. From a customer perspective, RAS operators in the BSR can serve a diverse portfolio of market segments. Retail supermarket chains are increasingly committed to sustainability criteria and look favourably on local, traceable fish products with low environmental footprints. High-end restaurants value the consistent quality and flavour profile of Arctic charr and trout raised under controlled conditions. Regional smokehouses and processors seek year-round supply to stabilise production, while environmentally conscious consumers, particularly in Estonia and Finland—prefer low-impact, antibiotic-free fish. For export markets in the Nordics and Central Europe, Baltic-produced RAS fish offers a competitive alternative to Norwegian imports, especially for premium and niche categories. A simplified customer relationships include:

- Direct engagement (farm tours, tastings)
- Consumer education on sustainability and health benefits
- Loyalty programs
- Feedback collection and continuous improvement

5. Revenue Streams

Primary revenue derives from fresh and processed fish sales and also extends beyond simple fish sales. Primary revenues come from whole fish, fillets and smoked products, with Arctic charr, in particular, offering strong premium potential. Secondary revenue streams include the sale of juvenile fish or smolt, which is especially relevant for hybrid systems where RAS feeds into offshore or flow-through farms. Additional income may derive from tourism, training programs, or consulting services, particularly as the region seeks to expand its RAS knowledge base. Some RAS operators also benefit from selling by-products such as offcuts or nutrient-rich sludge, to pet-food manufacturers or agricultural users. A summary of the revenue streams will be:

- Primary fish sales: whole fish, fillets, smoked products
- Juvenile/smolt production for other farms
- Value-added processing (smoked charr/trout, ready-to-cook portions)
- By-product utilization (fertiliser, pet food inputs, collagen)
- Research & innovation partnerships
- RAS training, consultation, and study visits

6. Key Resources

Core resources include RAS facilities, advanced monitoring and control systems, skilled technicians, broodstock and juveniles, and reliable water and energy access. Automation and sensor technologies are essential for operational stability. Operating a successful RAS facility in the BSR requires a robust set of resources. Physical infrastructure includes tanks, biological and mechanical filtration units, oxygenation systems, degassing technology and insulation suitable for cold climates. Biological resources, high-quality broodstock, fingerlings and species-tailored feed are equally critical. Human capital is another defining element of competitiveness: skilled technicians, aquaculture specialists and staff trained in automation and water chemistry are scarce in the region, making partnerships with universities and training institutions essential. Digital infrastructure, monitoring sensors, SCADA control systems, AI feeding optimisation and early-warning tools plays a central role in minimising operational risk and ensuring system stability. A concise key resource is listed below:

- RAS facilities (e.g.tanks, filtration, buildings)
- Reliable water source and treatment systems
- Monitoring and control technology
- Skilled staff trained in aquaculture operations.

7. Key Activities

Daily operations involve sophisticated water-quality management, biological husbandry, feeding optimisation and biosecurity routines. With Estonian and broader Baltic experience showing that water chemistry is a key determinant of performance (particularly for Arctic charr), RAS farms require stable monitoring regimes and contingency systems to mitigate risk. Market development, contract negotiation, participation in research trials, and continuous process improvement form equally important parts of the operational landscape and include the following:

- Fish husbandry (breeding, feeding, harvesting)
- Water quality monitoring and management
- Marketing and sales activities
- Research and development for efficiency improvements

8. *Key Partnerships*

Key partnerships underpin the success of RAS ventures. Collaboration with research institutions provides access to species trials, feed optimisation studies and operational support. Government agencies influence permitting, compliance and access to EU funding instruments. Partnerships with energy companies or industrial clusters offer opportunities to reduce operating costs by integrating waste heat or renewable systems which is an increasingly important factor in the Baltic context where energy prices remain volatile. Technological alliances with RAS engineering providers support system resilience and contribute to innovation capacity. The summary is listed below.

- Feed and equipment suppliers
- Research institutions
- Regulatory agencies
- Marketing and branding firms

9. *Cost Structure*

The cost structure of a BSR RAS farm reflects both global patterns and regional particularities. Energy costs are notably high in Estonia and neighbouring countries, making efficiency measures and industrial symbiosis essential. Feed remains the largest variable expense, constituting up to 60% of operational costs, and is subject to international commodity fluctuations. Labour costs, although moderate by EU standards, are rising as the demand for skilled technical personnel increases. Capital expenditure (CAPEX) for a mid-sized Baltic RAS facility typically ranges between €10 and €20 per kilogram of annual production capacity, meaning that a 300-tonne operation may require €3–€6 million in investment. Regulatory compliance costs especially environmental monitoring that is added to ongoing expenses, while insurance and maintenance budgets ensure system reliability and risk mitigation. The structure includes the following layout.

- Operational costs (labour, utilities, maintenance)
- Initial system setup and technology investment
- Marketing and outreach
- Compliance with regulatory standards

12.2 RAS Cost Structure Overview

A clear understanding of the cost structure is essential for evaluating the financial viability of RAS operations in the Baltic Sea Region. The following overview outlines the major cost categories that influence capital investment, operational performance, and long-term profitability. Major cost categories include:

- **Initial setup costs**:
  – Tanks, buildings, filtration systems
  – Sensors, automation, digital monitoring
  – Bore wells and water treatment
- **Operating costs:**
  – Feed (largest cost component)
  – Electricity & heating (variable; mitigated by waste heat)
  – Labour and training
  – Oxygen supply and CO_2 removal
  – Water quality testing and biosecurity
- **Maintenance and consumables:** replacement of pumps, filters, sensors
- **Insurance:** liability, property, system failure
- **Marketing and logistics:** packaging, distribution, advertising
- **Regulatory compliance costs:** environmental monitoring, permits

12.3 RAS Cost Ranges

Indicative cost ranges for typical RAS operations (actual values depend on local conditions, species, and scale).

1. Initial Setup

- Infrastructure: $50,000–$500,000+ (large systems: over $1 million)
- Technology: $10,000–$200,000
- In-vestments range from appr. 10 to over 20 euros per kg estimated yearly production.

2. Annual Operational Costs

- Labor: $30,000–$100,000
- Utilities: $5,000–$20,000
- Feed: $10,000–$50,000
- Health Management: $2,000–$10,000

3. Annual Maintenance

- Equipment maintenance: $3,000–$15,000
- Facility upkeep: $1,000–$5,000

4. Research & Development

- Innovation projects: $5,000–$50,000
- Staff training: $1,000–$5,000

5. *Regulatory Compliance*

- Permits: $1,000–$10,000
- Quality control/testing: $500–$5,000

6. Marketing & Sales

- Promotion: $2,000–$10,000
- Distribution: $3,000–$15,000

7. Insurance

- Liability: $500–$2,000
- Property: $1,000–$4,000

12.4. Financial Projections for a BSR RAS Farm

To ground the business model in realistic economic terms, the following financial projections outline the expected performance of a 300-tonne RAS facility producing rainbow trout or Arctic charr. These projections derive from Canadian, Baltic and Northern European RAS benchmarks and align with the cost profiles observed in the Estonian State of the Art analysis.

Assuming a production capacity of 300 tonnes per year, wholesale prices of €7.50/kg for rainbow trout and €12/kg for Arctic charr, and typical feed conversion ratios of 1.0–1.2, annual revenues range from €2.25 million to €3.6 million. Operational expenditures for such a facility are expected to fall between €1.1 million and €1.3 million annually. Energy consumption—one of the most sensitive cost components can vary widely depending on access to waste heat, system design efficiency and insulation quality, but for modelling purposes an annual energy cost of €200,000–€300,000 is typical for the region.

Labour costs for a 5–7 persons team would approximate €220,000–€260,000 per year, while feed would represent the largest single operational expense, estimated at €400,000–€500,000 depending on species and market prices. Routine maintenance, veterinary care, oxygen supply, biosecurity and insurance requirements add a further €80,000–€100,000 annually.

On this basis, a rainbow trout RAS farm operating at 300 tonnes per year would likely achieve annual net operating margins in the range of €800,000 to €1.1 million, resulting in an estimated payback period of roughly 4–5 years on a €3.25 million investment. Arctic charr, given its higher market price, significantly improves the financial outlook, with net earnings potentially exceeding €2 million annually and a payback period of approximately two years under stable market conditions.

These outcomes, however, depend heavily on effective risk management. Factors such as energy price volatility, feed inflation, system downtime or water-quality failures can substantially affect profitability. Mitigation strategies including co-location with industrial sites, automation to reduce labour demands, strong biosecurity planning and diversified revenue streams can improve resilience and financial performance.

12.5. The business model canvas

The business model canvas (Figure 3) is given below.

Key Partners	**Key Activities**	**Key Resources**
▪ RAS engineering & equipment suppliers ▪ Research institutions & universities ▪ Regulatory & permitting agencies ▪ Energy providers (waste heat, renewables) ▪ Retail & logistics partners ▪ Financing & investment institutions	▪ Fish husbandry: breeding, feeding, grading, harvesting ▪ Water quality & environmental control ▪ Biosecurity & disease prevention ▪ Processing & packaging ▪ Marketing, sales & export coordination ▪ R&D, species trials, efficiency improvements	▪ RAS infrastructure (tanks, filters, biofilms) ▪ High-quality broodstock & juveniles ▪ Skilled aquaculture staff & technicians ▪ Digital monitoring & control systems ▪ Water & energy infrastructure ▪ Cold storage & processing capacity

Value Proposition ▪ Ultra-low environmental impact, high water reuse ▪ Compliance with Baltic Sea nutrient restrictions ▪ High-quality, pathogen-free fish ▪ Year-round stable production ▪ Full traceability from broodstock to market ▪ Premium species: Arctic charr, trout, pikeperch	**Customer Relationships** ▪ Long-term retail & HoReCa contracts ▪ Transparency & sustainability reporting ▪ Direct engagement: tours, events, chef partnerships ▪ Digital traceability tools ▪ Continuous feedback & improvement cycles	**Channels** ▪ Retail chains (BSR & Nordic markets) ▪ Restaurants & catering ▪ Online direct-to-consumer platforms ▪ Farmers' markets & regional food networks ▪ Export hubs (Tallinn, Riga, Klaipėda)
Customer Segments ▪ Retail supermarkets & distributors ▪ Restaurants & smokehouses ▪ Eco-conscious consumers ▪ Nordic and EU importers ▪ Public procurement (schools, hospitals) ▪ Specialty seafood markets	**Cost Structure** ▪ Feed (largest operating cost) ▪ Energy: heating, cooling, oxygenation ▪ Labour & training ▪ RAS maintenance & oxygen systems ▪ Insurance & regulatory compliance ▪ Logistics, packaging & marketing	**Revenue Streams** ▪ Whole fish, fillets & smoked products ▪ Smolt & juvenile sales ▪ Consulting, training & research ▪ By-products (fertiliser, pet food inputs) ▪ Tourism & educational programmes

Figure 3: *RAS Aquaculture Business Model Canvas for BSR*

Conclusion

The assessment of Recirculating Aquaculture Systems (RAS) within the Baltic Sea Region (BSR) demonstrates that land-based aquaculture represents not only a technological opportunity but a strategic necessity for meeting EU food-security, sustainability, and blue-economy objectives. With traditional marine aquaculture constrained by ecological sensitivity, nutrient-load limits, and tightening regulatory frameworks, RAS emerges as one of the few scalable solutions capable of expanding regional fish production without increasing pressure on the Baltic Sea environment.

Current aquaculture performance in Estonia illustrates both the challenges and opportunities ahead. National production reached 963 tonnes in 2024, with rainbow trout alone accounting for 86.7% (835 tonnes). Despite steady growth, Estonia meets only 42.3% of its fresh-fish consumption, signalling substantial potential for domestically produced, high-quality RAS-grown fish. Sector value reached €7.8 million in 2024, marking a 36.8% increase from the previous year, evidence of strong and growing demand across domestic and regional markets.

Comparative case studies from Norway, New Zealand, the United States, Australia, Canada, and the wider Baltic region reinforce that successful RAS development requires cautious scaling, biological validation, robust governance, and dependable capital structures. New Zealand's NIWA project demonstrated the benefits of a 20-year research foundation, while the U.S. experiences (Atlantic Sapphire, Nordic Aquafarms, Pure Salmon) illustrate the structural risks of premature industrial scaling, regulatory disputes, and community opposition. Australian examples further underscore the need for organisational maturity, Huon's Forest Home facility succeeded by focusing on juvenile production, whereas Project Sea Dragon faltered under governance and financing weaknesses.

Cold-water species such as Arctic charr present particular promise for the BSR. Canadian flagship projects (e.g., Sapphire Springs, targeting 5,000 tonnes/year) and Baltic pilots (e.g., SIA Blue Circle in Latvia, NORAS LT in Lithuania) confirm the commercial viability of charr in RAS under northern climate conditions. Their experiences demonstrate scalable technology, strong market demand, and energy-efficient systems capable of high-water recycling (>95%). These models are directly applicable to Estonia, where small-scale charr trials already show biological feasibility and increasing consumer interest.

The cost structure of RAS remains capital-intensive, with investment requirements ranging from €10–20 per kg of annual production capacity. Operating costs are dominated by feed and energy, two variables that can be stabilised in the BSR through renewable integration, industrial symbiosis, and access to waste heat. Production cost estimates for RAS-reared rainbow trout (to 360 g) currently sit at approximately €6/kg, which is competitive when positioned in premium, traceable, sustainably produced markets.

Across the analysis, the most consistent message is that RAS success depends on system-level planning rather than isolated technological deployment. Critical factors include energy security, water access, workforce skills, long-term financing, community acceptance, and regulatory clarity. When these elements are aligned and is supported by strong research networks, industrial partners, and EU investment instruments in the Baltic Sea Region has the potential to become a leader in sustainable land-based aquaculture.

In conclusion, RAS offers the Baltic Sea Region a credible, scalable pathway toward resilient aquaculture development. By embedding lessons from global case studies, leveraging regional strengths, and rigorously validating pilot projects, the BSR can advance toward a future where high-quality, environmentally responsible fish production supports food security, economic growth, and the broader transition to a sustainable blue economy.

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