Routledge Explorations in Environmental Studies

MAKING CO$_2$ A RESOURCE

THE INTERPLAY BETWEEN RESEARCH, INNOVATION AND INDUSTRY

Edited by
Øyvind Stokke and Elin M. Oftedal

Making CO_2 a Resource

This interdisciplinary book explores how CO_2 can become a resource instead of a waste and, as such, be a tool to meet one of the grandest challenges humanity is facing: climate change.

Drawing on a Norwegian narrative that has significance for a global audience, Øyvind Stokke and Elin Oftedal introduce in-depth, multi-perspective analyses of a sustainable innovation research experiment in industrial carbon capture and utilisation technologies. Building on extensive literature within marine sciences, sustainability research, and environmental philosophy and ethics, this book documents how a misplaced resource like CO_2 can become valuable within a circular economy in its own right, while at the same time meeting the challenge of food security in a world where food production is increasingly under pressure. The book is diverse in scope and includes chapters on how to reduce the environmental footprint of aquaculture by replacing wild fish and soy from the Amazon, how to optimise the monitoring of aquatic environments via smart technologies, and how to replace materials otherwise sourced from natural environments. The authors also analyse the pivotal role of the university in driving innovation and entrepreneurship, the pitfalls of different carbon technologies, and explore how the link between petroleum dependence and CO_2 emissions has been addressed in Norway specifically.

Making CO_2 a Resource will be of great interest to students and scholars of climate change, environmental ethics, environmental philosophy, sustainable business and innovation, and sustainable development more broadly.

Øyvind Stokke is Associate Professor in the Department of Philosophy at UiT The Arctic University of Norway. His research focuses on environmental philosophy and degrowth, climate ethics, the assessment of technological sustainability, and deliberative democracy theory. Stokke has been co-leading the research project Transforming CO_2 to capital *by* interdisciplinary CCU optimisation strategies (iCCU) (UiT 2017–2023), which explores CO_2 Capture and Utilisation (CCU) by taking into account environmental, ethical, information-technological and economic aspects, and was the leader of the pre-project *The ARC Methodology* (UiT 2021) exploring the grounds for a methodology assessing technological sustainability based on synergy effects between nature and technology. He was member of the research consortium in the project *Political Philosophy looks to Antarctica* (RCN 2017–2020) which explored moral and legal issues of natural resource justice in the Antarctic Treaty System. Stokke initiated and led Environmental Philosophy Research Group and was a member of the leader group of the Arctic Center for Sustainable Energy at the UiT from 2016 to 2020.

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Environmental democracy and climate protest in the era of marketisation, *Norwegian Journal of Philosophy*, 2–3, 2021; Thinking like an ocean: A climate ethic for the Arctic marine environment, in: Eva Pongrácz, Victor Pavlov, Niko Hänninen (Editors): *Arctic Marine Sustainability: Arctic maritime businesses and resilience of the marine environment*. Switzerland: Springer Polar Sciences, 2020.

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1 Making CO_2 a resource

Green innovation for an ecological economy. An introduction

Øyvind Stokke and Elin M. Oftedal

Post-normal science for a post-normal age

In the article “Science for a post-normal age”, Silvio O. Funtowicz and Jerome Ravetz give the following verdict over the state of science in our industrial age:

> Science always evolves, responding to its leading challenges as they change through history. After centuries of triumph and optimism, science is now called on to remedy the pathologies of the global industrial system of which it forms the basis. Whereas science was previously understood as steadily advancing in the certainty of our knowledge and control of the natural world, now science is seen as coping with many uncertainties in policy issues of risk and the environment. In response, new styles of scientific activity are being developed.
>
> (Funtowicz and Ravetz, 1993, p. 739)

“The science appropriate to this new condition,” the authors continue, “will be based on the assumptions of unpredictability, incomplete control, and a plurality of legitimate perspectives.”

The research project presented in this book meets these conditions of a post-normal science, i.e., a science that does not avoid but manages strong uncertainty, irreversibility, sustainability, precaution, and complex ethical issues and provides a response to the inadequacy of scientific as well as political responses to these problems. Located in Finnfjord in Northern Norway, the ferrosilicon company Finnfjord AS is Norway’s 14th largest emission point with annual emissions exceeding 300,000 tonnes of CO_2 equivalents (2020) (Øystese, 2022). Founded in 1960, Finnfjord AS,[1] like science itself, now exists in the post-normal age, characterised by the dual environmental crises of accelerating climate change with the loss of biodiversity.

Responding to these environmental challenges, the company entered into a collaboration with UiT The Arctic University of Norway in 2014 to explore biological carbon capture and utilisation (CCU) by means of microalgae to reduce CO_2 emissions from the smelter. Being an exemplar of responsible research and innovation (RRI) in itself, the collaboration is an important part of the Finnfjord company’s

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vision to become the world's first CO_2-free smelter. If science needs to become reflexive, i.e., to cope with "the pathologies of the global industrial system of which it forms the basis," it is equally important for *innovation* to become reflexive. This shift occurs when the rules and expectations that ensure a continuous cycle of creative destruction (the continuous quest for new products and services) under capitalism become problematic *themselves*. Capitalism is an innovation society that has created a second-order system for social reproduction, a system of institutionalised uncertainty: but when these institutionalised second-order rules for reproduction become problematic, a third-order innovation society arises, where the aforementioned second-order system becomes the subject of reflection. Along with science, then,

> innovation has lost its certainty, with its future its progress . . . The direction of innovation society becomes an issue, not least because the expansion and deepening of markets undermine its own social and ecological preconditions . . . The unintended consequences of innovations no longer fit together into a narrative of an invisible hand creating overall benefits . . . put into doubt by climate emergency and persistent unsustainability.
>
> (Ziegler, 2020, p. 4)

Therefore, innovation needs to become collaborative,[2] and responsible science and innovation both need to extend their peer communities: as reflexive science is explicitly built on values and techno-scientific interests, the evaluation of scientific inputs to decision-making requires that more stakeholders become involved in the process. "With mutual respect among various perspectives and forms of knowing, there is a possibility for the development of a genuine and effective democratic element in the life of science" (Funtowicz and Ravetz, 1993, p. 741).

With this open-minded post-normal spirit, the research group *Transforming* CO_2 *to capital by interdisciplinary CCU optimisation strategies* (iCCU) based at the UiT has analysed and explored this complex RRI project since 2018. Through interdisciplinary research collaboration, marine biology, computer science, economics, social science, and philosophy have all contributed to the biological and industrial CCU effort at the Finnfjord AS smelter. The result has been The Algae Project where university-based marine science meets traditional steel industry in Northern Norway with the aim of making CO_2, a waste product from the ferrosilicon production, a resource. By cultivating masses of marine microalgae, *diatoms*, in photobioreactors integrated into the Finnfjord factory production line, high CO_2 footprint industrial processes are being replaced with low CO_2 footprint ones by means of sustainable innovation. The ambition is for at least 50% of the factory fume CO_2 (150,000 tons/year) released during the factory production to become bound by photosynthesis in the diatom mass-cultivation process. Beyond reducing greenhouse gases, the aim is to produce nutrient-rich biomass for fish feed and other valuable products, thereby creating a sustainable and renewable utilisation of marine resources (for an outline of the project, see Eilertsen et al., Chapter 2). On the other hand, if you take the perspective of the Norwegian government, CO_2

is posited solely as an externality and a waste product, to a considerable extent produced through the exploitation and combustion of oil and gas, which indirectly harms the planet through global warming. As a consequence, the government in September 2020 launched the *Langskip* project, a national effort introduced by the government to capture industrial CO_2 emissions off- and on-shore and store them under the ocean floor, based on the technology of CCS. But how did CO_2 become a problem, a waste product to be buried, rather than utilised for the benefit of both industry and nature?

Economics, perhaps more than other disciplines, has traditionally exemplified "normal" science (in the sense of Thomas Kuhn), apparently able to maintain its credibility by relegating uncertainties in knowledge and complexities in ethics firmly to the sidelines.

> But when we are confronted by the scientific enigmas and policy riddles of global environmental policies, we can no longer maintain the fiction of a "normal" economic science. Ecological variables cannot be measured by simple analogy with the cloth fairs of Adam Smith's day. If the valued goods that give richness to our lives are reduced to commodities, then what makes those lives meaningful is itself betrayed.
>
> (Funtowicz and Ravetz, 1994, p. 197)

This introduction starts with a critical analysis of how the unintended side effects of instrumental means-end rationality embodied in the scientific and capitalist enterprise have destructive consequences for internal and external nature. Moreover, as these side effects are produced through human practices without anyone having intended to produce them, they appear as *natural* phenomena, external to our practices. Analogous to Marx's analyses of how transactions between isolated individuals in the market hide how the commodity form is a *social relationship* between people, the practices that created global warming were engaged in by private individuals, even by those having the best intentions, yet when aggregated, the consequences of those practices went far beyond what the individuals intended in private (Vogel, 2015, p. 200). Marx portrays a classical collective action problem known as the tragedy of the commons.

Since the beginning of the Industrial Revolution in England in the early 19th century, as the steam engine substituted the water wheel, production and consumption have grown uncritically as industry has slowly turned the productive forces into destructive forces. Society has historically endorsed the fossil fuel sector, since it provided energy accessibility and, in its wake, numerous innovations, which have led to higher standard of living. The awareness of the negative externalities propagated by these industrial activities upon the natural environment has risen. Nevertheless, there is, at the same time, a resistance in accepting that the fossil-driven industry, which has contributed with higher standard of living, is now accountable for a global crisis.

An increasing number of scholars indicate that the need for constant fossil fuel consumption, in addition to an industry drive to expand, is responsible for the current environmental crisis (Malm, 2016; Moss, 2019; Scavenius, 2019). According to this view, the "Anthropocene" is a misnomer: humans (Anthropos) have populated the earth and changed it, but without challenging its ecological boundaries. Rather, the history of global warming merges with the history of fossil capital.

Modernity, Anthropocene, or the fossil economy?

Modernity – the idea of human emancipation from parochialism, serfdom, and the self-imposed limits of traditional and religious norms through the powers of scientific knowledge, enlightenment, and the public use of reason – has become reflexive (Beck, 1986). Throughout human history, man has met challenges through innovation. However, the world is now struggling with the *unintended side effects* of the emancipatory project of modernity. Especially the postwar era of economic growth, prosperity, progress, and welfare that consolidated democratic capitalism in the West has produced a series of risks and crises – economic, financial, environmental, and viral – the management of which has become the dominating task before us. Our current environmental crisis is definitely the aggregated result of these side effects (Beck, 1986; Vogel, 2015, p. 90; Soper, 2020, p. 14).

According to Schumpeter (1938), the process of economic development consists of three parts: invention (conceiving a new idea or process), innovation (arranging the economic requirements for implementing an invention), and diffusion (whereby people observing the new discovery adopt or imitate it). From the cotton spinning machine in the 1780s that increased the aggregate wealth of society by decreasing the cost of production, to today's AI revolution, innovation has created solutions to some of our problems. As such, Schumpeter identified innovation as the critical dimension of economic change. He sought to prove that innovation-originated market power can provide better results than the invisible hand and price competition (Nakamura, 2000), and he focused on radical innovation that would significantly alter societies and start new business cycles. Technological innovation often creates temporary monopolies, allowing abnormal profits that would soon be competed away by rivals and imitators. These temporary monopolies were necessary to provide the incentive for firms to develop new products and processes (Nakamura, 2000); however, research has also shown that incremental innovation can have consequences for economic development (Abernathy and Clark, 1985; Christensen, 1995). On the other hand, innovation presents a downside when new problems arise due to negative externalities elsewhere, referred to above as the *unintended side effects* we now have to struggle with.

While we now are aware of both the positive and the negative impact that innovation and economic growth may have in society, current innovation research focuses on value creation in more than the economic dimension and reducing negative externalities where they may exist. Such externalities might include CO_2 emissions from smelter plants. However, externalities may alternatively be viewed as misplaced resources, and this book documents how those resources can be made valuable by being put in the right place. This way of *rightening the balance* includes creating a circular economy in its own right without employing oil as an additional energy source in the production process. In this way, transforming CO_2 into valuable products represents, paradoxically, a technology to take us beyond the fossil economy (the main driver behind the continuous economic growth in our time) as well as beyond its mortal side effects including global warming and loss of biodiversity.

Rationality, collective action problems, and alienation

Instrumental rationality, based on means-end considerations, has dominated modernity's approach to nature and ourselves. Based on scientific knowledge of our inner and outer nature, we as a society have learned to utilise natural and human capital in ways that have unleashed a colossal productive force. Scientific data from the last three decades clearly document that current climate hazards and biodiversity loss are the price we pay for this rational and objectifying treatment of humans and nature. Let's take a closer look at *how* instrumental rationality impacts the environment. In one of the most defining contributions to contemporary climate ethics, Stephen S. Gardiner depicts climate change as a global moral storm, i.e., as a wicked collective action problem doubling at the intersection of space and time: if the absence of global institutions leaves us with poor prospects regarding the enforcement of any international agreement designed to protect our generation from the disastrous consequences of climate change, those prospects are even worse with regard to future generations (Gardiner, 2006). Behind the wicked structure of climate change is the tragedy of the commons, explaining how individual behaviour following instrumental rationality turns out to be irrational at the collective level.

In his book *Thinking like a mall* from 2015, the environmental philosopher Steven Vogel explains how under the capitalist economy our world building has the same structure as the tragedy of the commons. He reminds us that even though we as individuals do not intend to build them, the different kinds of threats toward the environment *are* in fact produced by *us*, the individuals who make up the society. The environment (including nature) is not produced by something outside our social practices and institutions, or by greedy politicians or corporate interests around the world beyond our control. It is built by us, for good and for bad, Vogel says. Marx analysed this situation of *alienation* as one of the isolated and strategically acting individuals in a market, unable to coordinate their actions in a rational way. Alienation occurs when a human-made object or a social phenomenon is conceived as something beyond human knowledge and control, thus becoming an alien power standing over and against us. Under capitalism, humans become alienated from their economic and social relations because these relations, according to Marx, become external to us, appearing as they do as relations between things, not between persons. More specifically, our material environment consists of objectified human work, most of which is "dead labour," i.e., materialised work, or *capital*. Existing outside of humans, this material exercises power over them and in that sense is alienated human labour. In his famous analysis of the commodity form, Marx extends this perspective to the whole economic system. Profit, market, money, prices, needs, even time ("Time is money") are objectified forms of human-productive labour taken under the alienation of capitalism and which exert coercion over the social life from which they are abstracted. Although these phenomena appear to be objective, they are in fact phantoms that hide how the commodity form is a social relationship between people who "in their eyes assumes the fantastic form of a relationship between things" (Marx, 1889, p. 43). Consequently, the crisis produced by capitalism, like the financial crisis and the climate crisis, appears to us as facts of nature, and not as the results of our own doings (Vogel, 2012, p. 303).

What we are alienated from, then, is the environment, and this specific kind of alienation has fatal consequences in terms of what we are doing to that environment. An environmentally concerned industrialist (like the CEO at Finnfjord AS) or fisherman or commuter all face the problem of the commons. Their praiseworthy acts of investing in green technology, protecting the fish stocks, and of starting to use collective transport to work will, in fact, have no significant impact on achieving the goals of preventing pollution, saving the fish stocks, and preventing global warming (Ibid., p. 309).

Furthermore, the history of the fossil economy seems to confirm Vogel's point that the capitalist social order functions like a kind of nature, what G.W.F. Hegel called "second nature," and that the capitalist ecology of the market is intertwined with the first "natural" ecology endorsed by environmentalists. And since both kinds of nature have their own autonomy, something can be built through our practices, without our having intended to build it. Something about our factories, oil wells, and combustion engines escape our intentions: no one intended global climate change or acidification of the oceans, even though we built those artefacts through our practices. Most environmental problems are caused, not with the intention to dominate or spoil nature, but by social practices that result in unintended and often harmful effects on the world. Still, since *we* are the ones who build our environment through those harmful practices, we are responsible for *changing* them. We are "under the obligation to build the sort of community capable of averting further climate change." This ethical obligation, however, links climate change (and climate ethics) to *democracy:* it is an obligation to move from the realm of the market to the realm of politics (op. cit., p. 214).

CCU between Norwegian modernisation and fossil capitalism

The Carbon Majors Database documents 90 companies as being responsible for 63% of the world's total emissions of CO_2 and methane (Heede, 2014, p. 229; see also Climate Accountability Institute). Some of these corporations have long engaged in coordinated campaigns to resist necessary changes while knowingly destroying the planet.[3] One could argue that these companies do not have good intentions. Another viewpoint posits that the companies are caught up in a fossil capitalist system from which they cannot fully disentangle themselves. A question to be asked in our project is: How can we help them? Here we might turn to Mariana Mazzucato, who emphasises the significant role of the state to foster innovation and new industry. The state can give a "directional push" to innovation activities and successful innovation, often involving collaborations between the public and private sectors where the public sector sets a clear goal and helps stimulate innovation to reach that goal (Mazzucato, 2013, 2018, 2021).

A decade after the first smelter plant was opened in the location of Finnfjord in 1960, Norway was busy exploring the seabed within its 200 miles Exclusive Economic Zone – with great success. Andreas Malm's distinction between the proto-fossil economy and the fossil economy provides an excellent analytical framework for understanding the position of Finnfjord AS at the crossroads between the democratic and the fossil power circuits. The opening of the Ekofisk oil field on the Norwegian continental shelf in 1971 marks the beginning of Norway's and Finnfjord's integration into a global fossil economy based on a "self-sustaining economic growth . . . depending on the increasing consumption of fossil fuels . . . which generate[s] sustained growth in emissions of carbon dioxide" (Malm, 2016, p. 11), an integration that became complete when Norway entered the *globalised fossil economy* in the early 2000s. Then the largest players in working life, business, and the oil industry decided to "work to maintain the competitiveness of the Norwegian continental shelf, so that Norway remains an attractive investment area for the Norwegian and international oil and gas industry" (https://konkraft.no/). This turn meant nothing less than "Norway's economic shift towards becoming a major oil producing (and dependent) economy . . . in the context of globalisation" (Kristoffersen, 2007, p. 46). The story to come was a story of Norway and the Finnfjord company being integrated into the global fossil economy based on "self-sustaining growth" as defined by Malm in the above quotation.

In contrast, coal-fired smelters like Finnfjord AS fall under the definition of a *proto-fossil economy*, i.e., an economy – to rephrase Andreas Malm – in which (1) a coal industry has developed, with underground mines and regular trade; (2) coal has penetrated industry as a heat provider; and (3) impressive rates of growth in coal consumption are achieved during the phases of substitution, *without any self-sustaining economic growth being predicated on fossil fuels* (Ibid., p. 52).[4] This is a crucial point when assessing the sustainability of any industrial ecology, for if it's the *capitalist* character of production, i.e., the competitive drive for endless consumption and growth in order to increase the profit rate, which "[generates] a sustained growth in emissions of carbon dioxide" causing global warming, then it's simply wrong to blame the installation of the coal-fired electrolyte process in the production line *as such* for its cumulative effects on the climate. Global warming is caused not by innovative industry using regional resources like hydropower and coal but by a mix of an interminable consumption and extensive capitalist accumulation of wealth that converts living and regenerating nature (including the atmosphere) into death, i.e., into money. To paraphrase a message from eco-philosopher Teresa Brennan: *Money does not regenerate life, only nature does* (Brennan, 2000, p. 2). In the algae project, exactly *nature's* own photosynthesis is being used to reduce the environmental footprint of aquaculture by replacing exploited stocks of wild fish, as well as soy grown in the Amazon and shipped to Norway, with sustainable aquaculture feed made from algae biomass. In this way, CO_2-capture nurturing mass cultivation of algae, which in turn is converted to aquaculture feed for the local region,[5] could make up a green circular economy of its own.

This point is crucial to the project: that we need to "now" develop a clear history of which actors and choices led us to where we are today. Writing history is not, as Walter Benjamin reminds us, to enlist the sequence of events, discoveries, and victories that confirm the progress and ultimate goals of civilisation, but to uncover what has been overlooked, forgotten, and discarded, above all that which cannot be interpreted as a contribution to a "progress" having become a problem to itself. Surprisingly, one of the hidden treasures to be uncovered from our recent history is that the Norwegian welfare state was strong and healthy well before the discovery of oil under the country's continental shelf (Skirbekk, 2011). Sustainable industrial innovation at Finnfjord AS should take advantage of that precious, pre-oil heritage of ours. However, that this heritage was formative of Norwegian resource management in the early days of the country's oil trajectory as well finds support in Kristoffersen 2014 in a comment on the political system's management of resources:

> Through an established so-called Keynesian welfare state and the politicians' ability to steer political and economic developments during the oil crises, legitimacy was established, as was support in society at large, based on the state's adherence to the principles of the two aforementioned negotiations in parliament (moderate pace and the ten "commandments").
>
> (Kristoffersen, 2014, p. 22)

We have characterised the early history of the Finnfjord company as a classic story of Norwegian industrial modernisation, as well as classified the early phase of the company's ferrosilicon production as proto-fossil, as Norway had not yet become a petroleum-dependent economy. The question is how we ended up in that dependent, fossil economy. By the 1990s, Norway had fulfilled its first objective as a petroleum nation, namely control and ownership over the petroleum resources and a moderate pace of extraction of oil and gas resources. Several de- and re-regulative moves were initiated, typical of how states reorganise and develop strategies to capture a greater share of the global market and which, in the case of Norway, gave the industry a "steady hand on the wheel" (op. cit., 20). This reorganisation, as well as the tripling of oil and gas production in 15 years (1989–2004), marked a new era in the Norwegian history of oil, while deeply affecting its climate credentials. Oil was monetised through the establishment of the petroleum-financed Government Pension Fund of Norway, and, thus, not anymore seen as a limited resource – the perspective dominating in the 1970s when the strategic principles and plans were made.

Thus, Norway's entering the globalised fossil economy can be analysed according to changing statehood, and the ways in which the oil industry partnered with different branches of the state. As mentioned above, the public–private partnership Konkraft has played a pivotal role in maintaining petroleum dependence and strong state-industry ties, with political implications for Norway, including the way CO_2 emissions have been addressed. According to Kristoffersen, these changing priorities reflect how the state as an actor is not static or neutral, existing separate from the economy and civil society. Statehood is always shaped by "evolving social relations, actively produced and transformed through socio-political struggles at various geographical scales" (Brenner, 2004, cited in Kristoffersen, 2014, p. 52). This leads in the final analysis to the current weakening of the power of the oil industry as there is a competing focus on green re-industrialisation reflected in statehood, especially in Northern Norway where few oil and gas projects have materialised. This is currently being played out in competing projects between fossil-fuelled CCS projects, on the one hand, and industrial CCU, on the other, in Northern Norway.

An avant-garde nostalgia: Norwegian (post-)modernisation

Historically, Norwegian modernisation in many respects represents successful attempts to institutionalise solutions to the kind of collective action problems discussed above. Part of our aim in this book is to show how the Finnfjord company is the legitimate child of *socio-cultural learning processes* that were in place well before Norway became part of the global fossil economy. In fact, Norway has brought important natural resources out of the market and into the realm of politics through its social model. Ownership of the oil and gas in its continental shelf was brought under national (state) control from the very start, and the revenues from the exploitation of those resources were democratically redistributed for the benefit of public infrastructure and welfare, and eventually invested in the world's largest national welfare fund. Norway has also based its fishery policies on scientific knowledge, and the Norwegian government took strong political measures during the cod crises resulting from overfishing in 1980. As a result, the cod stock in the Norwegian and the Barents seas is the world's strongest. A third effort in political resource management by the Norwegian government is the entrepreneurial flagship *Langskip*, a national effort introduced by the government to capture industrial CO_2 emissions off- and on-shore and store them under the ocean floor, based on the technology of CCS.

Our example of public–private R&D cooperation at Finnfjord Ltd. belongs to this historical trajectory of Norwegian modernisation based on three success factors: *the entrepreneurial state*, *knowledge*, and *trust*. But as philosopher Kate Soper argues in the spirit of degrowth hedonism:

> The environmental crisis cannot be resolved by purely technical means . . . Green technologies and interventions (renewable energy, rewilding, reforestation and so on) will prove essential tools for ecological renewal, but only if they go together with a cultural revolution in thinking about prosperity, and the abandonment of growth-driven consumerism.[6]

The task before us of fundamental importance is to revive this heritage of sustainability so strong in the past, to save a whole *culture of frugality* with its related vocabulary and set of practices from oblivion, an attitude of prudence in resource management evident in phenomena as different as the petroleum guidelines formulated by the Norwegian government in the early years of extraction on the continental shelf – the *Ten oil commandments*[7] – our traditional culture in Norwegian seascapes valuing practices that had stood the test of time, prescribing lifestyles within the parameters of the local seascape environment, practising conservation, and respecting the contributions from our predecessors.

That there existed such a culture and attitude among the politicians responsible for the management of the oil and gas sector in the early years of the Norwegian petroleum trajectory is evidenced by the findings of Berit Kristoffersen discussed in Chapter 6. A powerful temporal element of social trust is inherent in this attitude, expressing a principle of resource justice between generations, i.e., the attitude of frugality. Finnfjord AS in many ways embodies this heritage of sustainability and prudence in the management of natural resources, corporate social responsibility, and personal commitment in terms of being Norway's last family-owned steel smelter. This uncovers an important relationship between trust and sustainability, as justice between generations is a core principle in any robust conception of sustainability.[8] But if the culture of frugality is based on social trust, what is the source of this trust?

In order to understand the significance of – and the challenges to – the three success factors *entrepreneurial state, knowledge,* and *trust*, it is helpful to look at the specific trajectory of Norwegian modernisation during the last 200 years. The philosopher Gunnar Skirbekk reconstructs modernisation as unfolding *action-based rationality* situated in historical agents and institutions (for a conceptual clarification, see chapter 1 in Skirbekk, 2011). In contrast to the picture painted above, rationality contains more than techniques for exercising dominion over nature: scientific and socio-political practices constitute learning processes based on multiple forms of practice-inherent rationality.

For instance, means-end (instrumental) rationality has been important in developing the natural sciences, as interpretive rationality has been for interpreting texts and law in the human and legal sciences. Argumentative rationality (as the embodiment of validity claims of what is true and morally right, and a discursive attitude of being open to the better argument) not only connects all these sciences but also signifies a specific kind of modern rationality: reflexive and self-critical argumentation is often said to characterise modernisation processes in important ways (Habermas, 1981). Rationality as practice is located in the form of development and use of scientific knowledge in technology and industry, in the political use of expert knowledge, and in socio-political learning processes of social movements and education (Skirbekk, 2011, p. 186).

This historical and situated conception implies that we need to seek rationality-as-practice in the development and use of scientific knowledge in technology and industry, and in the formation of public trust through socio-political learning processes. More specifically, the Norwegian history of industry, energy, and natural resources is intertwined with some *institutional* learning processes that were in place long before our engineers discovered oil. This institutional model is not taken out of thin air: the foundation for both the *redistributive state* and the *knowledge* *providing state* is the Constitution of 1814 and the slow building of state institutions, a competent and loyal civil service in the 19th century; the incorporation of popular movements through democratic processes, the formation of an enlightened public, public education and equal rights to education for all during the first half of the next; and finally the building of health services and hospitals along the entire coast up to the high north (Finnmark) paid for by, first, the fishermen's coffers, and subsequently by the state before and after the Second World War: all these processes merged in the march towards the strong, entrepreneurial state *before Norway started extracting oil in 1971,* but certainly was conditioned on *prepolitical virtues* and *public trust* among citizens, their elected representatives, and the state administration.[9] No doubt, the early history of the Finnfjord company is a classic story of industrial modernisation, Norwegian style. We can imagine that the family owner starting up in 1960 wanted to achieve some private (and public) goals: to expand a business, to create jobs for the benefit of the community, and to live in that community. He never intended to contribute to global warming nor to be forced into a global process of *self-sustaining economic growth predicated on fossil fuels*.

To sum up, the primary goal of the green transition in industry must be to secure its own (and the rest of the planet's) natural capital. In order to obtain this, we must make our economy less dependent on the export of oil and gas, and – based on the best of Norwegian traditions within industry and energy – build a circular economy bottom-up. The public–private R&D project at Finnfjord AS contributes to this task which is as much political as technological. However, for the needed cultural revolution of sustainable frugality, necessary for a transition away from consumerism, to succeed, we need to reflect on the concept of prosperity in a more dialectical way than is common in the dominant and evolutionary narrative of modernisation processes. This could open up for a more complex narrative on the old/new divide, "a transcendence of the current binary opposition between uncritical progressivism and elegiac nostalgia. It would recast certain forms of retrospection as potentially avant-garde" (Soper, 2020, p. 154; for a dialectical conception of a future scenario for a "prosperous way down" based on a pulsing cycle of consumption, descent, and decession,[10] characterising any natural or social system, see Odum and Odum, 2006). Far from being an uncritical elegy for values in the past, the distinctive property of Soper's idea of avant-garde nostalgia is the element of *critique*. Reminiscent of the Hegelian concept of immanent critique in the tradition from Critical Theory, where social critique aims at the unfolding of the emancipatory potential inherent in our contemporary social institutions, our task is "to restore what is lost, but in a transmuted and (so to speak) corrected form" (Soper, 2020, p. 155) through a critique of a contemporary social and economic order driving overconsumption of nature through consumerist lifestyles. In this promising context, responsible innovation could prosper by combining a backward-looking and a forward-looking perspective by way of creative destruction (Schumpeter) bringing on the wisdom and attitude of frugality from the era of Norwegian modernisation before oil as it creates markets for sustainable products and lifestyles for the future ahead. The old/new solution lies where the cultural revolution of revived trust and frugality meets responsible innovation. In the sustainable markets thus created, responsible consumers would buy products exclusively from producers taking corporate social responsibility and respecting limits in nature.

An environmental vision: biological capture of factory emissions

"The economic growth and affluence made possible by the yoking of scientific technology to a modern market economy served to legitimise public power for several centuries," writes Seyla Benhabib in a recent essay, and continues: "We have reached the end of this cycle and we need a science in the service of reversing the damages inflicted by the Anthropocene on the earth" (Benhabib, 2021, p. 1). The public–private CCU R&D project at Finnfjord Ltd. is an undertaking of that task – albeit with one important qualification of Benhabib's statement: as testified by the history of the fossil economy, the damages that science is now attempting to reverse are inflicted by *Capitalocene* whose main energy source has been fossil fuels. The project's physical starting point is a family-owned smelter plant and one of the world's largest ferrosilicon producers. The energy basis for the production of ferrosilicon was the construction of the Innset hydropower plants at the large lake Altevann in Bardu in Troms county. Without skilled hydropower engineers trained and employed by an active state in a postwar Norway characterised by stability, competence, and industrial development, this industrial company would never have seen the light of day. Eleven years later, however, Norwegian engineers discovered the large *Ekofisk* oil field on the Norwegian continental shelf. That event in 1971 heralded Norway's path into the global fossil economy, the main driver of dangerous climate change already harming countless people and ecosystems on the planet. The Finnfjord smelter plant became a huge CO_2 emission point during the 1960s and 1970s, yet it was not part of any such global fossil economy. The fact that the company, like any other company in the world, was eventually forced into that economy, changed its terms radically.

Thus, in 2007, and perhaps against all odds, it launched a plan to become the world's first carbon-neutral smelting plant. In 2012, the company installed an innovative energy recovery system with a capacity to generate approximately 340 GWh/year of electric power. In Chapter 2, Hans Chr. Eilertsen, Richard Ingebrigtsen, and Anja Striberny present a unique collaboration with UiT The Arctic University of Norway, launched 2014 where many years of research on marine microalgae (diatoms) were to merge with North-Norwegian industrial history in the form of biological capture of factory emissions of CO_2. After one and a half decades and nearly EUR 100 million worth of investments and technological innovation within energy efficiency and climate abatement, Finnfjord now claims to be the most energy-efficient and environmental-friendly smelting plant in the world (see Chapter 2 in this book; Knutsen, 2017, p. 1).

The Algae Project primarily tests the concept where marine microalgae (diatoms) are mass cultivated during all seasons of the year. Initial challenges to this concept included the polar night and winter sea temperatures below zero. As the project progressed, these challenges were overcome by applying artificial illumination in conjunction with large light-efficient local diatoms adapted to northern latitude climates. Algae production takes place in cost-effective vertical column photobioreactors integrated into the Finnfjord factory production line. The largest reactor (300,000 L) is probably world's largest vertical column photobioreactor. The project has attracted large interest from industrial as well as R&D partners and is now facing upscaling to full industrial size. The ambition is that at least 50% of the factory fume CO_2 (150,000 tons/year) shall be bound by photosynthesis in the diatom mass-cultivation process. The produced biomass has been tested with success as an ingredient in fish feed and other added-value applications related to, for example, human consumption. In addition, the diatom cell walls, being photonic crystals, show promise in improving performance in both battery and solar panels. Thus, the whole cell is being utilised. The main findings from the project are that the sequestration of factory fume CO_2 by photoautotrophic algae represents a sustainable production of biomass, life-cycle assessment (LCA) process evaluations revealing that local conversion of factory fume CO_2 to aquaculture feed has the potential to lower the overall CO_2 footprint of the aquaculture industry as well as release the pressure on exploited fish stocks. The first step in the production process is carbon capture, which reduces local pollution. In addition, it contributes to UN Sustainable Development Goals (SDGs) 2, 3, 9, 12, 13, and 14 (see Chapter 5). Microalgae cultivation must, therefore, as Eilertsen and Ingebrigtsen conclude, be considered a valuable supplement to future CCS processes.

New marine ingredients for future salmonid feeds

Aquaculture production is predicted to continue to grow, and, by 2050 Norwegian salmon industry, is predicted to need at least 6 million tonne of dry feed. There is growing concern that overexploitation of marine resources may have ecological implications on food availability for marine fish. In Chapter 3 Sten Ivar Siikavuopio and Edel Elvevoll, therefore, focus on farmed salmon and summarise emerging and assumed marine feed ingredients to be used in the future salmonid feeds. They argue that knowledge related to utilisation of new marine feed resources for aquaculture, like microalgae, marine invertebrates (mussels, copepods, and euphausiids), and mesopelagic resources, is important for sustainable growth and development. To increase the use of these new resources, the ingredients need to be available in large quantities, with a predictable supply, and at competitive prices for functional use. Feed may account for around 75% of greenhouse gas emissions in the national value chains (omitting airfreight to distant markets). Thus, the government has issued a specific mission to develop new and novel feed raw materials that reduce GHG emissions, while enhancing employment and secure development of this industry.

Sustainable development goals, human rights, and the capability approach in an Arctic context

The Special Report entitled "Global Warming of 1.5 °C" was released in October 2018 by the IPCC, offering a range of climate scenarios and projections. None of these projections suggests that a ceiling of a 1.5 °C increase in global warming above pre-industrial levels is compatible with fully realising the SDGs. Each scenario requires some level of compromise, necessitating the sacrifice of at least one SDG in the pursuit of climate adaptation measures.

With the SDGs rooted in human rights, which serve as their foundational bedrock, the United Nations emphasises the importance of viewing human rights as protectors of human capabilities. In this context, the Capability Approach, developed by economist and 1998 Nobel Laureate Amartya Sen, becomes vital. However, as noted in the UN Human Development Report, this approach needs further explanation and refinement. A nuanced framework based on capabilities is essential to effectively manage the compromises and trade-offs involved in pursuing SDGs grounded in human rights entitlements.

Anna-Karin M. Andersson helps illuminate this imperative in the ensuing chapter focused on understanding and managing trade-offs between SDGs, which is crucial for conceptualising and implementing adaptation initiatives, as exemplified by the development of algae-based aquaculture feed at the Finnfjord facility. Central to the chapter's discussion is whether the development of algae-based products can mitigate conflicts related to human rights.

As the chapter unfolds, it begins by highlighting the crucial role of human rights within the SDGs framework. The discourse then critically interprets selected human rights using the Capability Approach as a lens. Following this, the chapter clarifies the dynamics and nature of rights conflicts. It concludes by examining whether the development and introduction of algae-based products, like fish feed, can resolve or mitigate conflicts associated with human rights.

Transforming resources: the university as a CO_2 catalyst

Elin M. Oftedal and Øyvind Stokke tell the story of how the algae project at Finnfjord came into being through the lens of Institutional Theory and "Responsible Innovation" (RI). As delineated by Stahl et al. (2021), RI is a commitment to fostering technological research and innovation which is deemed socially desirable and enacted for the public good. This paradigm of RI weaves an integrated vision of an ideal future, crafting responsible processes and yielding outcomes that resonate with both silent and vocal stakeholders.

The framework portrayed by Stilgoe et al. (2013) is instrumental in advancing RI, incorporating elements of anticipation, reflectiveness, inclusiveness, and responsiveness. The aspect of anticipation encompasses the analysis of both intentional and potential unintended impacts emerging from the employment of digital technology within home health services. Reflectiveness examines the underlying purposes, impacts, uncertainties, and risks associated with the deployment of digital technology in home environments. Inclusiveness embodies a culture of dialogue and engagement to actively integrate perspectives from pertinent stakeholders, while responsiveness interrogates the adaptability of innovations and flexibility in delivering digital technology. In fact, Blok and Lemmens (2015) succinctly encapsulate the essence of RI, positing that it represents "regular innovation plus stakeholder involvement concerning ethical and societal considerations."

Yet, it is imperative to acknowledge that RI does not occur in isolation. Firms, notwithstanding their visionary ideals, ultimately navigate and negotiate with market forces, calibrating their strategies in response to the delicate balance of price and value dynamics, as noted by Oftedal et al. (2019).

"The Tragedy of the Commons" underscores the reality that while the cost of exploiting common resources is negligible for individuals, it accumulates into a significant societal burden. This cost–benefit misalignment incentivises individuals to persist in activities detrimental to society. Against this backdrop, Mazzucato (2015) advocates for enhanced state intervention in markets vital for societal welfare.

The Finnfjord Algae Project exemplifies this approach, engaging in collaborative endeavours with a public university and receiving state-funded financial backing. This collaboration represents a concerted Norwegian effort to harmonise market dynamics with political accountability for climate action.

Universities, integral components of the public sector, serve as crucibles for knowledge creation and innovation. The concept of the "entrepreneurial university" underscores the pivotal role of academic institutions in driving innovation and entrepreneurship, translating research into tangible innovations (Rothaermel, 2007). This chapter, using the Finnfjord case as its focal point, explores how universities can be invaluable instruments in pioneering and disseminating responsible innovations.

Opportunities and challenges in the CO_2 capture with Internet of Things (IoT)

One branch of the university–industry cooperation in the Finnfjord case included the IT. The large number of bioreactors used to provide the necessary production scale can also be utilised by computer science to run independent experiments for research and to optimise production by Internet of Things (IoT) technologies. IoT describes the data connections and exchanges between objects of the physical world, devices, and systems over the internet. Nowadays, information and communication systems are invisibly embedded in the environment around us – a fact speaking to Vogel's statement referred to above that our environment is *built* by us in certain ways. And the speed at which information technology changes our lives and our surroundings is certainly part of that building activity (see Introduction).

In Chapter 6, Roopam Bamal, Daniel Bamal, and Singara Singh Kasana first provide an overview of IoT technologies used in environments similar to the large bioreactors used in the cultivation of algae, such as fish farms. The end-user requirements have been identified using a set of high-level scenarios. One of the key insights is that the large number of bioreactors used to provide the necessary scale can also be used to run independent experiments for research and to optimise production. Multiple bioreactors also provide robustness: problems in one bioreactor should not influence other bioreactors. A distributed architecture is then proposed, reflecting these two observations. Edge computing is used to process data close to the sensors. This further supports robustness: the network can be partitioned if each bioreactor is able to observe, analyse, and control the local environment independently from the others. While the IoT ecosystem demands a lot of energy, new technologies continue to emerge – such as smart underwater sensor network (UWSN) – which enable new ways to monitor aquatic environments via sensors and improve the overall system.

From CCS to CCU and CCUS – the pitfalls of utilisation and storage

Presently, industrial processes are characterised by their intensive energy consumption, contributing to one-third of the global energy demand. These operations predominantly rely on fossil fuels to provide approximately 70% of their energy requirements (Al-Mamoori et al., 2017). This dependency is anticipated to persist, with fossil fuels projected to continue dominating the energy landscape for the ensuing five decades. Such fossil fuel-based energy consumption in the industrial sector is responsible for approximately 40% of global CO_2 emissions (Brown et al., 2012).

In this chapter, Oluf Langhelle, Siddharth Sareen, and Benjamin R. Silvester take a critical view on CCS, CCU, and carbon capture, utilisation, and storage (CCUS). The first part starts out with a brief history of the developments from CCS to the more recent focus on CCU and CCUS. In doing so, it outlines some of the key controversies and debates surrounding these technologies. These controversies are linked to different worldviews and key strategic choices following from these. It concerns different views on the role of technology and lifestyle changes, the possibility of eliminating fossil fuels, and what it might ultimately take to solve the challenge of living within planetary boundaries. The second part relates these controversies to the ferrosilicon factory Finnfjord Ltd. and the crucial question of whether CO_2 can or should be seen as a valuable resource. In doing so, different criteria for deciding the issue are discussed and problematised. Drawing on Morrow et al. (2020, p. 3), it is argued that two key issues should guide the analyses: "*Where does the carbon come from, and where does it go?*" These questions are then used to explore the question of whether CO_2 can or should be seen as a valuable resource and to what extent utilisation, the "U," makes sense from a sustainable development perspective.

Black is the new green: perspectives on the innovative use of CO_2 in the drive towards sustainable development

The United Nations, through its SDG 9, aims to catalyse transformative changes in industry, innovation, and infrastructure. The goal envisions the establishment of resilient infrastructure, the promotion of inclusive and sustainable industrialisation, and the stimulation of innovation. Finnfjord outlines an ambitious plan to upgrade infrastructure and retrofit industries by 2030, enhancing sustainability, resource-use efficiency, and the adoption of clean and environmentally friendly technologies and processes in line with each country's capabilities.

In the ensuing chapter, Ukeje Agwu, Tahrir Jaber, and Elin M. Oftedal delve into the Finnfjord case, framing it as a CCU project, with a particular emphasis on the diffusion of innovation aspect embodied by the "U" in CCU. The CCU mechanism is bifurcated into CCS and CCU, with the latter emerging as a potentially more feasible alternative. The CCU approach envisages the transformation of captured CO_2 into valuable products, leveraging it as a renewable feedstock, as opposed to its permanent storage.

The chapter subsequently engages with the diffusion aspect of CCU, exploring the innovative facet of algae cultivation for CCS. The diffusion process, crucial for determining the mitigation potential of projects like the algae initiative at Finnfjord, is understood in the context of innovation diffusion. Within this framework, Agwu, Jaber, and Oftedal critically analyse four product types to evaluate their contribution to sustainable diffusion.

Applying and extending Rogers's (2003) seminal diffusion framework through a sustainability lens, the analysis introduces four additional criteria: ecological integrity, economic viability, societal equity and welfare, as well as cultural and ethical norms. The term "substitution" also is discussed in this expanded framework, supplanting the concepts of triability, observability, and complexity. This substitution principle posits that a sustainably diffused product should ideally replace an existing product rather than generating new demand, unless such demand inherently aligns with sustainability principles.

On diatoms and the virtue of sustainability

The real strength of the local vision and initiative at Finnfjord Ltd. is the way it demonstrates how a modern factory can create its own, circular ecology versus economy connecting local, regional, national, and global levels. Hopefully, this effort will contribute to building an oil-free energy future beyond the *self-sustaining economic growth* of the fossil economy. The revolutionary significance of a circular economy concept is that it breaks the vicious cycle of continuous overconsumption of commodities, which, in the end, is predicated on a continuous overconsumption of nature: capitalist production for overconsumption "is based on the one process which fails to reproduce, or assist the reproduction, of other forms of life" (Brennan, 2000, p. 2; see also ch. 10, p. 187 in this volume). A recent UN report states that "nature is declining globally at rates unprecedented in human history – and the rate of species extinctions is accelerating, with grave impacts on people around the world now likely" (UN, 2019). In Chapter 9, Erik W. Strømsheim argues that mass cultivation and use of marine microalgae should have a prominent place in a wider sustainable programme to address this issue. Taking the perspective of *environmental virtue ethics* (EVE), Strømsheim reveals a great potential role for diatoms in a wider sustainable programme to address the problems associated with the decline of nature. By engaging in current debates between EVE and ecological ethics, he hopes to show that there is common ground which has the potential to further develop the concept of sustainability in a fruitful way in this context.

Conclusion: green innovation – grounds for a new economy?

Climate change must be explained as a result of a one-sided societal rationalisation where (1) the cognitive-instrumental, cost–benefit perspective of the capitalist economy has been institutionalised through private property rights; (2) that economy based on endless commodity consumption becomes predicated on fossil fuels. The unavoidable result is the tragedy of the commons. Global warming must accordingly be understood as a collective action problem that can only be solved by restoring the discursive connection to others that our alienation under capitalism has made impossible. Because environmental problems are structural problems, my ethical obligation as an individual consists in changing the social structure so that the form of real coordination of our individual actions becomes possible that respects the planet's ecological and climatic boundaries. In this concluding chapter, Øyvind Stokke and Elin M. Oftedal pick up the discussion threads from each chapter and connect them to the changing statehood, maintenance of petroleum dependence and strong state-industry ties with its implications for political space in Norway, including the way CO_2 emissions have been addressed. By having committed themselves to an extensive, collaborative private–public green innovation project, thereby providing environmental-friendly and healthy aquaculture feed as well as resources for commercial collaborations within eco-methanol, solar panels, and battery production, Finnfjord Ltd. have arguably shouldered that obligation. After all, the iCCU project is a demonstration of the argumentative rationality of the doctoral research programme, ideally an open and informed discussion, in a common search for the better argument, meeting the instrumental and strategic forms of the rationality of the industrial company through a private–public partnership motivated by a vision of a "green" economy. Coming from different scientific disciplines, participants in this type of academic activity must be open to (and interested in) relevant counter-arguments, directed at one's own claims: a common argumentative search for better reasons, away from less good reasons, as one is open to counter-arguments, even about one's own presuppositions – this is what the researchers at the high-quality academic university have in common.

Notes

1 KS/AS Fesil Nord was founded on 1 March 1960. After the bankruptcy in 1982, the company Finnfjord AS took over the production units and restarted operations (www.finnfjord.no/no/).

2 Cf. the subtitle of Rafael Ziegler's book: *Innovation, ethics and our common futures: A collaborative philosophy*.

3 Exxon Mobile is the most striking example, see Cook et al. (2019). I owe the general point to Jens Kaae Fisker at the University of Stavanger who stressed this important aspect of the fossil fuel industry in his comments to this introduction.

4 This historical three-step definition of the fossil economy is a slight modification of Malm's own definition which contains five steps.

5 Importantly, Finnfjord AS is located close to Senja, Norway's fifth biggest island, the location of a significant part of the country's aquaculture industry.

6 Soper (2020, p. 1).

7 Cf. Kristoffersen, B. 2007. *Spaces of competitive power*. Master thesis. Department of Sociology and Human Geography. Oslo: University of Oslo, p. 48. Kristoffersen's citation of Bjørn Vidar Lerøen, senior advisor in the Norwegian oil company Statoil, expresses a deeply held attitude to resource management embodied in the oil commandments:

> The Norwegian petroleum politics created in the early 1970s were built on bold and mature and long-term political considerations and decisions. And my summary after all these years is that the generation that wrote the ten oil commandments . . . Well, there are not many politicians of that kind today. The boldness, the nerve and long-term perspectives are not there anymore.
>
> (Lerøen, Statoil)

8 According to Chris Armstrong (2021),

> The claim that we are obliged to preserve natural resources for future generations is one that many people find intuitively compelling. To degrade the natural world so as to leave future people with an impoverished environment in which to live, by contrast, is widely believed to represent a clear instance of wrongdoing.

9 Skirbekk, 2011; on the health care services and hospitals along the coast financed by the fishermen's coffers, see Elstad (2011, pp. 35–42):

> The public hospital system in Northern Norway was built on the wealth from the sea, closely linked to the Lofoten fishery and the spring cod fishery in Finnmark. We got a decentralised hospital structure in Northern Norway, formed by coastal settlements and local fisheries.

10 For an outline of the semantic meaning of the word decession, see Odum and Odum (2006):

> There are many new words being used for this future scenario, such as decession, the opposite of succession . . . The expectation of general systems concepts of self-organization for any system is an alternation between slow production, growth and succession followed by a pulse of consumption, descent and decession. Pulsing on each scale is an accumulating build up of products converged to centers, followed by descent with sharp, short diverging dispersal. Many assume that the only way down is to crash and restart. But many systems program orderly descent and decession that is followed later by growth and succession again. For example, in the past, ecosystems and human cultures in northern latitudes expanded and contracted seasonally. They decreased populations, stored information, and reduced function with such mechanisms as spore and seed formation, hibernation, migration, and staging inactivity and rest.
>
> (Odum and Odum, 2006: 22)

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2 Industrial CO_2 capturing by mass cultivation of microalgae (diatoms)

Processes, sustainability, and applications

Hans Chr. Eilertsen, Richard A. Ingebrigtsen, and Anja Striberny

Project background and diatom cultivation

In the 2012–2013 academic year, a research group at UiT The Arctic University of Norway, with expertise in the physiology and ecology of planktonic microalgae, took on the challenge to test industrial mass cultivation of certain species of microalgae. This ambition was driven by the increasing focus on photoautotrophic (photosynthetic) microalgae as future biofuels, as well as a source of feed and food (Demirbas, 2009; Ratha & Prasanna, 2012). However, mass cultivation of microalgae at high concentrations demands a carbon (CO_2) source at concentrations far above natural levels in the air or sea. At the same time, the ferrosilicon factory Finnfjord AS (which releases 300,000 tonne of CO_2 and 1000 tonne NO_x factory fume/year) was actively seeking more sustainable production processes. In this context, carbon capture and storage (CCS) was, for obvious practical reasons, not considered a viable alternative; but practising carbon capture and use (CCU) by sequestering CO_2 with microalgae from the fume – and, at the same time, performing biosynthesis of nutritious biomass – seemed attractive and possibly economically sustainable.

Finnfjord AS in northern Norway is one of the world's most energy-efficient and environmentally friendly ferrosilicon producers. Located in Finnfjordbotn, the company has a total production capacity of 100,000 tonnes of ferrosilicon per year. The ferrosilicon produced at Finnfjord is used in a variety of applications, including the production of steel, iron castings, and aluminium alloys, and is committed to sustainable production and works to reduce its environmental impact. Finnfjord utilises an energy recovery system where factory fume heat is used to generate around 340 GWh of electric power by means of a steam turbine and a generator. Further, Finnfjord has invested in a number of energy-efficient technologies and is developing new ways to utterly reduce its greenhouse gas emissions. The research facilities at Finnfjord today include four reactors (2 × 6000 L, 1 × 14,000 L, 1 × 300,000 L) with infrastructure, integrated into the factory production line. Finnfjord is today the only privately Norwegian-owned ferroalloy plant in Norway.

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Finnfjord AS lies in close proximity (1 hour) to UiT, in the city of Tromsø. Introductory meetings between UiT and Finnfjord soon revealed this common interest in CCU by introducing fast-growing microalgae as CO_2-sequestering agents. After some basic funding was raised, the first cultivation attempts were initiated by UiT and personnel at the Finnfjord factory in early 2015.

Many considered this a high-risk initiative, in part because the plan would inject "bulk" fume with CO_2 directly into the culture, i.e., production would use the same fume that would otherwise be released into the air from factory chimneys. Fortunately, this concern has since become mute, since the algae does not take up harmful substances from the fume. In fact, algae biomass produced with fume exhibits lower heavy metal and PAH16 content than biomass produced with injected air (Eilertsen et al., 2022). Significant to note, this mass cultivation violated several commonly accepted cultivation concepts, such as employing a large diatom microalgae, rather than the small green species (e.g., *Chlorella* sp.) which had commonly been used in most previous biorefinery attempts. Yet these departures from previous norms produced success that seemed driven by luck, for example, the large cells exhibit lower self-shading than small cells, and thus allow for the use of a large (300,000 L) simple vertical column reactor with long optical depths (Eilertsen et al., 2023). Following this path, the UiT – Finnfjord cooperation has developed positively and is now one TRL level away from the full industrial scale. Successful to an exemplary degree, the interdisciplinary academia–industry cooperation has produced a result with vast potential for both positive ecological impact and commercial return, for example, sustainably produced lice-deterring aquaculture feed for salmon (as we describe below). Detailed results from the project are in Agwu et al. (2022) and Eilertsen et al. (2021, 2022, 2023).

Diatoms

- Are unicellular photosynthetic microalgae found in all types of aquatic habitats.
- Comprise at least 100,000 species.
- Dominate as primary producers in areas with high production of fish (upwellings).
- Have silica (transparent glass, SiO_2) cell walls, and the size ranges from 1 to 1000 µm.
- Can grow (divide) fast, i.e., maximum > 2–3 doublings/day.
- Are highly diverse with respect to size, growth potential, and physiology.
- Are highly nutritious with respect to omega-3 fatty acids and protein.
- The species we cultivate (*Porosira glacialis*) has 19–33% lipid and 9–14% omega-3 (mainly EPA).

Interest in industrial mass cultivation of microalgae is not new, but began in the early 1950s, when microalgae were first used to transform light (natural and artificial) into nutritious and energy-rich organic biomass. This early interest was motivated by the theory that microalgae could, for example, become new suppliers of sustainably produced biofuel (Wijffels et al., 2010; Granata, 2017; Chowdhury & Loganathan, 2019). In recent years, this interest has expanded with the aspiration to replace fossil fuels with sustainably produced oil products, and thereby reduce global CO_2 emissions. Yet, while several large-scale production initiatives have been implemented, none of these have yet met success at scale, and the annual global production remains far too low, i.e. 50,000–60,000 tonnes (Moody et al., 2014; FAO, 2021).

Global energy-related CO_2 emissions increased in 2022 by 0.9% (i.e., 321 million tonnes), reaching a new high of more than 36.8 billion tonnes, due to an increase in world population and industrial activity (Iglina et al., 2022). The response to this, according to the IPCC Sixth Assessment Report, must be drastic reductions in CO_2 emissions (IPCC, 2022). These reductions can only be achieved by minimising the use of fossil fuels, along with capturing and sequestering CO_2, while pursuing the development and implementation of new and more carbon-neutral technologies and energy sources.

The first initiative to reduce CO_2 emissions was the Kyoto Protocol in 1997, followed in 2016 by the Paris Agreement. The main aim has been to maintain the average global temperature at its present level and, eventually, to mitigate climate change through diverse means (Aichele & Felbermayr, 2012; Kuriyama & Abe, 2018; Bauer & Menrad, 2019; Maamoun, 2019). In this pursuit, many initiatives have been launched to decarbonise carbon-intensive industrial sectors. Yet we experience an increasing demand for alternative sources of energy and fuel, i.e., specifically biofuel. The so-called first- and second-generation biofuels are based on, for example, sugar, starch, vegetable oil, animal fat, and non-food parts of plants (Chowdhury & Loganathan, 2019). These biofuels are not without effect on the environment, economy, and society (i.e., what we collectively term as sustainability). Therefore, together with the fact that climate drivers (e.g., CO_2) vary, it seems crucial to be able to quantify sustainability. However, this is not an easy task (Muraille, 2019), largely due to problems with apparent incommensurable entities (Melas, 1995). Such approaches traditionally have been based on the three-pillar conception, i.e., social, economic, and environmental sustainability (Purvis et al., 2019). These are, in fact, of unclear academic origin and, for obvious reasons, difficult to compare quantitatively.

Photoautotrophic (photosynthetic) members of the first generation can capture CO_2, but there is a threshold above which they cannot produce enough biofuel without threatening food supplies and biodiversity. Some of them are also prohibitively expensive while producing only limited greenhouse gas emission savings. Life-cycle assessments of first- and second-generation biofuels have often shown that they exceed those of traditional fossil fuels, in terms of environmental sustainability. This causes biofuel of the third generation to emerge on the sustainability scene, being made up primarily of biomass of micro- and macroalgae and utilisation of fertilisers (N and P) and CO_2 as feedstock. Thus, cultivating microalgae also come to the fore as important players in CCU processes (Nguyen et al., 2023). CCU processes can be upgraded to result in value-added (VAPs) products with various lifetimes, whereas some end up as permanent storages of carbon. Similar to CCS and CCUS, CCU reduces CO_2 emission, but can decrease the consumption of exhaustible fossil resources, and increases emissions-free economic value. CO_2 can function as a precursor of VAPs such as fuel, urea, methane, acetic acid, methanol, dimethyl ether, dimethyl carbonate, and succinic acid through various processing pathways, also biological (algae culture) ones (Daneshvar et al., 2022).

Microalgae are highly diverse with many hundred thousand species divided into different genera with sizes ranging from 1 to 1000 μm. Yet a large part of the species are in the range from 5 to 35 μm. It is important to note that most production initiatives have previously relied on a few small species (5–10 μm) such as Chlorophycean (green algae) and Cyanobacteria (blue-green algae) (Eilertsen et al., 2022).

The species selected for the present mass-cultivation experiment is from the diatom group. In nature, this group dominates fish-rich areas (e.g., upwellings) with high primary production levels (Kale & Karthick, 2015), in oceans typically dominated by low temperatures, compared to surrounding warmer waters. Further, the annual primary production in the Arctic, where dim light and low temperatures dominate, is 50–150 g C m^{-2} (Eilertsen et al., 1989; Pabi et al., 2008). Further south along the coast of Norway, the typical annual production is 100–200 g C m^{-2} (Matthews & Heimdal, 1980). This indicates that ocean primary production is not temperature limited, but rather alternates between nutrient (phosphate, nitrate, and silicate) and light limitation. This is seldom emphasised in a commercial microalgae production context, since most initiatives take place in tropical or temperate areas. Nevertheless, cold-adapted primary production species have naturally adapted to cold environments by, for example, evolving cold-adapted photosynthesis enzymes which allow better utilisation of light (Valegård et al., 2018).

As mentioned earlier, the Finnfjord – UiT project is now ready to enter full industrial-scale production. From the start, optimisation of the microalgae production process has been a major focus, to increase the environmental impact as well as economic sustainability; and researchers have extended this same focus to aquaculture's salmon production process. This means decisions have sometimes been based on sustainability factors rather than budgets and short-term economic profitability. In this context, implementing a circular economy focus has been important in producing both the ferrosilicon and the algae, as well as in responding to changing markets and volatile prices, for example, salmon. In short, the project has largely been driven based on the premise that capturing CO_2 from factory fume and turning it into an economic commodity will be highly appreciated as a circular economic business model for the future. As pointed out by many authors (Rizwan et al., 2018; Bhattacharya & Goswami, 2020), photoautotrophic biosynthesis at rates (more than 200% increase/day) that far exceeds land crops will surely be important to the future production of food, feed, and fuel.

There are, although, certain factors to be aware of, in pursuing optimal industrial mass cultivation of microalgae, including the following:

- Mass cultivation of aquatic microalgae in a biorefinery takes place at much higher concentrations than can normally be observed in nature. Yet we know microalgae have been adapting to natural environments for at least 1.6 billion years, since microalgae physiology exhibits such imprints (Mock et al., 2016). Thus, certain adaptations towards "wanted" properties may be achieved by adaptive laboratory evolution, or, "breeding."

- Microalgae in the oceans experience seasonal variations in the environmental growth factors, affecting both growth rates and stock biomass. Typically, growth and standing stock peaks during the spring and autumn blooms. In a reactor, the opposite is true, as the cultivation environment is usually constant.
- Microalgae grown in reactors are constantly transported through gradients of environmental factors with much higher turbulence than experienced in nature. As a result, cells are exposed to short-term (seconds and fractions of seconds) variations in light intensity and quality (wavelength), as well as potentially destructive current shears.
- Microalgae in natural environments live in diverse communities with multiple other algae, zooplankton, and marine animal species, in addition to a plethora of bacteria species. Cultivation in reactors is based on monocultures.

Due to these factors, the choice of species to cultivate is critical, as well as realising that knowledge regarding species growth traits in natural conditions, is not directly transferable to bioreactor scenarios. In the UiT – Finnfjord project, species were selected for high photosynthetic efficiency, a low degree of self-shading, and the ability to handle low temperatures (Finnfjord is situated at 69.2 °N and winter darkness lasts two months). To avoid the introduction of "alien species" to the local environment, it was important for us to use local microalgae species. While we support this choice for environmental reasons, Norwegian Law, in fact, prohibits the introduction of alien species to the environment.[1]

Early on, the present project was recognised as a CCU project with CCUS possibilities, where the CCUS "part" depends on the ultimate fate and application of the algae biomass (Daneshvar et al., 2022). The lifetime of the factory fume-originated carbon will be determined by the product´s application after the consumer's gate. Chemical absorption, membrane separation, and physical adsorption techniques are commonly used methods for post-combustion CO_2 capture, prior to projected "permanent" storage methods. These methods (e.g., deep ocean or geological storage) are currently unsustainable, both economically and environmentally. If we are to reach the Paris Agreement and practise global carbon neutrality by 2045, captured carbon should be utilised rather than buried (Li et al., 2023). Another issue here, relating to the "S" in CCUS, is introducing the algae as fish feed, which is produced with a low CO_2 footprint, as a potential replacement for conventional fish feed, which exhibits a high CO_2 footprint (Rotabakk et al., 2020). At present, since the industrial process has not yet been implemented, we cannot provide accurate sustainability analyses regarding the process of factory capture of fume/CO_2 through algae cultivation that is then used for feed production and aquaculture.

Status quo of microalgae cultivation and the Finnfjord initiative

Due to the hope for microalgae to become the next generation of fuel and food/feed, mass cultivation of microalgae has, as mentioned, had much industrial focus for more than 50 years (Han et al., 2019; Vonshak, 1990). Despite this, mass cultivation of microalgae must still be considered in its infancy, since global annual production is merely around 50,000 tonne (Nethravathy et al., 2019; FAO, 2021). The world total production of soy is today ca. 400,000,000 tons, about 9000 times greater than world algae production. The underlying reasons why microalgae mass cultivation has not gained greater momentum are diverse – for example, reactor malfunctions due to construction details, or reactors that can only handle small volumes yet demand high energy, de-watering, and illumination. Yet these various factors yield a simple conclusion: today's applied production processes are too expensive and complex (Eilertsen et al., 2022).

Today's microalgae photobioreactors (PBR's) are either open (pond) culture systems or closed (flat plate, tubular, and vertical column design) PBRs. The final purpose/use of the cultivation initiative will, although, determine the overall design of the reactor system, i.e., the geometry, mixing, power consumption, mass, and heat transfer capacity. These factors are determined by the species' physiological properties, temperature, pH/CO_2, and dissolved oxygen concentration. It is also crucial to minimise the effect of self-shading (Lee, 1999). Today's reactors, except from vertical column designs, are constructed to handle short light depths due to the high self-shading of the small species applied. These constructions are complicated and expensive devices that take up large areas versus volume cultured. From this, the ideal photoautotrophic cultivation system, in terms of production volume and area use, will be a photosynthetic-efficient and large species (low self-shading) in a cost-effective vertical column reactor (Rajendran et al., 2013). We, therefore, concluded in 2015, at the outset of the Finnfjord AS – UiT project, that the best combination would be a large photosynthetic, temperature-tolerant species in a large vertical column airlift photobioreactor (Eilertsen et al., 2022).

Importantly, our reactor system at Finnfjord was integrated directly into the factory's production line (Figure 2.1). Factory fume CO_2 and NO_x are fed to the

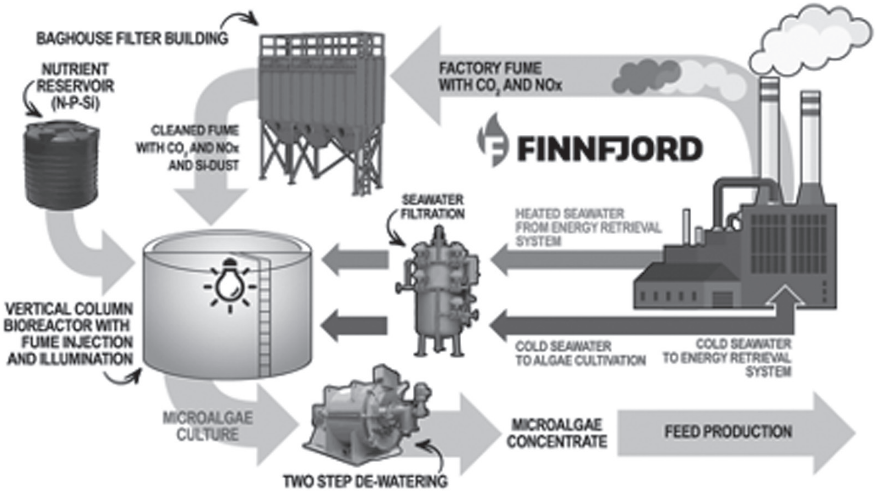

Figure 2.1 Inventory of the Finnfjord project reactor system.

vertical column reactor in a bottom-rotating dispersion device while inorganic nutrients (N, P, and Si) are fed at amounts compensating for the uptake by the growing algae in the reactor. Growth is regulated so that biomass concentration in the reactor is constant, and growth gain is harvested above this in a drum filter and a large bowl centrifuge and thereafter stored frozen (−20 °C).

As mentioned earlier, the project is now one TRL level away from upscaling to full industrial size. We have, from the start of the project, been aware that the three main drivers had to be the following: (a) production must be as environmentally sustainable as possible; (b) it must be profitable; (c) the final product must be attractive to relevant markets. Further, all processes are under constant survey for optimisation, especially those concerning illumination and integration in aquaculture industrial processes.

The biological–physical pillars and product attractiveness of the Finnfjord project

Large vertical column photobioreactors demand efficient illumination (Lee, 1999), especially in the north where winter darkness prevails (Eilertsen et al., 2023). The main biological–physical pillar in our project was, therefore, to achieve optimal use of light (natural as well as from artificial LED lamps), and thereby energy. We, therefore, applied a large diatom species in the cultivation. Large species have larger volume-to-area ratios than small species, which leads to lower biomass/biovolume specific absorption than for smaller cells, i.e., longer optical depths. Further, the main photosynthetic pigment Chlorophyll *a* has maximum absorption in the blue light regime (440 nm) while short wavelengths (blue) is absorbed less in water than longer wavelength light (red). In our concept, this is paired with blue pulsing light to “A large species blue pulsing light concept” that, in fact, can reduce energy requirements up to 50%, compared to conventional “white light” LED lamps (Eilertsen et al., 2023). Hence, we are operating a new concept that has not, to our knowledge, yet been tested and implemented in large-scale microalgae biorefineries.

Longer optical depths at a given biomass concentration also allow for the use of large and low-cost vertical column (tank) reactors (Eilertsen et al., 2022). These constructions have the advantage that the larger the tank-volume is, the less steel or glass fibre is needed per unit tank-volume (because volume and area increase with third and second potency representatively). Also, the cultivation environment (temperature) can be kept more constant in larger volumes and is less influenced by, for example, surrounding temperature changes. As mentioned, we cultivated large photosynthetic-efficient northern/Arctic (low temperature) diatoms. The final choice of species was, however, determined after thorough literature studies, as well as long-term ordinary batch growth experiments and numerous P versus I (photosynthesis vs. irradiance) experiments (Jassby & Platt, 1976). A thorough description of the project and some results are in Eilertsen et al. (2022, 2023), as follows:

The main product application of the biomass we aimed for was as an ingredient in fish (salmon) feed, or in fact as whole feed. Especially interesting here was also to test out diatom biomass as start feed for white fish species (Siddik et al., 2023). Published and ongoing tests where our microalgae/diatom have been applied as salmon feed additive, has shown substantial and statistically significant reductions in salmon lice infestation (Eilertsen et al., 2021), and this has been improved during tests in 2023. The evaluation of the potential of diatom (microalgae) biomass as a lice reducing ingredient in salmon feed was based on a hypothesis originating from own former experiments with fish larvae, sea urchins and other published results with copepod grazing deterrence induced by diatoms (Eilertsen & Raa, 1995; Hansen et al., 2004; Caldwell, 2009). The original hypothesis was based on the fact that polyunsaturated aldehydes (PUAs), e.g. 2-trans, 4-trans decadenial (A3) produced by diatoms can function as grazing deterrents and harm copepod development. Salmon lice (*Lepeophtheirus salmonis*) is a copepod, and we therefore intended to test if inclusion of diatom biomass in the feed could reduce the infestation of lice on salmon. We have ongoing experiments with more extensive testing than in Eilertsen et al. (2021), and we have improved results indicating more than 40% reduction in lice infestation vs. ordinary (control) feed (own unpublished). It is therefore a probable future scenario that the diatom added feed can experience prices well above todays feed or fish meal based ones.

Salmon lice can cause disease and reduce growth, and at high concentrations it can cause death (Grimnes & Jakobsen, 1996). The annual total cost of delousing in Norway now has passed 6 billion NOK, not including losses related to reduced growth and exaggerated mortality (Kaldheim & Nordbotn, 2019). From a fish health, welfare and economical viewpoint it will therefore be necessary to find ways to reduce lice infestations substantially. The current Norwegian government has implemented strict regulations with respect to prevalence of lice. This has led to a plethora of delousing methods, all being based on mechanical, chemical and, e.g., cleaner fish. The disheartening result from this is that mortality in Norwegian salmon aquaculture has increased dramatically (Overton et al., 2019). In addition, negative side-effects of chemical delousing agents, for example emamectin benzoate, on the environment have been reported and complicate an environmentally sustainable development of the salmon aquaculture industry further (Bloodworth et al., 2019). Biological ecological (natural) methods to fight lice is therefore the ideal scenario in futures “war” against salmon lice. Therefore, our contribution will be/is to offer feed with diatom biomass to deter salmon lice (Eilertsen et al., 2021).

Another reasoning behind our intention to apply the produced biomass as a salmon feed ingredient (or as whole feed) was diminishing stocks of small pelagic wild fish. Amongst other reasons increased human consumption of pelagic fish, marine ingredients in Norwegian salmon feed has gradually

> been replaced by terrestrial crops (Aas et al., 2022; De Roos et al., 2017; Hansen, 2019). This has led to changes in the biochemical composition of the feed, and perhaps most important is a reduced polyunsaturated fatty acid (LC-PUFA) content. At the same time, negative effects of PUFA deficiency on salmon growth, and robustness, for example stress handling in connection with de-lousing (*Lepeophtheirus salmonis*) operations have been reported (Bou et al., 2017; Rosenlund et al., 2016). Other important issues relating to the overall sustainability of the salmon aquaculture industry are general environmental impacts, and escapees (Torrissen et al., 2011; Jansen et al., 2012; Sistiaga et al., 2020). Another negative result from this can be reduced positive health effects of omega-3 on humans (Hamre et al., 2013; Midtbø et al., 2015; Marvin et al., 2020).

Mass cultivation of large marine diatoms in volumes relevant for bulk applications (rather than for niche products) is new in age (Eilertsen et al., 2022; Eilertsen et al., 2023). Despite numerous proposed applications of diatom biomass, there has not been much focus on developing disruptive methods to achieve the scale necessary for economic and market-relevant volumes, with a few notable exceptions (Lane, 2022). Today, it is well established that some of the largest operations rely on optimised tubular systems with very high capital expenditure (CapEx) to volume ratios. Others rely on similarly well-optimised systems, such as hanging bags, with lower CapEx to volume ratio, but high operational expenditure (OpEx). Other open systems, such as open raceways, do not provide the necessary operational stability needed for continuous operation, due to occasional culture crashes caused by contaminations or other influences from the surrounding environment, for example, temperature alterations (Borowitzka, 1999). Furthermore, assessed production costs vary considerably, causing uncertainty in production strategies (Hoffman et al., 2017). So, the businesses are often left with the choice between two evils, which, in the long run, yield the same result: prohibitive cost. This has left many potentially profitable business cases to collect dust. However, market situations may change, diatom physiology and biochemistry are backed by a substantial volume of scientific literature. If the diatom biomass produced in the Finnfjord – UiT project can enter the marked as "lice-deterring" feed, this can certainly increase potential price points. Furthermore, much of the research done on microalgae (diatoms) is based on the assumption that production costs will lower across time. Thus, a realistic way of attaining profitable production is to use a multiproduct approach (Grobbelaar, 2010).

In the case of the Finnfjord project, the main goal is to produce salmon feed (Eilertsen et al., 2022). However, diatom biomass has other interesting potential uses that might prove economically important in the future. One interesting case is where diatom frustules (cell walls) made up of biogenic silica are being used to improve the performance of lithium-ion battery anodes (Blanco et al., 2020). Usually, this part of the diatom is regarded as a waste product since it holds no particular nutritional value, but this presents the potential for the utilisation as an important and valuable side stream. Especially in the research field of diatom nanotechnology, the properties of the dielectric photonic crystal cell walls of diatoms have sparked considerable interest, based on the manifold uses they can serve (Gordon et al., 2009; Rea & De Stefano, 2022). It is now two decades since the research field was coined (Drum & Gordon, 2003), and whole books have been written about it (Mitchell et al., 2017). Interesting examples include functionalised 3D structures (Brzozowska et al., 2020), biomimetics (e.g., tooth repair, Zhou et al., 2023), biosensors (De & Mazumder, 2022), solar panels (Khan et al., 2022), and drug delivery systems (Terracciano et al., 2018). Specific pigments such as fucoxanthin are an area of interest where the access to more mono-species diatom biomass might prove important. Fucoxanthin is a pigment common in heterokonts such as diatoms and brown seaweed which is very highly priced and has a number of applications due to its bioactivity and antioxidant activity (Keerthi et al., 2013; Singh et al., 2022). *Odontella aurita* is being approved as a novel food in, for example, EU and being marketed as a superfood or food supplement (Sousa et al., 2008). Eicosapentaenoic acid (EPA) is a valuable essential fatty acid, and the polysaccharide chrysolaminarins which also have bioactive properties are other examples of well-known valuable compounds from diatoms (Yang et al., 2020). These examples are only a few of all the proposed or putative products from diatom biomass (Lebeau & Robert, 2003). Still, the applications and examples have one thing in common: they all depend on reliable access to high-quality diatom biomass to become a market reality.

Diatom mass cultivation, pros and cons, and sustainability

Another aim of our mass-cultivation project is to help improve the overall sustainability (environmentally and economically) of the salmon aquaculture food chain as a whole. This includes CO_2 from the factory as well as the algae cultivation. As part of the implementation of a full-size (3,000,000 L) reactor with infrastructure, evaluation plans encompass a thorough sustainability/LCA analysis including fume/CO_2, algae cultivation with infrastructure, salmon feed production, and salmon aquaculture with resources. While out of the scope of this text, we will, in the following, clarify some important pros and cons issues based on data and experience during pilot runs of the 300,000 L reactor we are currently operating.

It is clear that the present project must be categorised as CCU, and it falls into an interesting category because it can establish a new “atmosphere-to-atmosphere” carbon cycle and thus indirectly offer huge potential in carbon reduction (Zhang et al., 2022), especially in a supposed transient period between CCU and more extensive CCS.

The Finnfjord project also comprises several circular energy and economy elements, i.e., reuse of resources and energy as shown in Figure 2.2. These include the following:

(A) Heat energy contained in the factory fume is retrieved as electricity by means of a steam turbine that drives an electrical generator. Some of this electricity can then be used as auxiliary algae cultivation LED illumination.
(B) Carbon originally used in the ferrosilicon production is sequestered as CO_2 from the factory fume by cultivating diatoms.

(C) The fate of this C is mainly inclusion in salmon feed produced by a feed producer and subsequently stored in salmon at the aquaculture company. Some of this is respired by salmon in the sea, and by fish eaters beyond consumers' gate.

(D) Seawater pumped in and used as a cooling medium in the heat retrieval system is filtered and used as a diatom cultivation medium (with fertilisers, i.e. N, P, and Si added). N and P in incoming seawater are also consumed.

(E) Surplus heat from factory fume can be used to dry-process the produced diatom biomass.

(F) Surplus oxygen produced by microalgae can be used to oxygenise tanks with, for example, salmon smolt or compressed utterly for industrial purposes.

The sustainability of the whole process (fume CO_2 production, algae cultivation, feed production, and aquaculture) is substantially affected positively by the retrieval of fume heat as electricity (Table 2.1). The energy recovery system was installed in 2012 and has been constantly improved since, which is an ongoing process. In

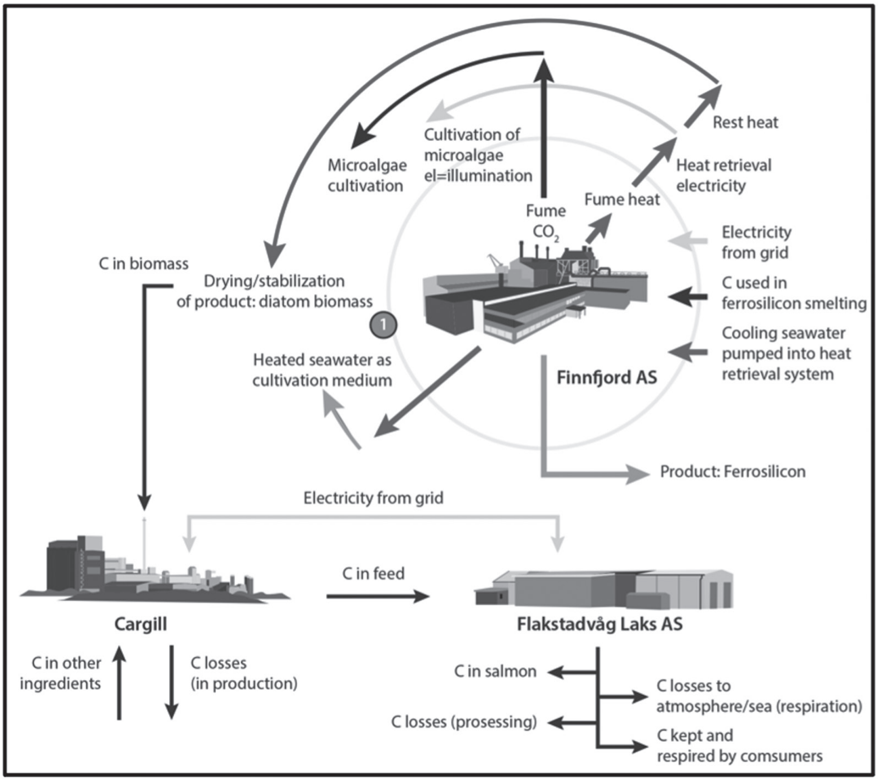

Figure 2.2 The circular economy concept applied in the Finnfjord AS project. Cargill is the feed producer/supplier and Flakstadvåg laks is the salmon producer.

Table 2.1 Variables and standardised sustainability parameter values characterising the results and estimated improvement potentials from the Finnfjord AS project 300,000 L reactor.

Variable	*Energy (Wh, MJ/kg, %)*		*CO_2 – O_2 footprint (kg CO_2/kg produced)*	
	Present	*Improvement aim*	*Present*	*Improvement aim*
General technology				
Recovered electricity	340 GWh	620 GWh		
Common use of factory resources	20%	30%		
Finnfjord Scope 1 and 2 FeSi prod.			3.86	Significantly
Cultivation technology				
Production biomass	0.5 g/L/day	1.0 g/L/day		
Production loss in de-watering, etc.	0.07 g/L/day	0.01 g/L/day		
Efficiency of CO_2 uptake in reactor	67%	80–85%		
Compressing gas		66.1 MJ/kg		
Energy used to compress gas	66 MJ/kg	30 MJ/kg		
Energy to artificial illumination	11 MJ/kg	11 MJ/kg		
Drum filter	1.26 MJ/kg			
Centrifuge	0.48 MJ/kg			
Pumps	0.2 MJ/kg			
SO_2 scrubbing	100%	0%		
CO_2 emission/sequestration (±)			−2.2	Not possible
Inorganic N fertiliser	25%	10%	+0.05	Not possible
Inorganic P fertiliser	25%	5%	+0.01	Not possible
O_2 production			+2.1	Not possible

2022, Finnfjord used ca. 780 GWh while ca. 340 GWh of this was recovered, illustrating the substantial reduction in energy from the grid and thereby costs. Clearly, this reduces energy imported to Finnfjord needed to serve all power-demanding processes at the factory, resulting in reduced Scope 1 and 2 CO_2 footprint, and this also includes the microalgae mass-cultivation–related processes. Further, it is clear that microalgae will be a cornerstone in an upcoming Scope 3 analysis.

Eventual reduction in overall emissions (Scope 1) will result from algae photosynthesis as it takes up CO_2 from the factory fume, and some of this carbon will be released again as salmon respiration (in the sea) or decided by its fate following reaching consumers' gate. If a 3,000,000 L pilot reactor is established in addition to the present reactors, the annual uptake will be ca. 1000 tonnes, illustrating that CO_2 will not be a limiting commodity in a projected future biorefinery. Some of the fossil carbon (5%) used in the production (coal and choke) at Finnfjord is replaced by biocarbon (woodchips), and a large part of the planned reduction of Scope 1 emission shall be achieved by increasing the use of wood-biocarbon. In addition, if the lipid (fatty acids) and amino acids (protein) from algae feed replace terrestrial crops and especially fish oil with larger environmental footprints, this will utterly improve the sustainability of aquaculture as a whole.

When evaluating the success of the present Finnfjord AS project, the framework of The United Nations' Sustainable Development Goals (SDG's) is pivotal. Yet an obvious limitation of this framework is the division of these goals across different areas such as food, water, and materials. In a sustainability evaluation/description of, for example, the Finnfjord AS project, a comprehendible approach would necessarily combine circular economy, societal, and environmental effects (including CO_2), and resource savings/gains – and quantify these against each other, if possible (Figure 2.3). At the same time, some effects (such as societal and economical ones) are highly challenging to quantify and compare to, for example, environmental traits. Still, in developing future scenarios which increase sustainability in processes that involve high-energy use, pollution, and emissions of greenhouse gases – it is needful that we find ways to assess these seemingly immeasurable processes, in order to report and evaluate (as quantitively as possible) production processes and situations.

The efficiency of uptake of CO_2 injected into the 300,000 L reactor is, at present, measured to be 50–60% (Table 2.1). This is today considered high (Comley et al., 2023). Further improvements here will have a large positive impact on the overall C budget, and we are confident that a projected uptake of 80–85% will be reached by installing (own produced) revised fume dispersion equipment (Table 2.1).

Energy presents a major cost factor during the upscaled production of microalgae biomass. In the pilot study at Finnfjord (Table 2.1), microalgae cultivation was quite energy intensive, with an estimated total energy use of ca. 78 MJ/kg algae mass produced. The main driver here (66 MJ/kg, i.e., 84%) was energy used to compress factory fumes, rather than, as we had expected, artificial illumination (11 MJ/kg, i.e., 14%). By comparison, energy used for the production of conventional salmon feed ingredients has by some been modelled to be about four to five times lower than this (Pelletier et al., 2009). However this will change if e.g. total environmental

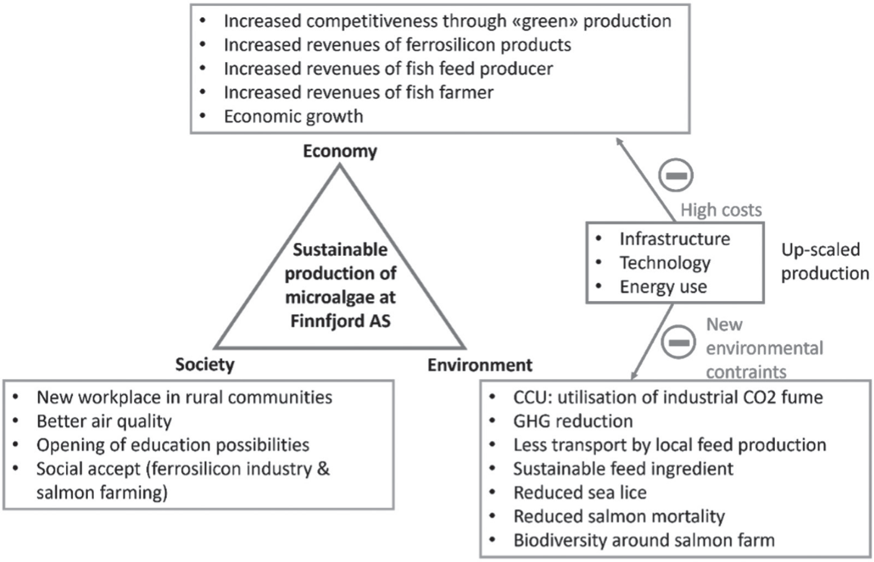

Figure 2.3 Sketched "triple bottom line" pros et cons applicable to the UiT – Finnfjord microalgae (diatom) mass-cultivation project.

footprint is considered, included potential de lousing savings/reductions. It is, therefore, important to find more power-efficient solutions to inject gas and introduce mixing in the culture, and thereby substantially reducing the energy footprint. Yet the environmental footprint of cultivated microalgae in salmon feed will also be highly impacted by the energy mix used in its cultivation and processing. In Norway, 98% of the produced electricity comes from renewable energy sources, mostly hydroelectric power. The environmental footprint of LED lamps needed in an upscaled production must also be quantified. Previous LCAs have shown that the environmental performance of LED lamps is highly dependent on the energy mix used, as electricity use is the largest contributor to emissions (Pennisi et al., 2019). As mentioned earlier, applying blue pulsing light possibly can save up to 50% in illumination energy, while we also use electricity that is recycled from fume heat (Figure 2.2).

The demand for green energy has increased during the last 10 years, as has the cost of electricity, which was 3.5 times higher in the first quarter of 2023 than the first quarter of 2012 (Statistics Norway, 2023). As such, electricity consumption and costs pose a potential constraint to the success of all projects involving fermentation. If these are applying photoautotrophs, it will be mandatory to combine photosynthetic-efficient organisms with meagre use of illumination. One advantage of the Finnfjord project is a priori that no energy is needed to heat the culture during winter since the selected species grow well down to −2°C. Further, warmer water is available in the return water from the energy capture system at the factory.

As is well known and as illustrated in Table 2.1, microalgae are highly efficient carbon sequesters (2 kg CO_2 yields ca. 1 kg nutritious algae biomass). This can lead to a gross reduction in CO_2 emissions of −2.2 kg CO_2/kg algae. Obviously, this needs to be adjusted to include carbon emissions linked to external production processes (including the production of LED lights, centrifuges, refrigerators, packaging, etc.). Most of these will be reduced as reactor size is increased. Further, O_2 is produced in the same amounts that CO_2 is sequestered (Table 2.1), and if this O_2 is captured, it can as mentioned earlier, for example, be used in aquaculture or other processes as another value-added product.

At the farm-gate-level, feed production has in analyses been identified as the major contributor to the environmental footprint of produced Atlantic salmon, accounting for 93% of cumulative energy use, 100% of biotic resource use, and 94% of global warming and acidifying emissions (Pelletier et al., 2009). Further, the authors of this study did not take into account possible negative effects of, for example, land-use change (deforestation), and water use. However, Rotabakk et al. (2020) communicated in a fish-feed review that soy SPC had a high CO_2 footprint of 3.2 kg CO_2/kg SPC.

In Norway, 1,976,709 tonnes of salmon feed were utilised in 2020 with 91.7% and 8.3% of the feed ingredients being imported to and produced in Norway, respectively (Aas et al., 2022). The Norwegian government has the goal that all ingredients of fish feed for aquaculture production shall come from sustainable sources by 2030. Feed is not only the number one contributor to the environmental footprint of Atlantic salmon but also represents 50% of the overall cost for Atlantic salmon producers (Iversen et al., 2020).

The algae feed ingredient we produce deters lice when mixed with ordinary feed at 3% algae inclusion. The consequences of sea lice impose major negative economic effects on salmon production. Sea lice-related loss has been reported to vary from 3.62% to 16.55%, depending on farm location. It has been estimated that the total costs of sea lice for the salmon farming industry in 2011 were 436 million dollars (Abolofia et al., 2017), and amounts today probably exceed 6 billion NOK. These studies illustrate the huge potential of reducing the carbon footprint of farmed Atlantic salmon by finding new sustainable resources for feed production. If these resources reduce sea lice infestations, the environmental footprint and costs could be further alleviated. A full life-cycle assessment (LCA) according to ISO 14040 and 14044 standards will be required to quantify the environmental impacts of Atlantic salmon fed with feed containing microalgae compared to other feed resources. This requires a clear definition of goal and scope, a complete life-cycle inventory, impact assessment, and interpretation. The life-cycle inventory of the microalgae project will be established in parallel with the project's progression.

Another challenge in quantifying the CO_2 budget is that a large part of the CO_2 captured by algae, originating from the factory fume, is released in the sea as salmon respiration, which can remain there. This follows evident physical laws and is based on that the coastal areas in the north are undersaturated with respect to CO_2, i.e., partial CO_2 pressure is lower in the sea than in the air CO_2 (Takahashi et al., 2002; Aalto et al., 2021). The same is true of some of the factory fume CO_2 released directly into the air (as shown in Aalto et al., 2021). This mechanism may prove important in future sustainability analyses, and this hypothesis needs to be validated with properly designed research. Further cooling of the sea in the north causes surface seawater to sink and be transported southwards with deep slow currents (Eilertsen & Skardhamar, 2006; Aalto et al., 2021). This can possibly lead to the conclusion that aquaculture is more sustainable in the north relative to southern areas. Other issues that can result from the use of microalgae in feed is that bacterial breakdown/organic nutrient recycling of salmon faeces can be altered (Hutchins et al., 2009).

The degree of reduction of the carbon footprint in salmon feed through the inclusion of microalgae will also depend on the amount of conventional ingredients that can be replaced by microalgae. Upscaling to a production of, for example, 1 tonne of microalgae per day using 3,000,000 L bioreactors, would yield ca. 365 tonnes of microalgae annually. Our project partner Flakstadvåg AS has a production capacity of 9000 tonnes of salmon per year. Assuming an economic feed conversion ratio (eFCR) of 1.28, this scale of production requires 11,520 tonnes of feed with algae inclusion at ca. 3%. Potential lice-deterring effects of the feed at an inclusion rate of 3% could reduce the overall eFCR and, hence, lead to a more environmentally sustainable use of resources. Whether this is also economically viable depends on the costs related to microalgae production and processing, and especially the feed price.

An LCA study from the Netherlands compared the environmental performance of soybean meal with microalgae meal and found that the resource footprint was 10^2 lower in soybean meal imported from Brazil than that of algae meal (Taelman et al., 2015). Yet, the authors of this study concluded that the production of microalgae meal as a feed ingredient is a new industry operating at a pilot scale that cannot be directly compared to the technically mature soybean production and future upscaling, and the use of renewable energies can potentially result in a similar footprint between the two feed ingredients. Further, in the cited Netherland study, they used small green species and not large diatoms, and surprisingly much energy was used in inoculum production (55%). In our project, inoculum adds up to a fraction of 1%, emphasising that generalisations in sustainability judgements should be performed with great care. Yet this again indicates that process optimisation and energy reduction in algae cultivation scenarios are necessary to obtain a sustainable economy.

The figures are from pilot runs, i.e., unpublished own estimates/measurements as well as from references: (1) Eilertsen et al. (2022), (2) Agwu et al. (2022), (3) Eilertsen et al. (2021), (4) Svenning et al. (2019), (5) Artamonova et al. (2017), and (6) Landa (2022).

Conclusion

Microalgae cultivation is not new of age, but has not yet gained sufficient momentum. Today’s global production is negligible, despite an increased focus on bioenergy and food, and especially “green” feed production. We believe that the main reason for this is prohibitive production costs combined with the lack of functional reactors to produce large (bulk) volumes of microalgae biomass. The main hindrance to upscaling to large production volumes has been small species cultivated in complicated (and expensive) low-volume reactors, operating at short light depths.

Our concept utilises CO_2 as a resource for biosynthesis by cultivating (new) large photosynthetic-efficient diatom species at long light depths, in large cost-effective vertical column reactors which allow for large production volumes. The project is, by basic definition, a CCU project with CCUS potential, since it exploits CCU as a resource. Yet the process we examine here can also replace existing organic biomass processes that require higher energy and impress a larger CO_2 footprint.

There are multiple CCU processes available and implemented in the industry, and the use of these depends on the technological process used to capture and store CO_2, and also on the energy used in the efficiency of the process (Peres et al., 2022). Examples here are fuels, food and feed, pharmaceuticals, pulp and paper steel (injection to metal casting), and water treatment. While CCUS can be divided into CCS and CCU according to how they handle CO_2 abatement, CCS can largely represent direct CO_2 reduction, but is, on the other hand, normally less efficient for direct reduction (Zhang et al., 2022). This is because, in the case of CCU technologies, the CO_2 which is consumed by the process will ultimately be emitted at the end of the product life cycle (Stevenson, 2019). One advantage of CCU is its ability to represent indirect reduction of CO_2 emissions by avoiding the use of fossil carbon. This is, as in our project, an “atmosphere to atmosphere” carbon cycle, replacing the common “lithosphere to atmosphere” one (Hepburn et al., 2019). Here the overall CO_2 reduction capacity of CCU can be high enough to apply considerable impact on carbon neutrality, and it is also likely to create economic benefits.

Our project, as it involves “atmosphere to atmosphere” carbon cycle, utterly in our opinion has focused insufficiently upon the advantage that the process emits an amount of O_2 which is equal to the CO_2 produced (Table 2.1) – O_2 being, in fact, a climate gas essential to the well-being of humans and animals. The O_2 content of air can be reduced as a consequence of the combustion of fossil fuel (which binds it into a CO_2 molecule), while biomass also consumes O_2 (Bender et al., 2005). Therefore, reintroducing O_2 into the atmosphere represents a stabilisation of atmospheric conditions. A conclusion resulting from this is also that, in fact, geological CCS removes O_2, i.e. CO_2, hence, contributing and possibly strengthening the global atmospheric decline in O_2 concentration.

We categorise our project as a successful academia–industry initiative. Importantly, we attribute this success to innovative industrial leadership, easy access to the industrial process, and engineer competence – paired with an applied-research university attitude. Close proximity between the factory and UiT has also contributed to the success of this project, as well as accommodations for researchers in the factory area.

Two main challenges for the future of salmon aquaculture will be to reduce the inclusion of terrestrial crops (today 72%) in the feed and to reduce lice infestation in a sustainable way. This seems to prioritise the value of positive health (reintroduction of omega-3 in the salmon feed) and lice-deterring effects. While it is clear that optimisations are needed in the microalgae cultivation processes, we hope our concept can inspire and pave the way for the development of new innovative solutions.

It is clear that today's new enterprises, due to an intensified awareness of the interplay among "profit, people, and planet" (the triple bottom line), will increase a focus on sustainable decisions (Figure 2.3). Sustainably produced products already sell with competitive advantages, thus allowing people to experience health effects of both an improved environment and higher food quality.

Note

1 Norw: "Naturmangfoldloven" and "Forskrift om fremmede organismer" (The Natural Diversity Act and Regulations on Foreign Organisms).

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3 New marine ingredients for future salmonid feeds

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Introduction

This chapter discusses how to obtain more food and biomass from the oceans in a way that does not deprive future generations of their benefits. In the future, there will be increased competition for natural resources driven by factors such as population growth and climate change. Aquatic foods are increasingly recognised for their key role in food security and nutrition, not just as a source of protein, but also as unique and extremely diverse providers of essential omega-3 long-chain polyunsaturated fatty acids (n-3 LC PUFA) and bioavailable micronutrients. Knowledge related to utilisation of new marine feed resources for aquaculture, like microalgae, macroalgae, zooplankton (copepods, euphausiids), mesopelagic resources, as well as strategies such as integrated multi-tropic aquaculture (IMTA) with marine invertebrates (mussels) and seaweed will be important for sustainable growth and development of this industry. To increase the use of novel resources, new ingredients must meet the requirements of being appropriately nutritious, safe, and available in large quantities, while having a predictable supply chain, and being competitively priced for functional use.

The sustainability of different human diets is constantly being compared, and vegetarian and vegan diets have gained popularity even in Norway, where consumer diets have traditionally included meat and fish. Consumption of animal foods (meats) is criticised in the public sphere due to higher greenhouse gas (GHG) emissions and use of land, water, energy, and other resources in their value chains. Globally as well as nationally, the supply of sustainable feed challenges growth in the aquaculture industry. Sustainable production of farmed salmon and trout is important for the green transition of Norway. Feed may account for around 75% of GHG emissions in these (omitting airfreight to distant markets) value chains. Thus, the government has issued a directive to develop new and novel raw feed materials through means that lower GHG emissions, and, at the same time, enhance employment and secure the development of the aquaculture industry. Thus, it is important to develop more sustainable feed ingredients and, to secure that goal, to document the environmental impact of feed resources by, for example, life-cycle analysis or life-cycle assessment (LCA).

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The goal of LCA is to create a comprehensive picture of the total environmental impact of a product's life cycle. Such documentation is important – for the industry itself, for decision-makers, and for the consumer, as well as the general public. This chapter focuses on farmed salmon and summarises the sustainability of various emerging marine ingredients in salmonid feeds. The main finding/takeaway in the chapter is that there are underutilised marine resources that can be harvested in a sustainable way.

The global aquaculture industry

Aquaculture of fish and crustaceans has developed substantially over the past 50 years. The global production of aquatic animals was estimated to be 178 million tonne (mmt) in 2020, a slight decrease from the record of 179 mmt in 2018. Today about 30 species of shrimp/shellfish/crustaceans and more than 300 finfish species are cultivated commercially worldwide, with production estimated as more than 88 mmt in 2022 (Hertrampf & Piedad-Pascual, 2000; Hardy & Kaushik, 2021; FAO, 2022). The first sale value of global aquaculture production was estimated to USD 265 billion. In addition to aquatic animals, 36 mmt (wet weight) of algae were on the market in 2020, of which 97% originated from aquaculture, mostly marine aquaculture (FAO, 2022). In 2018, the global production of cultured microalgae, including cyanobacteria, was estimated to be 87 thousand tonne (FAO, 2020a).

Driven by increased human consumption and market acceptance, global aquaculture is expected to increase by more than 7.1% between 2020 and 2027 (Nagappan et al., 2021). The UN's Food and Agriculture Organization (FAO) has predicted that cultivated aquatic species will provide around 53% of the world's supply of seafood by 2030. A projected increase of 26 mmt in global aquaculture production by 2030 will require an additional 40 mmt of feed (Albrektsen et al., 2022).

Farming of aquatic animals requires knowledge of nutrients, feed, and feeding regimes. Compared with the knowledge of terrestrial livestock's nutritional needs, the science surrounding aquatic species' nutritional needs is relatively new. Like terrestrial-farmed animals, their aquatic counterparts require protein, lipids, carbohydrates, vitamins, minerals, and other feed additives to meet their physiological needs for optimal growth and reproduction (Hardy & Kaushik, 2021). Feed for aquatic species is seldom obtained from a single source, as single sources used today seldom fulfil all nutritional requirements (Hertrampf & Piedad-Pascual, 2000; Aas et al., 2022b) while, at the same time, being economically viable as well as sustainable. Common carbohydrate ingredients/sources include wheat, rice, maize starch, and potato starch (Hertrampf & Piedad-Pascual, 2000; Hardy & Kaushik, 2021). Protein sources in the feed are derived from animals, plants, insects, and microbial sources. Fish meal, feather meal, blood meal, animal waste, seafood waste, and fish silage are major animal-based protein sources used in feed (Mo et al., 2018; Hertrampf & Piedad-Pascual, 2000). Plant protein sources typically include soybean meal, guar meal, corn gluten, potato protein, wheat gluten, peas, co-products of cane sugar, macroalgae, canola, cassava, and wheat (Hardy & Kaushik, 2021; Nagappan et al., 2021). Insect, bacteria, yeast, and microalgae are the microbial sources of protein used in fish feed (Hertrampf & Piedad-Pascual, 2000; Kousoulaki et al., 2016; Jones et al., 2020). Lipid sources include fish oil and vegetable oils like soya oil, rapeseed oil, sunflower oil, and algal oil (Turchini et al., 2011; Hardy & Kaushik, 2021). Other ingredients, such as fibre, vitamins, minerals, and specific amino acids, are essential, thus required in smaller quantities for optimal fish performance. Farmed fish and crustaceans may require 40 essential nutrients (D'Abramo et al., 1997; Hardy & Kaushik, 2021) including a few, mainly minerals, obtained directly from their surrounding waterbody. Thus, dietary requirements of minerals focus on the minerals that need to be supplemented. The vitamin requirements in the feed are not a critical economic concern; therefore, the research can focus on vitamins associated with specific metabolic requirements (Hardy et al., 2021).

Salmon feed development

Growth in aquaculture production is predicted to continue, and, by 2050, the Norwegian salmon industry is projected to need at least 6 mmt of dry feed (Gjøsund et al., 2020). There is growing concern that overexploitation of marine resources may have ecological implications on food availability for marine fish (Fauchald et al., 2011; Atkinson et al., 2004). At the same time, capture fisheries have levelled off, and thus also the feed supply from capture fisheries stagnates and fails to meet demands that arise from population growth and the corresponding need for an increase of incomes in developing countries, and the changing food preferences in developed countries. Thus, the need increases for sustainable, economically viable, and novel alternative feed ingredients. In 1990, salmon feed contained 24% marine oils and 65% marine protein. Since 1990, the share of marine raw materials has steadily declined, replaced by vegetable ingredients (Aas et al., 2022a). In 2020, the average Norwegian salmon feed was produced from 12% marine protein sources, 10% marine oils, 41% vegetable protein sources, and 20% vegetable oils (Aas et al., 2022a). In addition, 0.4% new ingredients, such as insects, krill, and microalgae meal, were used. According to Norwegian public data, in 2020, 1.98 mmt (DW) of ingredients were used to produce 1.47 mmt (WW) of salmon and 0.9 million tonne of rainbow trout (Aas et al., 2022a). Norway has a national ambition to produce 5 million tonne of farmed fish by 2050 which will require an estimated 2 million tonne of protein and 2 million tonne of oil, including approximately 135 thousand tonne of eicosapentaenoic acid (20:5 EPA) and docosahexaenoic acid (22:6 DHA) (Almås et al., 2020). This will require nearly 6 mmt (DW) of feed and strongly increase the demand of nutritious, economically viable, and sustainable feed ingredients. All intensive production or harvest of resources for feed has an impact on climate (by emission of GHG) and the environment (by use of land, water, energy, and other resources). The high integration of soy as feed ingredients in the Norwegian salmon industry has significant indirect land-use effects, and the prospected growth can be expected to contribute to overall deforestation (Rainforest Foundation Norway, 2018).

Marine fish oil (FO) has traditionally been used in fish feeds to provide essential fatty acids (EFA) and energy. In Norway, the salmon aquaculture industry is the major user of FO, with the main driving force being a supply of the LC PUFA n-3, EPA, and DHA to the feed. The use of fish, krill, and other marine organisms caught solely for reduction, meal, and oil production is currently under scrutiny due to the sustainability of capture fisheries as well as the possible direct use as human food or food ingredients (Turchini et al., 2011). A growing aquaculture industry in combination with a decline in available marine oils and the nutritional requirements of the fish challenges and speeds the search for novel sources of replacements or substitutes (Albrektsen et al., 2022). In addition to the well-known roles of the fatty acids EPA and DHA (essential due to low biosynthesis), the main finding/takeaway in the chapter is that there are underutilised marine resources that can be harvested in a sustainable way. Several other fatty acids, notably arachidonic acid, have also been shown to be essential in some fish species (Hardy & Kaushik, 2021).

As mentioned, the inclusion of marine oil and protein in the Norwegian salmon feed industry has decreased as marine ingredients have gradually been replaced with alternatives, primarily of terrestrial origin (Aas et al., 2019, 2022a). This has led to reduced n-3/n-6 LC PUFA ratios in farmed salmon which equates to compromised nutritional value in the final product, fattier with less n-3 LC PUFA (Jensen et al., 2020). One portion of farmed Atlantic salmon provides EPA and DHA comparable to a portion of wild salmon. However, the farmed portion provides excess fat/energy as well as n-6 fatty acids. At the same time, farmed salmon contains fewer contaminants such as dioxins, dioxin-like poly-chlorinated biphenyls (dl-PCBs), and heavy metals (Jensen et al., 2020). Thus, farmed Atlantic salmon is still a positive contribution to our diet, and one 150 g portion per week provides more than the recommended weekly intake for adults of EPA and DHA (Torrissen et al., 2011; Aas et al., 2022a).

In addition to the low levels of n-3 LC PUFA in salmonid feed, vegetable sources further introduce antinutrients which hinder the digestibility, bioavailability, and utilisation of nutrients. The nutritional values of vegetable ingredients are thus generally lower than marine sources, fishmeal, or fish oil due to antinutrients, lower contents of essential nutrients, and poor digested components, all creating challenges for fish-feed formulators (Hardy & Kaushik, 2021). Thus, we examine a range of different paths forward.

There is a growing interest in the nutritional value of underutilised marine sources and by-products. It has been suggested that harvesting, fermenting, or cultivating organisms from the base (or lower end of the marine food web) might present the largest potential to increase sustainability across the industry (Nagappan et al., 2021). Photoautotrophic organisms (especially diatom microalgae) convert inorganic nutrients (N, P, Si, etc.) to all chemical compounds that fish species need. In nature's fish-rich areas (Barents Sea, upwellings, etc.), diatom microalgae represent the feed throughout the food web, from zooplankton to finfish. In addition, there is an increase in the harvesting and fermenting of mussels, copepods, and euphausiids for feed and food purposes. For our current discussion, we examine prime candidate resources including macro- and microalgae, zooplankton (copepods and euphausiids), mesopelagic fish, crustaceans (krill), as well as by-products and strategies such as integrated multi-trophic aquaculture (IMTA) with marine invertebrates (mussels) and seaweed, in combination with fish farm.

Future marine feed resources microalgae

Microalgae are the main producers of EPA and DHA in the marine food chain (Borowitzka, 1997; Brown et al., 1997). Microalgae are natural food resources for zooplankton in the food chain. Sardines, anchovies, and sometimes capelin and herring, may prey directly on diatoms (Van der Lingen, 2002). In aquaculture farming, microalgae are also used to feed fish larvae, crustaceans, and molluscs (Brown et al., 1997). Hence, there is a new and growing interest to explore the use of microalgae as a future ingredient in formulated feed for farmed fish (Kousoulaki et al., 2016; Eilertsen et al., 2021). Today it is primarily small green and blue-green algae like *Chlorella* spp., *Dunaliella salina*, *Arthrospira* spp., etc. that are mass cultivated (Spolaore et al., 2006), while in fact, diatom species that dominate the base of the marine food web, in, for example, upwellings, are underexploited (Levitan et al., 2014).

In 2018, the global production of cultured microalgae, including cyanobacteria, was estimated at 87 thousand tonne (FAO, 2020a, 2020b). One example of successfully commercialised industrial-scaled diatom cultivation is the use of the species *Odontella aurita*, presented on the market as an n-3 LC-PUFA-rich dietary supplement (Mimouni et al., 2012). In comparison to fish meal, the protein content is lower, the lipid content is at the same level or higher, and the amount of carbohydrate is higher in microalgae (Skrede et al., 2011). In terms of protein quality, all essential amino acids were present, and the composition and digestibility of the fatty acids were as required for feed ingredients (Svenning et al., 2019; Eilertsen et al., 2022; Guschina & Harwood, 2009). Microalgae protein can also be of good quality, with amino acid profiles comparable to that of other protein sources (Becker, 2007; Eilertsen et al., 2022). When compared to land-based crops, industrial production of photoautotrophic microalgae must be considered still in its infancy, due to the low production volumes (Eilertsen et al., 2022). Such production faces challenges including complex, expensive processes related to the use of energy pumping, downstream processing, de-watering, contamination, temperature control, gas exchange (CO_2, O_2), and especially issues connected to illumination of the culture.

True photoautotrophs rely on external inorganic carbon sources and light energy, while heterotrophic microalgae cultures absorb external organic carbon (e.g., sugar) to synthesise biomass and reproduce in darkness (Přibyl & Cepák, 2019). Very few microalgae have full or facultative heterotrophic growth, inasmuch as they lack mechanisms for the uptake and utilisation of extracellular organic carbon and organic nitrogen (Nzayisenga et al., 2018). Different microalgae adapt to different types of organic carbon, but in aquaculture, expensive glucose remains the main carbon source. Overall, photoautotrophic microalgae may be the more important alternative feed ingredient, not only for sustainability reasons as they are “true” primary producers in the lower end of the marine food web but also because they are nutritious and can be produced in systems that do not compete with terrestrial production.

Macroalgae

In 2018, global production of marine macroalgae reached 33.3 million tonne (wet-weight basis), of which more than 97% was from aquaculture (32.4 million tons) (FAO, 2018). The chemical composition of macroalgae varies considerably related to species, typically around 90% water, while the dry matter fraction consists of 3%–35% protein, 30%–60% carbohydrates, 2%–13% lipids, and 10%–45% ash (Albrektsen et al., 2022). The protein content is the lowest for brown seaweeds (3%–15% of DM), intermediate for green seaweeds (3%–35% of DM), and the highest for red seaweeds (up to 45%) (Kim, 2012; Fleurence et al., 2018; Wan et al., 2019).

Compared to both fishmeal and soybean meal, the lysine proportion in macroalgae is lower, but most macroalgae species have a higher proportion of methionine than soybean meal (Angell et al., 2016; Øverland et al., 2019). Whole macroalgae inclusion at medium to high levels in aquafeed has often resulted in reduced growth performance of salmonids, but for omnivorous fish species such as tilapia, there are some promising results (FAO, 2020c). Previous feeding experiments have shown that there are discrepancies in the digestibility of different macroalgae species when included in formulated feeds (Wan et al., 2019). Much of this could be attributed to the levels and types of complex polysaccharides found in the macroalgae (Wan et al., 2019). *In vitro* digestibility tests, using pepsin, suggest that macroalgae proteins have low digestibility, around 17%–57% relative to a casein standard (Fleurence et al., 2018). The digestibility must be improved, including removing both polysaccharides and phenols, prior to aquafeed applications (Wan et al., 2019). Until now only a small fraction of macroalgal species have been considered as potential aquafeed ingredients (Wan et al., 2019).

Zooplankton

Zooplankton can be a source of both protein and n-3 fatty acids in salmon feed. Zooplankton are free-living, heterotrophic organisms. They feed on microalgae, smaller zooplankton, bacteria, and other particles that drift in the water masses. The group includes jellyfish (from cm to metres in size), krill (20–60 mm), copepods (3–4 mm), and small copepods (2 mm) (Almås et al., 2020). These include large stocks, such as Antarctic krill (*Euphausia superba*) in the Southern Ocean and the copepod *Calanus finmarchicus* in Norwegian waters. The current catch limit for krill in the entire southwest Atlantic sector of the Southern Ocean is 0.62 million tonne year $^{-1}$, equivalent to approximately 1% of the regional biomass estimated in 2000 (Hill et al., 2016). The production of *C. finmarchicus* in the Norwegian Sea is estimated at 190–290 million tons. It is also produced in surrounding areas such as the Icelandic Sea and the Barents Sea. In Norway, *C. finmarchicus* has been harvested in trial fisheries since 2003, with a maximum quota of 5000 tonne per year in coastal water. Recently, a commercial fishery has opened, and the total quota in 2021 was 254,000 tonne (Nærings-og Fiskeridepartementet, 2019).

The nutraceutical market for EPA and DHA is promoting fishing for *Euphasia superba* and *Calanus finmarchicus*. Calanus and krill oil are marketed as a human nutrient supplement, while meal is finding a niche in the production of certain aquafeeds (FAO, 2022). However, processing still entails practical challenges – for instance, for krill, the fluoride content of the raw material needs to be reduced. Both zooplankton species are essential in their ecosystems, as they occupy the intermediate level in trophic webs, where they link primary producers with predators (Atkinson et al., 2004; Fauchald et al., 2011). Climate change is affecting the stocks and geographic distribution of these zooplankton species (Atkinson et al., 2019; Prado-Cabrero & Nolan, 2021), and, in the case of Antarctic krill, there is a debate about possible detrimental effects on the fishery (Watters et al., 2020; Prado-Cabrero & Nolan, 2021).

Amphipods are among the most diverse group of crustaceans with regards to their lifestyles, trophic level, habitats, and sizes. Amphipods inhabit a variety of marine and freshwater environments and consequently show a high diversity of feeding habits (Guerra-García et al., 2014). Due to their nutritional characteristics, amphipods could serve as an adequate alternative feed resource for aquaculture (González et al., 2011). Among them, *Gammarus insensibilis* shows adequate characteristics for use as a novel aquatic organism to replace ingredients in formulated diets or to be used as live feed in aquaculture (Jiménez-Prada et al., 2018). The lipid fraction accounts for 6.5%–14% of dry weight and contains both n-3 and n-6 fatty acids. Analyses show that the lipid fraction may consist of as much as 22% n-3 fatty acids, where DHA and EPA make up 5%–10% and 8%–12% of the total amount of fatty acids, respectively. Lipid content and fatty acid composition are affected by the feed they prey on (Almås et al., 2020). No complete process has been developed that enables the cultivation of *Gammaridas* at an industrial scale. The cultivation technology today is at TRL level 5 (technology validated in relevant environment) (Almås et al., 2020).

Mesopelagic fish

Mesopelagic fish are found in all oceans from Antarctica in the south to the Arctic in the north and represent a biomass significantly larger than other fisheries. Population estimates in this area varying from 1000 to 10,000 million tonne (Gjøsaeter & Kawaguchi, 1980; Irigoien et al., 2014) demonstrate a high potential, large stocks, as well as the high uncertainty in the estimates. A significant biomass is also expected to be present in the North Atlantic within the Norwegian economic zone, but there is still a lack of both biological and technological knowledge in relation to exploit this resource (Almås et al., 2020). The result of trial-fishing of *Maurolicus muellery* has varied from 17 tonne (2018) to 2000 tonne (2019). There are several challenges in establishing commercial harvesting and exploitation of mesopelagic fish in Norway. This involves management, detection, harvesting methods, and processing of the biomass (Almås et al., 2020). Based on a hypothetical annual catch of one million tonne of *Maurolicus muellery* (wet weight) this could yield around 150 thousand tonne of protein and around 20 thousand tonne of EPA + DHA, corresponding to 7%–8% of the protein requirement and around 15% of the need for EPA and DHA for the ambition of growing aquaculture production towards five million tonne in 2050 in Norway (Almås et al., 2020). An annual catch of one million tonne of *Maurolicus muellery* is a considerable volume, corresponding to almost half of the current Norwegian volume from all capture fisheries.

Bycatch and by-products

Better utilisation and processing of by-product materials from fish are important factors for the sustainable and economic development of the seafood industry. The fish-processing industry creates several side streams, and although most residual raw materials are utilised today, it mainly goes to low-value products (Almås et al., 2020). Residual raw materials from fish are a good source of marine oils and proteins and can be used for many purposes, including the production of new and value-added products for feed.

A growing share of fishmeal and fish oil is being produced using fish by-products from capture and aquaculture with a positive impact on waste reduction. With no major increases in raw material expected to come from whole wild fish (in particular, small pelagic), any increase in meal production will need to come from fish by-products and other sources. Fishmeal from by-products has a different nutritional value, being lower in protein but richer in minerals in comparison with fishmeal obtained from whole fish. According to IFFO, in 2020, 27% of the global production of fishmeal and 48% of the total production of fish oil were obtained from by-products (IFFO, 2021; FAO, 2022).

In 2018, available residual raw materials from the Norwegian pelagic industry amounted to 205,000 tons. This is relatively small in relation to the available volume of fish since a large proportion is sold round or filleted and processed (Almås et al., 2020). Almost 100% of the residual raw material from pelagic fish is exploited in Norway, but only 59% from whitefish (Richardsen et al., 2019). In 2018, 52,100 tonne of shellfish (shrimp, brown crab, snow crab, and king crab) were landed. This resulted in 10,800 tonne of residual raw materials, of which approximately 3900 tonne or 36% were utilised (Richardsen et al., 2019). This indicates that it is mainly residual raw materials from whitefish and shellfish that may be exploited in the future.

Integrated multi-trophic aquaculture (IMTA)

One of the major challenges for the sustainable development of salmon aquaculture in Norway is to minimise waste or feed discharges that may lead to the degradation of the local marine environment. For this purpose, it has been suggested to cultivate extractive and filter-feeding species, for example, seaweed, tunicates, and mussels, close to fish farms in IMTA, thereby contributing to a more balanced ecosystem (Chopin et al., 2001, 2004, 2007, 2008; Handå, 2012). The biomass produced can be used as raw materials for feed and contribute to a more sustainable aquaculture industry. Mussels are an effective filter feeder on the ocean's microalgae and have a nutritional content that is expected to be well suited to fish feed. The protein content of mussels is about 65% on a dry matter basis, while the lipid content is about 8%. The protein is of good nutritional quality and the lipid is rich in both EPA (12%–21% of total fatty acids) and DHA (16%–22% of total fatty acids) (Naik & Hayes, 2019). The mean nutrient release from Norwegian salmon aquaculture has been estimated at 61% of feed-N and 69% of feed-P. Out of this, 41% N and 19% P are released in dissolved form, while 20% N and 50% P are released in particulate form (Olsen et al., 2008; Handå, 2012). The theoretically mean nutrient dispersal from Norwegian salmon aquaculture is accordingly: 24,250 tonne dissolved inorganic nitrogen, 1710 tonne phosphorous, 11,950 tonne particulate organic nitrogen, and 4430 tonne particulate organic phosphorus (Handå, 2012). The dissolved part constitutes a potential nutrient source for seaweed growth, while the particle wastes can potentially be utilised for the increased growth of filter feeders in IMTA. Fish feed contains approximately 50% of marine sources (Tacon & Metian, 2008; Olsen, 2011) and there has been an increase in the use of terrestrial sources in recent years (Dalsgaard et al., 2003; Skogen et al., 2009; Narváez et al., 2008) that have high proportions of, for example, n-9 (18:1) and n-6 (18:2) which can affect indirectly the nutrition quality mussel tissues as feed sources (Redmond et al., 2010; Handå, 2012).

In combination with mussels in IMTA, it is common to use macroalgae (Chopin et al., 2001, 2004, 2007). Direct use of seaweeds in salmon feed has been shown to impair fish growth performance and feed efficiency (Albrektsen et al., 2022). Residues generated, such as detritus or macroalgae, can be used by other organisms (e.g., amphipods) in the context of IMTA protocols (Guerra-García et al., 2016). Detritus comes mainly from fish faeces and uneaten fish pellets associated with tanks or ponds in aquaculture facilities. Moreover, it is also common for some macroalgae, such as *Ulva* sp., to quickly grow and spread in these facilities reaching high biomass associated with the main cultures (Shpigel et al., 2017). If these macroalgae are not being grown intentionally, their removal from the main cultures usually involves high costs. The potential use of these waste products to feed and grow amphipods is, therefore, a promising topic to be addressed. However, overall production and processing costs must be significantly reduced, while production capacity must be significantly increased, before mussels become a relevant raw material for salmon feed. Yet such a streamlined production resulting in lower price for shells would probably also increase the demand for mussels as human food. Consequently, their use as fish feed would then compete in terms of their value for direct human consumption (Almås et al., 2020). Worldwide, a total of 1.5–2 mmt of mussels are grown annually, and a third of the production takes place in Europe (Almås et al., 2020).

Finally, another "IMTA strategy" can be to bind up CO_2 with microalgae reactors from GHG emission points, such as the Finnfjord AS producing of ferrosilicon

(Eilertsen et al., 2022). In combination with local seawater, based on infinite access to resources (sunlight, N, and P in sea), microalgae can then be used as raw material for salmon feed.

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4 The sustainable development goals, human rights, and the capability approach in an Arctic context

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This chapter discusses how an industry–university collaboration between ferrosilicon producer Finnfjord AS in northern Norway and UiT The Arctic University of Norway contributes to the mission of operationalising the United Nations Sustainable Development Goals (SDGs). The core of the project is to capture CO_2 by means of microalgae cultivation on an industrial scale. The microalgae, rich in omega-3 and other nutrients, is then utilised as a component of locally produced feed for locally bred salmon. Benefits of this project include CO_2 capture, reduction of the need for extensive transportation of feed, access to sustainable, and nutritious feed components that can be produced without depleting the stock of wild fish, or reliance on environmentally problematic production of soy, and without competing with production of food crops.

The project exemplifies a so-called food–energy–water nexus approach to resource governance, which aims at more efficient use of scarce natural resources. The nexus has been advanced as a tool to create synergies and reduce trade-offs between the SDGs, introduced by the United Nations in January 2016 as a "plan of action" to manage core global developmental challenges, including food security, access to clean water, and access to clean and affordable energy. The need to create synergies and reduce trade-offs between the goals has become increasingly more pressing due to resource scarcity intensified by a rapidly growing population with new dietary habits and economic growth built on fossil-based energy sources, all of which drive climate change.

The Intergovernmental Panel on Climate Change (IPCC) published the special report *Global Warming of 1.5 °C* in October of 2018. The report includes projections of possible climate scenarios. The report states that no climate projection that predicts the limitation of global warming to 1.5 °C above pre-industrial levels can accommodate all of the SDGs: "To date, no pathway in the literature proves to achieve all of the SDGs because several targets are not met or not sufficiently covered in the analysis, hence resulting in a sustainability gap" (IPCC, 2018). The United Nations identifies a knowledge gap regarding research aimed at meeting this challenge in specific contexts: "Limited literature has systematically evaluated *context-specific* synergies and trade-offs between and across adaptation and mitigation response measures in 1.5 °C compatible pathways and in the SDGs" (IPCC, 2018, emphasis added).

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The SDGs are, according to the United Nations, grounded in the *Declaration of Human Rights*, and the United Nations interprets human rights as protectors of human capabilities. Economist and 1998 Nobel Laureate Amartya Sen pioneered the so-called capability approach. In brief, the capability approach holds that quality of life should be measured in terms of what people are able to do and to be. The capability approach is grounded in criticism of accounts that interpret quality of life in terms of people's perception of their own quality of life, their share of certain resources, or Gross Domestic Product – an approach which needs elaboration. In addition, we need a capability-based account of how to handle the inevitable trade-offs between entitlements to enjoy fulfillment of the human rights-based SDGs. This chapter contributes to the endeavour of responding to these challenges. Particularly, the chapter addresses the need to handle trade-offs between the SDGs in an Arctic context. I will discuss how the aforementioned carbon capture and utilisation project based in the Arctic exemplifies a nexus among water, energy, and food management that can help alleviate conflicts between the human rights-based SDGs.

The chapter is structured as follows: the first section discusses the role of human rights in the SDGs. The second section examines the relationship between human rights and the capability approach. The third section explains what rights conflicts are. The fourth section describes how the water–energy–food nexus approach to the development of algae-based products, such as fish feed and biofuels, can help alleviate conflicts between the human rights-based SDGs. I also argues that an influential version of the capability approach, developed by Jonathan Wolff and Avner De-Shalit in their 2007 book *Disadvantage*, provides fruitful but unexplored theoretical support for such nexus approaches. The chapter finally illustrates how carbon capture and utilisation through the algae-cultivation project, developed in collaboration between UiT The Arctic University of Norway and Finnfjord AS, is a pioneering implementation of a water–energy–food nexus approach that creates synergies and reduces trade-offs between the sustainable development goals.

The role of human rights in the SDGs

The sustainable development goals were introduced to fill the gaps of the millennium development goals, which were introduced to manage core human development challenges by 2015. De Man (2019) notes that "the millennium development goals have been criticised for the limited role the human rights have played in their design and implementation." She emphasises the need to examine "to what extent the 2030 agenda incorporates human rights in all stages of development programming" (Ibid.). She suggests that more work is required to achieve such incorporation and that such incorporation would contribute to "close the gaps left by the MDG's" (Ibid.). She points out that during the preparation of the SDGs, several parties "called for the post 2015-agenda to be based on international human rights laws and principles" (Ibid.). Particularly, "in 2012 the UN task team called for a formulation of the post 2015-agenda to be based on equality, human rights and sustainability" (Ibid.). Further, "at the 2012 Rio+20 conference UN members states confirmed their intention to develop post 2015 goals that are in accordance with international human rights law" (Ibid.). De Man suggests that "the human rights framework provides the strongest and most accepted moral basis on which development can be based" (Ibid.). Despite this, she notes that "none of the goals is explicitly framed in terms of human rights" (Ibid.).

According to the *Sustainable Development Agenda 2030*, the SDGs, that comprise "a plan of action" for human development, are "grounded in the Universal Declaration of Human Rights" (UN General Assembly, 2015: 4). The *Human Development Report* of 2016 describes human rights as the "bedrock" of human development (UNDP, 2016: 85). The SDGs make frequent references to human rights. The following quotes comprise all of the references to human rights in the SDGs. The point of citing them in full is to provide a complete picture of the occurrence of human rights in the SDGs. This will enable us to probe into the function of human rights in the SDGs and illustrate how extensive and diverse these rights are. I number these references as follows:

1 "[The SDGs aim to] realise the human rights of all" (United Nations: 1) and "to protect human rights" (UNDP: 3).
2 The Agenda commits itself "to respect, protect and promote human rights and fundamental freedoms for all" (UNDP: 6).
3 "It is grounded in the Universal Declaration of Human Rights, international human rights treaties" (UNDP: 4).
4 The agenda recognises a "universal respect for human rights and human dignity" (UNDP: 4).
5 The Agenda will "strive to provide children and youth with a nurturing environment for the full realisation of their rights and capabilities" (UNDP: 7).
6 It claims to pursue a "human right to safe drinking water" (UNDP: 3).
7 "The new Agenda recognises the need to build peaceful, just and inclusive societies that provide equal access to justice and that are based on respect for human rights (including the right to development)" (UNDP: 9).

In these quotes, we can find support for three interpretations of what role human rights play in the SDGs:

1 Human rights are *progressive, aspirational goals*, or benchmarks to strive for.
2 Human rights are the *moral grounding* of the SDGs.
3 The SDGs are *a call for implementation* of the human rights.

I will argue that all interpretations are justifiable, although interpretations 2 and 3 gain the most support from the formulations of the SDGs and the *Human Development Report* of 2016.

Let us examine the references to human rights in the SDGs in order. The first reference "[The SDGs aim to] realise the human rights of all" (UNDP: 1) and "to protect human rights" (United Nations: 3) states that the SDGs will "realise" and "protect" human rights. These formulations support that SDGs are *a call for* *implementation* of the human rights (interpretation 3). The second reference which states that the Agenda commits itself "to respect, protect and promote human rights and fundamental freedoms for all" (UNDP: 6) states that the SDGs will "protect" human rights, and further supports that SDGs are *calls for implementation* of the human rights (interpretation 3). The third reference "It is grounded in the Universal Declaration of Human Rights, international human rights treaties" (UNDP: 4) describes the SDGs as "grounded" in human rights, which supports the interpretation that human rights are the *moral grounding* of the SDGs (interpretation 2). The fourth reference "The agenda recognises a 'universal respect for human rights and human dignity'" (UNDP: 4) states that the SDGs recognise "a universal respect for human rights." This claim is compatible with all interpretations including that human rights are *progressive and aspirational goals* to be strived for (interpretation 1). The fifth reference "The Agenda will 'strive to provide children and youth with a nurturing environment for the full realisation of their rights and capabilities'" (UNDP: 7). The fifth reference states that the SDGs will "realise" children's rights, which again supports that SDGs are *calls for implementation* of the human rights (interpretation 3) – as does the sixth reference, which states that SDGs will protect the alleged "human right to safe drinking water." The seventh reference "The new Agenda recognises the need to build peaceful, just and inclusive societies that provide equal access to justice and that are based on respect for human rights (including the right to development)" (UNDP: 9) describes the SDGs as "based" on human rights, thus supporting that SDGs are *moral grounding* of the human rights (interpretation 2). It is important to note that all of these interpretations are compatible with each other.

It is also important to note that although the SDGs might be interpreted as a call to implement these Human Rights, the United Nations has no legal authority to enforce such implementation.

The relationship between human rights and the capability approach

The United Nations specifies that human rights are entitlements, "claims," that correlate to duties in agents and institutions to provide certain resources, services, or to abstain from engaging in certain behaviour. The United Nations' *Human Development Reports* of 2000, 2002, and 2016 explicitly endorse the interpretation of human rights as claim rights. The *Human Development Report* of 2000 and 2016 states, "to have a particular right is to have a claim on other people or institutions that they should help or collaborate in ensuring access to some freedom" (UNDP, 2000: 21; UNDP, 2016: 86). "Duty holders support and enhance human development and are accountable for a social system's failures to deliver human development" (UNDP, 2016: 8). But merely describing rights as claims that correlate to duties does not tell us what the function of rights are, that is, what rights do for rights-bearers. The United Nations endorses an account of the function of human rights that is aligned with the so-called capability approach.

The capability approach can be used to explain what rights do, for rights-bearers have:

> The best way to secure human rights may be to consider rights in terms of capabilities. The right to bodily integrity, to associate freely, to political participation and all other rights are secured when the relevant capabilities are available. To secure a right is to enable people to be or do something that they have reason to value.
>
> (UNDP, 2016: 25, 86)

The United Nations hence explicitly endorses an account of human rights that is founded on a capability approach.

Amartya Sen introduced the capability approach in the *Tanner Lectures* (1979), subsequently published as his pivotal article "Equality of What?" (Sen 1980). The capability approach interprets well-being as real opportunity to exercise capabilities. Capabilities are the combinations of functionings that a person is able to achieve. Functionings are all of the valuable things that a person may do or be. Examples of valuable "doings" include interacting socially, earn one's living, voting, and participating in a public debate. Examples of valuable "beings" include being healthy, physically mobile, and well educated.

One important motivation for the capability approach was Sen's dissatisfaction with accounts that measure quality of life in terms of people's perceptions of their own quality of life, their share of certain resources, or Gross Domestic Product. Measuring quality of life in terms of perceived well-being is problematic because of the so-called adaptive preferences: people who have adapted their aspirations to their low expectations regarding their physical and mental health may *regard* themselves as satisfied. Measuring quality of life in terms of Gross Domestic Product is problematic both because this measure says nothing about the distribution of wealth within a population and because wealth does not necessarily bring the quality of life in a plausible sense of the term. Measuring quality of life in terms of people's share of certain resources is also problematic because people differ regarding their ability to convert resources into capabilities. For instance, physically disabled or seriously ill individuals may need to spend a large proportion of their income on equipment to aid their mobility, or on healthcare. Also, these individuals often have diminished earning capacity due to their infirmities.

Martha Nussbaum has provided significant contributions to the capability approach. Importantly, her perspective departs from Sen's to defend a list of 10 central capabilities that must be made available to every person if they are to lead "fully human" lives and realise their "dignity." Nussbaum holds that these central capabilities should provide the moral basis of constitutional rights. The list is cited in full in the Appendix. Sen's capability approach does not endorse any such list, but presents capabilities as a space of comparison with regards to people's quality of life. All versions of the capability approach include commitment to treating persons as "ends in themselves," and a commitment to pluralism of values (Nussbaum, 2011). The capability approach compels that we should treat each person "as an end in themselves" in the sense that the well-being of each individual, rather than the aggregation of a group of individuals' well-being, is of moral importance. Nussbaum's capability approach, like Sen's, presents itself as an alternative to measuring quality of life in terms of Gross National Product or the maximisation of perceived well-being. This message is clearly communicated in several additional formulations in her work (Nussbaum, 2003).

The capability approach is, further, committed to a pluralism of values since capability achievements differ in quality and "cannot without distortion be reduced to a single numerical scale" (Nussbaum, 2011: 19). This clearly communicates dissatisfaction with measurement of quality of life in terms of GDP. Ingrid Robeyns has suggested that a commitment to treating persons as "ends in themselves" and a commitment to pluralism of values comprise the only essential features that encompass all versions of the capability approach (Robeyns, 2016). Robeyns emphasises the distinction between the capability approach, which is a general theoretical framework that can be used for numerous purposes, and the theories or accounts that are partly based on the capability approach. She labels these accounts "capability accounts" (Robeyns, 2016).

The account of human rights advocated by the United Nations is, according to the United Nations, a capability account of human rights. Nussbaum stated in 1997, and again in 2003, that the relationship between rights and capabilities "remains yet unexplored" and that the conceptual relationship between the capabilities approach and rights "needs further scrutiny" (Nussbaum, 1997: 278). An important aspect of her capabilities approach is to "illuminate some of the issues that must be faced when one does attempt to connect the two ideas" (Ibid.: 279). Rights theorists argue about the logical structure, content, and function of rights, as well as about who has rights. Nussbaum holds that users of the rights concept need to "link their references to a theory that answers at least some of these questions" (Ibid.: 279). She holds that because of the need to develop such a theory, "a different language has begun to take hold in talk about people's basic entitlements. This is the language of capabilities and human functioning" (Ibid.: 275). According to Nussbaum, we need to combine the capabilities approach with an account of rights because "rights language reminds us that people have justified and urgent claims to certain types of urgent treatment, no matter what the world around them has done about that." "The concept of a right is closely connected with the concept of a capability because to secure a right *is* to put someone in a position of capability" (Ibid.: 295).

According to Nussbaum, a right is "an especially urgent and justified claim that a person has, simply by being a human adult" (Nussbaum, 1997: 293). Although Nussbaum endorses the view that it is uncontroversial to classify human adults as rights bearers, she also endorses the view that children should be provided resources and support needed to develop into adult human beings. The capability provides an account of privileges to which a person might lay claim: "To secure a right to a citizen . . . is to put them in a position of capability to go ahead with choosing that function if they should so desire" (Ibid.: 293). The core connection between human rights and basic capabilities is that "just by virtue of being human, a person has a justified claim to have the capability secured to her; so that a right in that sense would be prior to capability, and a ground for securing a capability" (Ibid.: 293). She then explains how the capability approach can help us "understand that what is involved in securing a right" which "is usually a lot more than simply putting it down on paper" (Ibid.: 293). Hence, the reference to capabilities indicates that respect for rights requires that people achieve actual access to the prerequisite capability sets for leading a dignified life. The reference to human rights indicates that every human being has a justified claim to these capability sets.

Conflicts of rights

Suppose we accept that all human beings are morally entitled to certain services and resources necessary to access certain capabilities. Suppose also that access to these capabilities is necessary to enjoy one's human rights. The resources needed to give all humans access to human capabilities are scarce. At the same time, all humans have equal claims to these scarce resources, according to the United Nations. How, then, can we alleviate conflicts of human rights? Equipped with the explanation of the significance of rights outlined in the previous section, we may address the challenge of rights conflicts. I will discuss some very simplified cases which require adjudications because the rights of two or more rights-bearers conflict. In such cases, actualising the rights of both rights-bearers is impossible.

Consider a rights conflict between persons A and B, characterised by the following features: (1) both rights-bearers have equal status as human rights-bearers; (2) both the conflicting rights are justifiably considered equally weighty; (3) no circumstances of the conflict offer reason to infringe on one right rather than the other. There is a clear and urgent tension between the prolific class of allegedly "universal," "integrated and indivisible" rights to essential resources and services (yet which are scarce) and the increasing pressure on these resources due to human exploitation. The United Nations and the World Health Organisation clearly state that particularly vulnerable groups should be prioritised (UN General Assembly, 2015; World Health Organization, 2017). However, the large number of particularly vulnerable individuals who are equally entitled to scarce resources will also arguably experience rights conflicts. Even if we assume that people are willing to "deliberate and decide, through give and take," deliberation does not always result in agreement on "common priorities" (Ibid.).

Examples of behaviour that contribute to global warming include burning oil-based fuels, certain industrial activity, certain farming, and certain forestry. Suppose that we can sustainably engage in some of these activities to a certain extent. To abide by the internationally endorsed Paris Agreement to limit the increase of earth's temperature to 2 °C, and preferably to 1.5 °C above pre-industrial levels, we may only engage in such behaviour to a very limited extent. Suppose that a group of people have moral rights to engage in such behaviour within the limits of the Paris Agreement, in order to earn their living. Rights to earn a living have been proposed as moral rights and are essential in order for people to enjoy numerous human rights. Rights to *work* are listed as human rights. Rights to work could defensibly be considered to imply the rights to earn a living, since work generates most people's income. But rights to *earn a living* might not *strictly* be interpreted as human rights. Nevertheless, rights to earn a living can certainly conflict with each other if the means of livelihood are scarce. These rights will arguably become increasingly restricted.

For instance, citizens of the Maldives – who have managed a very delicate ecosystem sustainably for generations, and who are arguably not responsible for the current climate situation, but who are particularly vulnerable to floods and raising sea levels – are arguably entitled to engage in certain activities that contribute to global warming to secure their livelihood. Examples of such activities include the expansion of airports, flight routes, and hotel chains to maintain and expand tourism, which, along with tuna fishing, is one essential source of income for Maldivians. These individuals' rights might conflict with each other. Such rights conflicts will arguably occur even if the entire current "carbon budget" would be disposed of solely by individuals who are not responsible for the current situation. This rights conflict is arguably caused by excessive consumption of the carbon budget by culpable third parties such as citizens of many industrialised countries. The rights conflict is not caused by the individuals involved in this rights conflict. But conflicts between equally weighty entitlements are genuine rights conflicts that require adjudication, even if they are caused by some third culpable party. Even if we assume that certain populations are entitled to the entire carbon budget, rights conflicts will most likely occur *within* each of these groups.

Martha Nussbaum argues that recognition of, and reflection over, genuine rights conflicts – "tragic predicaments" where any available course of action will involve a moral wrongdoing – can help us find ways to arrange societal functions which reduce the potential for future occurrence of such tragic predicaments. When facing such a tragic predicament, Nussbaum recommends that we investigate whether the tragic predicament is a conflict between entitlements to resources that people require in order to lead a "fully human," "dignified" life. If one of the entitlements is not of this character, and the other is, then the latter entitlement should be given priority. If both groups' entitlements are considered resources that are required to in order to lead a "fully human," "dignified" life, then any available course of action involves a wrongdoing. Although any available course of action necessarily involves a wrongdoing, reflecting over such predicaments is fruitful because such reflection can lead to insights as to how such predicaments might be avoided in the future.

Next, we focus on strategies to reduce the risk of future conflicts over resources that are necessary in order to lead a "fully human" and "dignified" life. One obvious way to reduce the occurrence of rights conflicts over scarce resources is to produce either more of these resources, or substitutes for these resources. In the next section, we will explore how a nexus between the development of fish feed and biofuel from biomass can reduce rights conflicts over scarce resources by providing substitutes.

Carbon capture and usage technology

Fish protein is a major source of nutrition worldwide. Merz and Main (2014) note that "In 2012 fish provided more than 2.9 billion people with almost 20% of their average per capita intake of animal protein, and 4.3 billion people with almost 15% of their protein requirement." The dependence on fish as a source of nutrition is greatest in developing countries. As wild fish stock is being depleted due to industrial overfishing, aquaculture has grown into the largest food industry in the world. A major challenge facing this industry is finding alternative sources of omega-3-rich fish feed, which is essential both for fish health and to ensure omega-3 richness in farmed fish products. The use of fish feed based on wild-caught fish is unsustainable. In addition, a rising demand for fish oil for human consumption further increases the demand on the fish stock, creating even greater needs for alternative sources of omega-3-rich fish feed. The increased use of waste products from wild-caught fish to produce fish feed is also problematic because such fish feed may be of lower quality which can decrease the level of omega-3 fatty acids in farmed fish products. Algae (and algae-based fish feed) is rich in omega-3s and can help address this conundrum. The use of algae-based fish feed also avoids the need to rely on genetically modified terrestrial plants such as soy. Thus, it avoids the climate impact of cutting down rainforest to create land areas for soy production, and the climate impact of transporting the soy around the globe.

Currently, the primary challenge in industrialised cultivation of algae is upscaling, to reach a competitive price point for the products. The similarities between manufacturing the products of algae-based fish feed and algae-based biofuel speak in favour of nexus solutions to reduce costs and decrease technical challenges. The dual challenge of developing fish feed to replace fish feed produced from wild-caught fish, and the development of biofuel to replace fossil fuels, currently receives significant attention, and "water-energy-food nexus synergies between the aquaculture and biofuels sector" are rapidly growing areas of interdisciplinary research focus (34). "Both industries will produce useful by-products in the form of algae oil that can be used to increase profits. Consequently, improvements in microalga production technology will benefit both of these large and important industrial sectors" (Ibid.).

The water–energy–food nexus approach was introduced to promote integrated planning and governance of water, energy, and food, to create synergies and reduce trade-offs between the SDGs. The approach received considerable international attention at the Bonn 2011 Nexus Conference for WEF Security Nexus Solutions for the Green Economy. Yet, despite the intense attention paid to the nexus approach by the interdisciplinary research community, practical implementation of the research output has been described as "lagging" (Byers, 2015; Daher and Mohtar, 2015; Liu et al., 2017; Galaitsi et al., 2018; McGrane et al., 2019; Nhamo et al., 2020; Naidoo et al., 2021).

The United Nations' 2018 special report explicitly emphasises the potential of nexus approaches to help alleviate conflicts between the SDGs: "Quantifiable pathway studies now better represent 'nexus' approaches to assess sustainable development dimensions" (IPCC, 2018). In such approaches, a subset of closely related dimensions in sustainable development are investigated together. The report explicitly states: "The water–energy–food nexus is especially important to growing urban populations" (Ibid.). Although the importance of nexus solutions is widely acknowledged, "an explicit cognition of its practicability in real-world is still lacking" (Ghodsvali et al., 2019: 266). The development of efficient means of cross-disciplinary communication between stakeholders within science and the industry is a major challenge. Potential responses to this challenge depend on geographical and social contexts. A recent comprehensive review of the nexus research concludes: "Extensive endeavors should be made to identify the key determinants of stakeholders' interactions, feasible communications, and procedures for advanced cooperative practices through real-world applications" (Ibid.: 276).

I will now examine the specific relationships between the water–energy–food nexus and the sustainable development goals, as well as the specific relationships between the water–energy–food nexus and algae cultivation for carbon capture and utilisation, as exemplified at Finnfjord AS.

The sustainable development goals are benchmarks for global human development in areas including food security, access to affordable, clean energy, water, and sanitation. These goals relate directly to the food–energy–water nexus: "the food–energy–water nexus is directly linked with SDGs 2 (zero hunger), 6 (clean water and sanitation), and 7 (affordable and clean energy). This nexus also directly or indirectly affects all other SDGs" (Liu et al., 2018: 472). The literature provides additional support for this view.

Liu et al. (2018) repeatedly emphasise the connection between the water–energy–food nexus and the sustainable development goals: "Food, energy and water interact and can affect all the SDGs" (Ibid.: 467). They specify how the nexus affects the entire set of SDGs: "The food – energy – water nexus approach can influence the achievement of all SDGs directly or indirectly by strengthening synergies, reducing trade-offs and creating cascading effects beyond food, energy and water sectors" (Ibid.: 468). They substantiate this claim even further: "Some indices in nexus studies overlap with SDG indicators, such as CO_2 emissions and environmental footprints, facilitating direct connections between nexus research and SDGs" (Ibid.: 471). However, the authors also note a significant research gap, which is the absence of empirical research necessary to support the significance of the nexus for realisation of each of the SDGs: "No quantitative nexus studies have linked with specific SDGs" (Ibid.: 469). They strongly recommend researchers to focus on filling this gap:

> It would be useful to apply nexus approaches to SDG implementation. Nexus approaches can help achieve SDGs because SDG goals are interconnected and linked with the sectors of a particular nexus. For example, the food – energy – water nexus is directly linked with SDGs 2 (zero hunger), 6 (clean water and sanitation) and 7 (affordable and clean energy). This nexus also directly or indirectly affects all other SDGs, such as improving human health and well-being (SDG3) by enhancing water quality and quantity, bolstering food safety and nutrition and energy security; advancing economic development (SDG8) through using food system residues to generate bioenergy, treating polluted water using the bioenergy and using treated water to grow food; and mitigating climate change (SDG13) through increasing resource efficiency and reducing CO2 emissions. As nexus frameworks can make

> direct or indirect relationships with and between SDGs clear, they can enable integrated SDG implementation as requested in the Agenda 2030. Accordingly, nexus approaches can also monitor progress towards integrated SDG implementation.
>
> (Liu et al., 2018: 471)

Hoff et al. (2019) also continue the quest to map connections between the water–energy–nexus approach and the sustainable development goals. They use case studies based in Jordan, Lebanon, and Morocco to quantify connections between the water–energy–food nexus and the sustainable development goals (Hoff et al., 2019: 9).

Having substantiated the connection between the water–energy–food nexus and the sustainable development goals, I will now discuss the connection between algae cultivation, particularly at Finnfjord AS, and the water–energy–food nexus. This will demonstrate the connection between the algae cultivation at Finnfjord AS and the sustainable development goals.

Bazilian and colleagues propose

> algal bioresources as a lens through which to consider aspects of this nexus. These three spheres [water, energy and food] are especially relevant in the case of algal bioresources. Due to a unique set of attributes, algal bioresources offer a potential for disruptive change through opportunities for increased energy resources, enhanced food supplies, greenhouse gas mitigation, or new routes to wastewater remediation.
>
> (Bazilian et al., 2013: 158)

They emphasise the suitability of algal cultivation as a test case for the study of the nexus: “Algal systems offer a unique opportunity to consider the energy–water–food nexus” (Ibid.: 161). Wibisono and colleagues concur: “Nowadays the world is facing vulnerability problems related to food, energy and water demands. The challenges in those subsystems are intertwined and thus require inter-discipline approaches to address them. Bioresources offer promising solutions of the dilemma” (Wibisono et al., 2019: 166).

The authors recognise the “great potential” of microalgae amongst these bioresources:

> “Microalgae therefore have great potential for addressing the challenges in the food-energy-water trilemma, judging from their important roles in the food-energy-water nexus” (Ibid.: 165). Specifically: “Microalgae are considered as bioresource materials which are useful for supplying food, energy and clean water.”
>
> (Ibid.: 166)

Having demonstrated the strong connections between microalgae cultivation, the water–energy–food nexus, and the SDGs, I will now discuss the importance of algae cultivation for carbon capture and utilisation at Finnfjord AS for the water–energy–food nexus and the SDGs. Interdisciplinary Carbon Capture and Utilisation (iCCU) is an interdisciplinary research project in collaboration between UiT The Arctic University of Norway and Finnfjord AS. According to the project website (The diatom mass cultivation project – iCCU (uit.no)) the project is "optimising industrially relevant technologies for chemical and biological CO_2 capture and usage (CCU) by taking into account environmental, ethical, and business-related aspects. The microalgae can provide a plethora of valuable products (food, feed, and biofuel), with fish feed currently being the main focus, due to the need of the aquaculture industry for feed with higher omega-3 content." The CCU project based at Finnfjord in northern Norway involves potentially large-scale CO_2 mitigation. It is estimated that algae contribute to approximately 20% of the total amount of carbon capture globally (4). Local production of fish feed could also reduce CO_2 footprint of fish feed due to shorter transport distances of ingredients.

The collaboration between UiT the Arctic University of Norway and Finnfjord AS is an example of an Arctic CCU project with the potential to contribute both to sustainable upscaling of aquaculture production and to the development of algae-based biofuels. The project currently hosts the largest algae growth facility in the world and has received substantial funding for continued upscaling of the production. Currently, the project does not involve the development of biofuels, although one potential large environmental benefit of this product is that it would reduce the need for long transports of fish feed.

Carbon capture and usage technology can reduce the risk of human rights conflicts over sources of nutrition and energy, by replacing scarce food and energy resources with bountiful energy resources. Replacement of fossil fuels with biofuels is one of the most efficient methods to reduce carbon emissions. A nexus between algae-based fish-feed production (which reduces the need for depletion of the wild fish stock in the process of fish-feed production) and algae-based biofuel (which reduces climate impact) can reduce human rights conflicts in relation to both nutrition and an environment that can provide resources necessary for sustainment of health. Assessment of the nexus' efficiency regarding the creation of synergies and reduction of trade-offs between the SDGs would need to include context-specific quantification of various elements including transportation needs, land-area needs, water consumption, and whether the cultivation must be seasonal due to local weather conditions (Miara et al., 2014).

Applying a context-adjusted implementation model to the algae cultivation project at Finnfjord would require context-specific mapping and quantification of the links among food, water, and energy on site. It would then require the identification of critical links and leveraging of the results in accordance with the implementation model. The algae cultivation at Finnfjord AS provides a unique test case for such an implementation model due to the project's industrial scale. Currently upgrading the algae cultivation capacity to 3,000,000 L demonstrates an increasing potential to realise a positive impact on the SDGs.

Daher and Mohtar (2015) have developed the most context-adjusted model to date. Nexus Tool 2.0. allows the user to submit information regarding a project's water, land, and energy requirements, to thereby assess the carbon footprint of the project. Yet, that model currently only addresses these questions within a national context. An adjusted version of this tool, tailored specifically for the industrial scale carbon capture and utilisation project at Finnfjord AS, would significantly contribute to context-specific quantification of the links between water, energy and food, and local implementation of the water–energy–food nexus. Such implementation provides a pilot study that, if replicated, could have a significant impact on the realisation of the SDGs. Research output related to the algae cultivation has already contributed to life-cycle analysis of the entire production process of algae cultivation, fish-feed production, and local salmon farming (Eilertsen et al., 2022). As trade-offs between environmental benefits (CO_2 capture, CO_2 emission reduction due to minimised need for transportation of feed), financial benefits (due to salmon production), and other types of benefits might be necessary, identifying explicit priorities among these considerations will reveal the normative dimensions of implementing the water–energy–food nexus. Explicit priorities and normative dimensions are needed since the SDGs are not ranked in order of priority, and prioritisation is necessary to avoid practical conflicts between the SDGs.

Novel developments of the capability approach provides theoretical grounding for the water–energy–food nexus approach. Breena Holland (2008) argues that Nussbaum's list of central human capabilities needs to be complemented by addition of the capability to live in conditions that are characterised by ecological sustainability, as an independent capability that is a precondition for realisation of all other capabilities. Conditions that are characterised by ecological sustainability include a temperature range conducive to human health and the availability of food sources.

Adding ecological sustainability as an independent capability and as a precondition for realisation of all other capabilities provides a new theoretical tool for meeting the knowledge gap regarding local solutions to conflicts between the SDGs identified by the United Nations – while it also suggests a very rough order of priority of Nussbaum's central human capabilities, and the human rights-based SDGs. Although labelling ecological sustainability as a separate capability might be challengeable, the suggestion that ecological capability is a prerequisite for the realisation of the ten central human capabilities is uncontroversial.

Jonathan Wolff and Avner De-Shalit, in their influential book *Disadvantage*, introduce a novel development of the capability approach that supports this order of priority. According to Wolff and De-Shalit, people are disadvantaged compared to others if they face "clusters" of capability deficits. They argue that scarce resources should be directed towards preventing deficits of capability protection that causes additional deficits of capability protection. Such deficits cause "corrosive disadvantages." They also argue that scarce resources should be directed towards protecting capabilities that, if protected, contribute to the protection of other capabilities. Such protections promote "fertile functionings" (Wolff and De-Shalit, 2007). Undernourishment and exposure to impacts of climate change arguably cause corrosive disadvantage, and protection of sources of nourishment and limitations of the impacts of climate change arguably protects fertile functionings.

Hence, nexus solutions such as the one between fish-feed production and biofuel production arguably merit high priority because they potentially reduce corrosive disadvantages while they promote fertile functionings.

Mapping of the complex interactions among water, food, and energy governance is a prerequisite for the successful implementation of the nexus. Failure to do so could result in unforeseen corrosive disadvantages such as reduced access to fertile land and excessive consumption of water resources. Due to microalgae's significant capacity to rapidly increase in density, capture CO_2, and flourish in wastewater, the cultivation does not require extensive amounts of freshwater and land areas. Replacing fish feed based on wild fish with fish feed based on algae, and replacing fossil fuels with biofuel, at least partly contributes to secure the capability for ecological sustainability. Protection of this capability by sustainable upscaling of the aquaculture industry, and potentially of the nexus between the aquaculture and biofuels industry contributes to reduce "clusters" of disadvantage for populations that are particularly exposed to the impacts of climate change, including nutritional deficits. The pioneering upscaling to the industrial scale of microalgae cultivation for fish-feed production could be regarded as a pilot project that, if successfully replicated in different geographical and socio-economic contexts, could contribute significantly to reduction of conflicts between the human rights-based SDGs on a global basis.

Conclusion

This chapter highlighted an important knowledge gap identified by the United Nations: the need to address inevitable conflicts between the SDGs in different geographical contexts. I focused on strategies to meet this challenge in an Arctic context. The discussion took an explication of the place of human rights in the SDGs as its point of departure, followed by a discussion of the capability approach understood as the moral grounding of human rights. From this normative framework, I defined human rights conflicts and outlined a method to reduce the risk of rights conflicts, which aligns with the capability approach. The chapter finally describes how the capability approach developed by Wolff and De-Shalit supports nexus solutions between the aquaculture industry and the biofuel production. Although the collaboration between UiT The Arctic University of Norway and Finnfjord AS currently focuses on the production of algae-based fish feed, the project has the potential to develop nexus solutions between the aquaculture industry and the biofuel production.

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Appendix

The central human capabilities

1. Life. Being able to live to the end of a human life of normal length; not dying prematurely, or before one's life is so reduced as to be not worth living.
2. Bodily health. Being able to have good health, including reproductive health; to be adequately nourished; to have adequate shelter.
3. Bodily integrity. Being able to move freely from place to place; to be secure against violent assault, including sexual assault and domestic violence; having opportunities for sexual satisfaction and for choice in matters of reproduction.
4. Senses, imagination, and thought. Being able to use the senses, to imagine, think, and reason – and to do these things in a "truly human" way, a way informed and cultivated by an adequate education, including, but by no means limited to, literacy and basic mathematical and scientific training. Being able to use imagination and thought in connection with experiencing and producing works and events of one's own choice, religious, literary, musical, and so forth. Being able to use one's mind in ways protected by guarantees of freedom of expression with respect to both political and artistic speech, and freedom of religious exercise. Being able to have pleasurable experiences and to avoid nonbeneficial pain.
5. Emotions. Being able to have attachments to things and people outside ourselves; to love those who love and care for us, to grieve in their absence; in general, to love, to grieve, to experience longing, gratitude, and justified anger. Not having one's emotional development blighted by fear and anxiety. (Supporting this capability means supporting forms of human association that can be shown to be crucial in their development.)
6. Practical reason. Being able to form a conception of the good and to engage in critical reflection about the planning of one's life. (This entails protection for the liberty of conscience and religious observance.)
7. Affiliation. (A) Being able to live with and toward others, to recognise and show concern for other human beings, to engage in various forms of social interaction; to be able to imagine the situation of another. (Protecting this capability means protecting institutions that constitute and nourish such forms of affiliation, and also protecting the freedom of assembly and political speech.)

(B) Having the social bases of self-respect and nonhumiliation; being able to be treated as a dignified being whose worth is equal to that of others. This entails provisions of nondiscrimination on the basis of race, sex, sexual orientation, ethnicity, caste, religion, and national origin.

8 Other species. Being able to live with concern for and in relation to animals, plants, and the world of nature.

9 Play. Being able to laugh, to play, to enjoy recreational activities.

10 Control over one's environment. (A) Political. Being able to participate effectively in political choices that govern one's life; having the right of political participation, protections of free speech and association. (B) Material. Being able to hold property (both land and movable goods) and having property rights on an equal basis with others; having the right to seek employment on an equal basis with others; having the freedom from unwarranted search and seizure. In work, being able to work as a human being, exercising practical reason and entering into meaningful relationships of mutual recognition with other workers (Nussbaum, 2000: 78–80).

The sustainable development goals

Goal 1. End poverty in all its forms everywhere.

Goal 2. End hunger, achieve food security and improved nutrition, and promote sustainable agriculture.

Goal 3. Ensure healthy lives and promote well-being for all at all ages.

Goal 4. Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all.

Goal 5. Achieve gender equality and empower all women and girls.

Goal 6. Ensure availability and sustainable management of water and sanitation for all.

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

Goal 8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all.

Goal 9. Build resilient infrastructure, promote inclusive and sustainable industrialisation, and foster innovation.

Goal 10. Reduce inequality within and among countries.

Goal 11. Make cities and human settlements inclusive, safe, resilient, and sustainable.

Goal 12. Ensure sustainable consumption and production patterns.

Goal 13. Take urgent action to combat climate change and its impacts.

Goal 14. Conserve and sustainably use the oceans, seas, and marine resources for sustainable development.

Goal 15. Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.

Goal 16. Promote peaceful and inclusive societies for sustainable development; provide access to justice for all; and build effective, accountable, and inclusive institutions at all levels.

Goal 17. Strengthen the means of implementation and revitalise the Global Partnership for Sustainable Development.

5 Transforming resources

The university as a CO_2 catalyst

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Introduction

As society awakens to the consequences of our vast utilisation of natural resources, a slight hope is found surrounding the role of innovation (Von Schomberg, 2019). The hope is that innovative solutions will address harmful economic activities that affect our shared resources, known as the commons. British writer William Forster Lloyd first introduced the notion of the commons, representing shared resources, in 1833. This idea was later brought into the mainstream by Hardin in 1968, who introduced the term "tragedy of the commons." This theory sheds light on the tendency of individuals to utilise the commons for personal gain without considering the accumulated effects on these resources. Such degradation results in shared losses, often renders the resources unusable, and affects third parties including the environment and communities closely aligned with nature. Hardin (1968) posits that the burden of managing the commons cannot work if assigned to the individual level of society, as this results in worry, mental stress, and confrontation among people as they seek solutions that serve the community and the environment. As individuals respond in various ways to such appeals, this can result in further imbalance in how the commons are handled. The author argues that responsible coercion from the state, such as taxes or legal regulation, could be more effective in curbing undesirable behaviour, as it allows a more rational decision-making process, through acknowledging the inevitability that some restrictions benefit society.

Mazzucato (2013) also highlights the state's substantial role in endeavours that are typically attributed to the individual – specifically, innovation. She emphasises the state's role in fostering radical growth-enhancing innovations by taking risks and creating a network of actors in partnership with the private sector. She argues that the state has played a leading role in technological revolutions (such as the computer industry, the Internet, pharma-biotech, and nanotechnology) to enable the development and commercialisation of new technologies. Therefore, she calls for a nuanced understanding of the state's role in innovation policy (beyond relying on data such as R&D expenditure or patenting) through strategic organising, directing, and evaluating state investments (p. 1). She argues that the state can proactively create strategies, invest in high-growth areas, fund uncertain research that the private sector avoids, and oversee commercialisation processes. While private-sector entrepreneurial activity is important, she holds that the state's role in supporting innovative breakthroughs is often overlooked.

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Mazzucato, similarly, highlights the role of the state in her book, the Entrepreneurial State (2013) Her controversial claim is that the state has a role in endeavours that are typically attributed to the individual – specifically, innovation where state's role in fostering radical growth-enhancing innovations is being performed by taking risks and creating a network of actors in partnership with the private sector. In fact, in the book, Mazzucato argues that in the US, the state has played a leading role in technological revolutions (such as the computer industry, the Internet, pharma-biotech, and nanotechnology) to enable the development and commercialisation of new technologies. Building on this insight, she calls for a nuanced understanding of the state's role in innovation policy (beyond relying on data such as R&D expenditure or patenting) through strategic organising, directing, and evaluating state investments (p. 1). However, while research and innovation are often seen as solutions to societal challenges, there is a risk of overlooking the significance of shared resources (commons), which can result in social and environmental issues (Von Schomberg, 2019). Thus, the introduction of new technologies, products, or knowledge can give rise to unforeseen difficulties including negative externalities.

Interest in responsible innovation (RI) is on the rise, as it seems to offer new potential solutions for these issues. The prospective framework programme *Horizon 2020* defines several Grand Challenges, which follow the Lund Declaration's call for a Europe that "must focus on the grand challenges of our time" (Lund Declaration Working Group, 2009). Responsible research and innovation extend beyond managing risks, to focus on achieving socially desirable outcomes, and aligning research with Grand Challenges[1] or broadly shared public benefits (von Schomberg, 2013). By focusing on addressing significant challenges (von Schomberg, 2013; Stahl et al., 2017) and improving externalities, RI offers a promising path towards progress.

In this chapter, we present a narrative grounded in the theoretical framework of responsible innovation and institutional theory, where we explore how industry and the academic sector can collaborate to devise novel approaches for the responsible development and dissemination of innovations. We focus on the innovation project that was developed at Finnfjord Smelteverk, which we present as an example of responsible innovation and, in which, we attempt to understand which mechanisms led to its fruition and success. We delve into a narrative of university–industry collaboration that enabled the development of ground-breaking knowledge to help address the challenges posed by climate change.

Theoretical framework

Our theoretical framework revolves around two fundamental concepts: RI and institutional theory. These frameworks offer critical perspectives on the challenges and prospects of innovation, as well as on the role of institutions in the innovation process. Together, these theoretical lenses provide a comprehensive understanding of innovation and institutional processes. RI offers a vision for innovation that is socially desirable and beneficial, while institutional theory provides insights into the structures, both formal and informal, that can support or hinder the realisation of this vision. The integration of these theories in the subsequent analysis will shed light on how innovation can be responsibly pursued and managed, within the boundaries and supports provided by various institutional arrangements, with particular attention to the role of universities in this ecosystem.

Responsible innovation

Von Schomberg (2013) claim that the challenge of RI is to design a debate in such a way that everyone is successfully engaged, and a vision is shared among powerful actors while still being represented by the voice of ordinary people. The macroeconomic justifications for investing in research and innovation emphasise the belief that innovation is the key to addressing societal challenges, such as economic growth, employment, and combating climate change (EC, 2011: 3). In contrast, the Lund Declaration proposes an alternative justification, linking research and innovation investments to responding to Grand Challenges and achieving sustainable economic growth by meeting societal objectives (Lund Declaration, 2009: 2).

The concept of RI thus emerges as a paradigm shift from a purely macroeconomic justification to a broader perspective. RI involves steering the innovation process towards socially beneficial objectives, considering normative anchor points in basic treaties and constitutions, and shared public values. It calls for specific governance requirements, including anticipatory and deliberative governance, ethics of co-responsibility, the use of normative principles for technology design, and interdisciplinary research practices. A definition for RI is "*a transparent, interactive process where societal actors and innovators mutually respond to the ethical, sustainable, and socially desirable aspects of the innovation process and its products*" (Von Schomberg, 2013: 63). Responsible research and innovation shift the focus from specific technologies and risks to the entire innovation process and its governance.

Most of the RI literature starts from the plausible premise that innovations are radically uncertain, and their societal and environmental consequences are virtually unpredictable (Özdemir, 2019). Therefore, the challenge of RI is to understand how we, as a community, can move away from our current practices to achieve the systemic change needed in society. RI predicates envisioning an ideal future, creating responsible processes, and developing an outcome responsive to a variety of stakeholders both silent and vocal. It is a process that seeks to promote technological research and innovation that is socially desirable and undertaken in the public's best interest (Stahl et al., 2021) such as focusing on society's grand challenges.

However, the concept of RI has faced criticism for its lack of realism (Von Schomberg, 2013; Von Schomberg, 2019; Stahl et al., 2017). It has become evident that the aspiration for responsibility clashes with the realities of existing innovation processes. Driven by short-term goals and the need for quantifiable outcomes, companies often focus on value spreading rather than value creation (Mannak et al., 2019). The main challenge of responsible innovation lies in the complexity of the innovation process, involving high stakeholder participation, uncertainty, and unpredictability of technological advancements. Experience from firms that begin with an idealistic vision reveals the influence of strong institutional forces that they must navigate (Oftedal et al., 2019). Additionally, "moral" and "political" factors, such as conflicting worldviews, interests, and value systems among stakeholders, as well as power imbalances, further complicate the implementation of RI (Von Schomberg, 2019). Organising for responsible innovation further necessitates novel institutional arrangements (Von Schomberg, 2019). Therefore, institutions play a crucial role in managing resources in a sustainable and viable manner.

Institutional theory

Hardin (1968) argues in "Tragedy of The Commons" that since natural resources are destructible, they should be formally managed. Hardin (1968) emphasises the role of formal institutions to control access to natural resources. Formal institutions are written down, introduced, and enforced by the state, so they can be perceived as laws. Yet when a lack of enforcement or willingness to employment arises, the formal institution can't always prevent natural resources from destruction. This regulative dimension of institutions deals with the formation of rules and regulations, as well as the processes to implement the same correctly and appropriately, including imposing penalties on the people who don't adhere to those rules and regulations over time (Scott, 2014). Mazzucato (2015) argues in the "Entrepreneurial State" the importance of the regulative dimension for innovation.

However, Ostrom (1990) criticised Hardin and shifted this concept to the informal institution. Informal institutions are unwritten but deeply rooted codes of conduct, traditions, customs, conventions of behaviour, sanctions, and taboos. These are often called the "normative" institutional dimension (Scott, 2014). These norms and values tend to define what is considered good or appropriate; in turn, these norms and values influence the entrepreneurial process and organisational forms (Sine & David, 2010). Ostrom argued that informal institutions can provide more realistic and resourceful plans to minimise the decline of natural resources by using the local level of community knowledge. This notion has been supported by Yami et al. (2009), finding that informal institutions have contributed towards achieving most of the sustainability outcomes in their proposition of the "tragedy of the commons" argument and that shared problems are sometimes better solved by voluntary organisations rather than by a coercive state.

Not directly discussed is the cultural-cognitive pillar which stresses the central role of the socially mediated construction of a common framework of meanings (Scott, 2014: 70). The cognitive dimension represents awareness and expertise of the individual (Busenitz et al., 2000) and is associated with knowledge (Andrade, 1984). Further, Von Schomberg (2019) discuss the challenges related to responsible innovation require institutional change through "challenge-based" universities. The way we interpret knowledge is shifting away from a traditional degree-based research model toward a more capability/experience-based model, which acts as a motor for RI. Thus, universities can fulfil a crucial role in fostering responsible innovation. This finds common ground in the "entrepreneurial university" literature (Rothaermel et al., 2007; Nelles & Vorley, 2016) which for a long time has monitored the development of universities shifting from teaching and researching units, towards innovative and entrepreneurial activities, research spin-outs, and promoting entrepreneurial methodologies across disciplines and in their general processes. Entrepreneurial universities actively engage with their local communities and contribute to innovation in various ways such as by spinning out innovations from their research and university–industry linkages (Perkmann et al., 2013). In this chapter, we use the lens of institutional theory to understand the role of the university in RI.

Methodology: constructing a narrative of the Finnfjord case

Drawing on Riessman's (1993) principles, we apply narrative methodology to scrutinise the Finnfjord project as an RI exemplar. This approach enables the dissection of its development and the identification of pivotal drivers steering its advancement.

Narrative methodology, underpinned by Polkinghorne's (1988) insights, serves as an appropriate lens to provide a nuanced understanding of complex processes and organisational dynamics inherent to the Finnfjord project. This method illuminates the contextual fabric – historical, cultural, and social – within which the case is embedded and facilitates accurate interpretation of findings. Narratives, thereby, not only humanise data but also resonate with readers, making the case study accessible and relatable.

The contextual background is key for narrative construction (Riessman, 1993; Squire et al., 2013; Andrews et al., 2008). Finnfjord Smelteverk (FM) is a ferrosilicon smelter situated in Finnfjord within the Arctic Circle. The company's history dates to 1960 when the first establishment began, and the first furnace was operational in March 1962. Finnfjord AS was founded in 1983 and has since become one of Europe's largest producers of ferrosilicon, manufacturing approximately 100,000 tonne of the material annually. Ferrosilicon is a crucial component in steel production and various steel products, making FM an integral player in the steel industry. Before they shifted their focus to the environment, FM emitted substantial amounts of CO_2, NO_x, and heavy metals into the atmosphere. This raised environmental concerns and highlighted the need for sustainable practices. FM is situated in Finnfjord, an area in Senja municipality, Norway. Senja is Norway's second-largest island, located in the Arctic region, and connected to the mainland by a bridge and speedboat ferries. The island has a total area of 1589.35 km^2 and a population of just under 8000, while Finnfjord itself is home to around 400 inhabitants. While the steel industry, including ferrosilicon production, is a global industry, European steelmakers, including FM, have encountered challenges such as drops in demand and overcapacities. Additionally, regulators have been increasing pressure to reduce CO_2 emissions, impacting the European steel industry's cost position.

As these challenges mounted, a researcher from the University of Tromsø approached FM with an intriguing idea. The researcher was interested in using some of the CO_2-filled smoke from the factory as nutrition for diatom algae. The management of Finnfjord saw potential in this collaboration, hoping it could foster relations with the university and generate goodwill toward the company. However, they didn't initially realise the transformative potential this idea held for their company and possibly the entire industry. The following narrative considers the challenges and transformations the project has undergone, with a particular focus on its environmental sustainability initiatives and collaborations, to explore the inception and realisation of innovative ideas.

Selecting the participants is central to constructing a good narrative (Polkinghorne, 1988; Clandinin & Connelly, 2000; Chase, 2005). Here, three distinct voices construct the story, providing readers with insights into the thoughts and decisions that shaped the project:

1. *The firm:* CEO and owner of Finnfjord Smelteverk is a lifelong resident of Finnfjord, deeply committed to creating value locally. Representing the third generation in his family to be involved with the organisation, he has a strong familial connection to the factory, and focuses on maintaining the company's local impact and ensuring its sustainable growth.
2. *The university:* Director of the Norwegian College of Fishery Science (NCFS) plays a strategic and administrative role in the collaboration. With extensive experience in university spin-offs and innovative projects, NCFS has been instrumental in supporting the Finnfjord project financially and ensuring its success. Established in 1972 as a joint responsibility of three Norwegian universities, NCFS underwent a reorganisation in 1988 to become a faculty at the University of Tromsø.
3. *The researcher:* although retired, continues to contribute to the project through specific financial arrangements between Finnfjord and the University. Having worked with the university since its inception in 1960, the researcher has witnessed its evolution and played a crucial role in the project. Their focus is on continuing the research and establishing an environment that can sustain the project's future.

The main data for the narrative comes from interviews with key participants, providing a platform for sharing personal stories and perspectives, with an emphasis on the project's various phases and future prospects. Subsequently, the data, transcribed verbatim, underwent a meticulous analysis process. We also collected data from some secondary sources, including company records and reports. The researchers conducting the study were deeply immersed in the case, using reflexive approaches (Etherington, 2004) and engaging extensively with the data and the informants. This immersion allows an in-depth view of the intricacies of the case and its context, contributing to the credibility and richness of the study's outcomes.

This process involved comparing diverse viewpoints and aligning them with theoretical frameworks pertinent to the narrative. Through this analytical lens, the narrative aims to offer a multifaceted understanding of the Finnfjord case by accentuating the perspectives and insights of each participant.

In crafting this narrative, we aligned the methodological approach with established principles and practices within the realm of narrative research. The Finnfjord project narrative, thus constructed, serves as a robust analytical tool for delving deep into the intricacies of the case while providing readers with a coherent, engaging, and insightful account of the project's journey and its broader implications in the field of RI.

Narrative

The starting point

The starting point of the Finnfjord project is marked by the CEO and owner of the company, who has faced challenges leading a small company in a relatively isolated area in a fiercely competitive global market. He emphasises the importance of remaining competitive while addressing high costs and the expectations and limitations posed by Norway's "licence to operate." The company has experienced interruptions in production due to market competition and financial crises, leading them to re-evaluate their approach to sustainability and environmental impact. The CEO's focus on cost-effectiveness and environmental responsibility is driven by the need to compete globally while complying with environmental regulations. He believes that investing in environmental improvements now is essential for the company's future viability, rather than waiting for unknown solutions in the distant future. Being a small company with short decision lines, they can act quickly and capitalise on their strengths.

> *I've been here since 2003, and twice we've had to stop production because of the market. Once, because we were outcompeted by Chinese manufacturers in 2005, and in 2008 we had to stop because of the financial crisis. And we had to ask ourselves: How on earth are we going to be able to compete? It's important to underline that we are exposed to the forces of competition anyway, and in our industry, we are exposed to global competition. Ferrosilicon has an infinite shelf life, so wherever you produce it, the customers are aware of price. So, we always have the competitive perspective with us. That is, we must think about the cost because our customers are not prepared to pay more for environmentally friendly ferrosilicon than a ferrosilicon that is produced as dirty as you can imagine. So, the cost perspective has to be included, and then you have to include the environmental perspective as well – because in Norway we have that 'License to operate' discussion. If you're not clean, no one really wants to work there, have you there, and you don't get to lend money, eventually. So you're kind of going to have to do something. For us, any discussion of what we can do for the balance works here . . . What can we do to keep the investment opportunity we have, for us is it really the balance then. What can we do to improve the cost situation and at the same time improve the environmental situation . . . We started looking at what it takes to clean out CO_2 – we found out that it is very energy intensive – but we thought that we have a lot of heat on Finnfjord. . . . In 2008 we started to envision becoming the world's first CO_2 free plant and that's what we were concerned about from the time I started here in 2003 . . . and*

> *then we realised that "this with CO_2 will be important in the future". We are making heavy investments, and taking giant steps on the way to becoming very much better than we are today. So, you could argue that this may not be good enough in 2050, but it must be better to do something now, that has an effect now, than to wait until something magical happens in 2050. Because I have no idea what we are going to do to become CO_2 free – we are a smelter. However, one of our advantages is that decision lines are short compared to big corporations . . . And our strengths are short decision lines. . . . We also have a great willingness to invest here because we want to secure that our assets stay in the region . . . So, we have a willingness to make an investment that may not be the best return on investment on short term, but we are trying to invest in something that will provide financial gain in the future, that also that improves the environmental performance of Finnfjord.*

On the University of Tromsø (UiT) side, their involvement in the project aligns with their mandate to focus on research and education related to the region's resources and needs. UiT has developed specialised knowledge in arctic marine resources, including crucial biotechnology expertise. The faculty director is aware of UiT's mission as a societal actor in the region and acknowledges the unique nature of the Finnfjord project, as the company had initiated several environmental initiatives independently before collaborating with the university.

> *In a way, UiT historically has contributed to create companies. Many of those who are in the Biotech North cluster come from us, they are sort of researchers. Or there are very many who come from BFE or the College of Fisheries in their time then, to these companies. But when it comes to Finnfjord, it's quite different because Finnfjord has stood on its own two feet. And I think that's the next answer: an industrialist and a family business, and the ideas they had to become CO_2 neutral, and they had also taken some steps. They had started on their own, without us being involved. The energy economisation project was something they themselves had initiated that made one began to talk. And it's the same with the other big project that I've been associated with bioprospecting, where you're going to "go around in the ocean and look for species that can have a medicinal effect." It's kind of like "needle in haystack" research, where you feel a little blind: Is that species and these molecular compounds known from before? Yes, we see them are toxic, but can they be used to something? Also, just test, test, test – a slow process. But now it's starting to throw off not true because has been going on for 15 years, even after SFI was finished because it takes time when you're blindfolded. So, it's really the polar opposite of the project at Finnfjord because it was sort of "straight in". He has been researching on a lab scale for many, many years – from the 80s onwards. So, he knew it was possible.*

The researcher's perspective sheds light on the early years of UiT, emphasising the significance of local identity, individual backgrounds, and personality in shaping research interests. During the university's formative period, there was a focus on developing research areas with local relevance and creating unique niches rather than replicating other universities' approaches. The proximity of researchers from diverse disciplines allowed for the exchange of ideas and a broader perspective on scientific pursuits. The establishment of UiT was influenced by discussions on local context and individual experiences, which shaped researchers' choices and interests. The region aimed to cultivate expertise and research areas that held local significance, fostering innovation rather than imitating other institutions. The establishment of the university was grounded in regional development, and researchers shared a sense of community, as they cohabited with colleagues from various disciplines, fostered mutual understanding, and broke down disciplinary barriers. The starting point of the Finnfjord project reflects a commitment to address challenges and seek innovative solutions that merge environmental responsibility with economic viability. Collaboration between the company and the university capitalises on their strengths, culminating in a transformative project with the potential to lead the industry towards a sustainable future.

> *I think that when the university was established, there was a lot more talk about local belonging and personality, and that in a way, so if you're going to do it something scientific, then of course Newton's laws and chemical laws are lots of balance and chemical reactions. That's the same thing, but. However, it matters what kind of personality you are, where you come from, how you grew up. If you are from the Northern Norway, you are from the west – it can influence the research of what you choose and do it. For example, if you work with chemistry, there are probably 10 million different things you can focus on when it comes to pharmacology, right? If you, if you work with medicine, right? Then, if you come from a coastal municipality in eastern Finnmark, where people perhaps would die at 50 due to heart defects – then maybe you have a propensity to think that it is important to work with heart attacks and not cancer, right? So there was a lot of talk about things like that when the university was started. It was one of the reasons for the start of the University of Tromsø that the region should be sown with expertise, right? And to develop research areas that had some local significance and that one should not repeat what they did at other universities, but rather create one's own niches. Also, if you go back in time at university, you even shared a house with social science researchers, and you got to understand the way they were thinking, and also know them, so it was a lot closer. In a way, it was subconsciously almost knowing that the division into discipline and scientific is largely humanised. . . . That nature and people and animals and things like that are not bounded by sharp lines, for example, between mathematics and chemistry or chemistry and human behaviour and whatever, social studies. So, it was a lot more like widespread looking over the fence to each other.*

Overall, the starting point of the Finnfjord project is marked by the recognition of challenges and the pursuit of innovative solutions that combine environmental responsibility with economic viability. It involves collaboration between the company and the university, leveraging their respective strengths to create a transformative project with the potential to lead the industry towards a sustainable future.

Drivers

The drivers behind the Finnfjord project are multifaceted, stemming from both the company's perspective and the university's standpoint. The firm's side was motivated by two primary drivers. First, former Labour Party Prime Minister Jens Stoltenberg provided an idealistic vision, as he likened the challenge of CO_2 capture to President John F. Kennedy's ambitious goal of landing a man on the Moon. This vision motivated Finnfjord to explore CO_2 capture possibilities, and take on a leadership role in the region. Second, carbon quotas and taxes provided an economic driver. The introduction of carbon quotas in 2003, along with a subsequent increase in electricity prices due to emissions trading schemes, and taxes prompted Finnfjord to explore more environmentally friendly solutions.

> *Our first idea of becoming CO_2 free was to look at coal-fired power plants with CO_2 capture. We were inspired by Stoltenberg (the "Mongstad Moon Landing") and we wanted build on the results from that. There we also – other actors such as Hermansen from "Det Store Norske"*[2]*– he thought that coal had a bad reputation. So why not use coal power to make energy? Then we had CO_2 capture, so we had a collaboration with them to CO_2 emission plant north, the price effect of the carbon quotas introduced in 2003. There was sort of no effect of them until 2004 or 2005. Suddenly we saw an inexplicable increase in the price of electricity that no one realised. Suddenly, we started learning about how this pricing actually works. Everyone predicted that the CO_2 taxes would only have a marginal effect in the market . . . Then came the marginal price effect: the entire market is controlled by the last megawatt produced. All analysts thought that the carbon quotas will have no bearing on prices, one cent max. And suddenly the price of electricity rose by like 10, 12, 15 percents. And it was an extreme amount and one wondered "what is going on" and there was an exchange: the last megawatt that is traded sets the price of everything and that is with full CO_2 – price mark-up and full mark-up and everything.*

The university found the project attractive for several reasons. First, collaborating with an established company like Finnfjord would provide potential employment opportunities for graduates and would complement the university's focus on spin-out companies from researchers. Second, the project would align with UiT's aim to develop unique competence in global topics like CO_2 capture and contribute to the climate debate. Third, the university's faculty director viewed the focus on CO_2 utilisation (CCU) as a more sustainable and effective solution compared to carbon capture and storage (CCS). The project would present an opportunity to create circular systems that counteract carbon emissions and improve the environment.

Additionally, success on the Finnfjord project could potentially be scaled up and shared globally through knowledge transfer.

> *From the university standpoint, our purpose is to educate candidates, and we will facilitate what the university develops, and support companies as well. In the north we have lacked companies, so it is great to achieve something new to the north which is high technology, that at the same time is traditional somehow, pertaining to marine challenges. Last, but not least, it is just as much – commitment to the* CO_2 *challenge. I think it's important to find a solution to that . . . I have a lot of faith in CCU as more of a solution than CCS. I see CCS as a typical solution for when mankind has created a problem in the world, we are not going to the root cause, but instead we are going to bury it. And to me it's kind of like crazy thinking. Instead, we must create sustainable, circular systems that make us survive on this planet. I think that's very interesting. We have to create processes that help counteract carbon: we produce more algae, we take them out of nature and up on land so we produce more oxygen also for the world, which is the main polar opposite of* CO_2*. It's easy to fall into the temptation and think that it's easier with CCS and think that then it will be gone, but with CCU it's more about life cycle and creating some products that you . . . Anyway, further, we remove a lot more that we don't think –* NO_X*, which is nitrogen which is also an environmental toxin – so there are other things that get lost as just . . . The whole world is so concerned about carbon, but there are also a lot of other things. And once you get started with this? Finally, it's a fun project. The fact that it's going so well is nice. And it also catches my personal interest. I do have a high belief in this project, not only that it will be a success on Finnfjord, but that it is a success for the world. Because if we get it done on Finnfjord, the plan is to distribute to the world through transfer of knowledge.*

The researcher is motivated by his belief in a better and more effective approach to working with algae. Insights from his prior work with algae growth, helped him recognise the potential for doubling biomass daily by growing algae quickly and efficiently. He sought to imitate nature's way of functioning and create a more sustainable system. He also enjoys colleagues and a good working environment.

> *I have worked with growing algae on a smaller scale, all the way back to the late 70s, so. I knew I could do that. I knew that if you're going to grow algae in large quantities, you must have a lot of* CO_2*, right? I knew that a good part of the* CO_2 *in the sea is taken up by algae. Of course, I understood that if you make them grow fast, you can double the biomass every day. If you get them and double every day, you produce highly nutritious biomass in large quantities, on a much smaller area than you do when you farm where you can only harvest and then once and twice a year. It's also because I knew we can do better than with our current methods. Just think about it. If you do fish*

> *farming, it's like you feed fish with fish. That's idiotic, isn't it? It's just like you have a fish on your plate and you're going to have dinner, and then you say no, I'm going to give this fish to another fish that can eat it, and then I'll take that fish and eat it. I thought there would be a better way by imitating nature's own way of doing it. Also, it's much more satisfying to do something that could have an impact . . . But even more satisfying to have fun and work with someone who is enthusiastic and believes in what they're doing – than, as I say, sitting in the office and giving the same series of lectures every single year.*

Challenges in innovation and in university–industry linkages

When focusing on the barriers encountered in the innovation process, we see scepticism and criticism from all three perspectives from possible stakeholders and peers, with doubts about the algae's usefulness and long-term viability. For the industry, trial and error was daunting and challenged the industry's bias towards finished engineering solutions posed challenges in adopting innovative ideas. The industry also referred to luck contributing to the project, which is not a solid foundation for decision.

> *I guess you've seen the first tank. It wasn't much. I guess that was the 60-liter tank. That's what we started with . . . We had a whole bunch of people who were sceptical, saying "The algae is toxic. You can't keep the culture alive over time. What happens when it gets cold outside?" There were many people who harshly criticised it, and I understand why, but you must try it out. It isn't easy. We've had a bit of luck too. Who would have thought that we have an algae tank that doesn't grow. It's super luck. After all, it's completely pure . . . And the operational experience going forward is very valuable. At the same time, the question is: how much trial, and error should you have? In the industry, if you've made up your mind, you don't want to take a development path, then you want to buy something that just works. So we're hoping that we'll get to a place where we have a concept that works, so we can we sell this to others. The industry is also very focused towards the best engineering environments, which is where all civil engineers are educated and finished solutions. If we have a problem, it's the environments we turn to. I myself am educated like that and I know people in that environment, So, it's kind of in the spinal cord reflex, that then we turn towards engineering. And when the University of Tromsø came, we thought, "No, no, no. That's just social science and it's s not so relevant."*

The University of Tromsø's involvement became crucial as the project progressed, investing significant resources. Successful milestones and positive outcomes made it easier to attract governmental funding partners and step-by-step extended university–industry linkages and access to funding for larger research projects facilitated stronger collaborations. This underlines the evolving nature of university–industry collaborations and the role of funding and milestones in fostering successful partnerships.

> *After we got access to funding for larger research projects, which is really a needle's eye to get through, it became easier to relate to funding partners. It is also important, before that time, when you get more and more news stories, and meet these milestones – that we have managed to document that the algae are not toxic, and also, that we also had smaller projects such as "effect on lice infestations." So, it's clear that there's more info coming out, then there's more interest in the project, and easier to get funding. So, it's probably easier to get money for the project now, and send applications now, than it was at an earlier stage. In the beginning, there was just some small backing from the governmental agencies, so Finnfjord and UiT have covered half of the money which was missing, all the way. So we definitely have used considerable resources, primarily by virtue of the fact that we have had our own manpower there, then, and some of the equipment funds and things like that. But it has been spent significantly. So there is a lot of UiT money that has been spent and Finnfjord. And it's because UiT had such faith in it – that we have to achieve this. And then one can ask oneself questions about for "wild projects" because it is hard to convince about its potential.*

The researcher quotes previous challenges of working with innovation. Trial and error is important in research as it accumulates knowledge which, again, can lead to better outcomes over time.

> *There are many pitfalls when working with research and development, and I can cite an example: Working here with cod farming. A very prominent researcher and I were creating a living feed chain that would feed cod larvae, right? And it was very innovative the scheme we had, and very good, right? We grew a special kind of copepods are very small sea creatures that we intended to. We wanted to revolutionise cod farming. The cod produces millions of eggs and millions of larvae. And in many cases, it doesn't feed well, and no one has survived. So we made a big scheme for it here, right? But to make a long story short: The feed ate the larva. So it's clear that there have been such cases, where it doesn't go the way, we want . . . But there is always the danger that you have ignored something on some level. One of the things that we feared the most, it was that factory smoke is factory smoke. It's not very clean, so we feared. that we might find out that we were producing toxic food. But it turned out that the smoke was not dangerous, but actually positive. Also, it is dangerous to draw strong conclusions without having practice within natural sciences. Often you will experience that what you thought would happen in an experiment, is very different from the outcome. It can be chemical reactions, it can be synthesis it can be rather extraordinary reactions and you discover that it's not at all the way you intended it. But you*

> *must try and learn from it. But we also were clear that this is not a "plug and play" concept something that you can just assemble and press a button . . . That's not how it happens. They (industry and university) knew that all along and nobody believed much in this at first. We have never said that we guarantee 100% that we will reach the finish line. But with a company that can take some risk and with whom you can talk openly to, we see an opportunity . . . We have said to the manager and to the board it might work and if it does, it is very good. Also, the support of the public is there, and therefore we have been getting money from governmental platforms such as the Green Shift project and such as from Innovation Norway.*

Removing the barriers: opening doors to the "crazy academics"

Delving into the area of research barriers, it was interesting that our informants shared a story about a "classical" or "old school" professor – a stereotypical researcher with "wild ideas," unique knowledge, and projects that meet extreme success or produce interesting side effects. This stereotype was often brought up during the conversations. The professor's involvement in a project at an industrial company was initially met with scepticism. Despite doubts and concerns about the algae's viability, the project exceeded expectations and proved successful. The project's growth was remarkable, and the researcher's broad knowledge, especially in marine biology, played a crucial role in its success.

> *Now if it hadn't been for the researcher this project would never happen. It's a completely crazy project really. It's wild. . . . And its success is against all odds. When we started, no one thought that any living organism would thrive in our polluted smoke. But though we had doubts, we thought, "Just let him come here and we can see how long it takes for the algae to die." And we had sort of said that we were going to be the world's first CO_2 free smelter. So, when he came knocking on the door, we had to give him a chance. It's amazing how biased you become. But it's been fun to get to know each other and he has so many complementary topics of knowledge too. He's such an old-fashioned professor type, with very broad knowledge – and to make it work down here, you have to mix biology with engineering knowledge. And I've never seen so many scientists at once, when you started to see that this was growing something incredibly fast, and it's crazy that it actually worked.*

The university management also uses the word "crazy" in relation to the project but nuances it a bit, since they are familiar with the researcher's history and the results that have been achieved from the academic perspective. Also, there was a feeling that the worst-case scenario was that the research would fail, which was not a very risky depiction since knowledge nevertheless would be generated. When the results of the cooperation exceeded expectations, it was credited as luck. Both the university and the industry cite the role that luck played in the project's success, particularly in finding the exact species of diatoms that best fit Finnfjord's smoke.

The following narrative highlights the surprise and disbelief at the positive outcomes, as each milestone was met and exceeded.

> *It's a funny story and indeed a bit random after all, that it became a match. Our researcher was matched with Finnfjord by our (then) dean, who saw the synergy properties with his research and their waste product. And that's how it started the whole thing there with our researcher, about bringing the algae research there and test on their smoke . . . I would never in a million year think that we would work with Finnfjord. In fact, it sounds completely absurd. It used to be an old ugly factory that emitting a lot of smoke. I must be honest and say I have known our researcher as a "crazy ideas" type. However, my approach was: What wrong can he do? I knew that he had done extensive research on a lab scale – which strengthen the belief in it. However, to see that it has gone from strength to strength? Every milestone was fulfilled all the time? Exceed my expectation and at each milestone we thought it would fall? But it hasn't done it never did. But at the same time, to know which species will be the best fit for the Finnfjord smoke? These things can't be planned . . . That was luck. I always tell him that he is clever, but he also was lucky for finding that exact species of diatoms.*

Finally, the researcher also referred to the view of their project as "crazy." They take issue with the focus on luck and explain how their expertise has taken them deep into a specific area that few others understand. As the barriers of knowledge break down, new ways of looking at the world emerge. They refer to philosophical principles in science such as "Occam's razor," which argues that the simplest way forward is usually the best one. Further, they use words like serendipity and synchronicity to describe how one might break into a new concept. So, while serendipitous discovery can be attributed to luck or chance, we prefer to attribute it to subconscious observations (that one might experience as instinct) and a flexibility in thinking that frees you to explore new directions. Serendipity builds on established knowledge and a willingness to constructively exploit whatever circumstances we may encounter. Synchronicity is defined as the occurrence of meaningful coincidences that seem to have no cause; that is, the coincidences are acausal. The underlying idea is that there is unity in diversity (Jung, 1960).

> *Speaking about this "crazy" project, Hmmm . . . I guess I haven't looked at it as so wild, though. However, there has always been the awareness that if you want to achieve new things then you must dare to walk on some "thin ice". And the ice can break and then you get damn wet. Further, I don't want to use the word luck in that context. It seems like, since there are a million species, so if you're looking long enough, then if you're going to have the very best, then you have to work with a million species and test them out, and then it's going to be over four generations, at least. It can be considered lucky that this particular diatom tolerated factory smoke so very well. I like to refer to*

> *the "Occam's razor" a kind of simplicity's principle that, that if you have hypotheses about a process you are going to explain, then you take a chance and go the easiest way, and then you make it work – instead of doing a thousand tests and examine all eventualities. Yes, and it may seem like luck. Another word that we can supplement it here with, is serendipity. Serendipity is the lucky coincidence, but which I have its prerequisites precisely, in the knowledge that you and your colleagues have had, right? At last, there is synchronicity such as a window fortunately opens for you. It happens coincidentally when you're just there, and that you see something that you needed to see, right? It is the atmosphere we are in, and breathe in. . . . And that is exactly why we have achieved what we have.*

A new horizon

Finally, the respondents say something about what this project means for the future. While there is a view that a potential new industry is born, all respondents have a great focus on the greater good of this project as opposed to the short-term individual effects.

The company foresees the project's economic potential as beneficial to both them and their community. They further reflect upon their responsibility as an agent, and the importance to identify knowledgeable private actors who understand the risk profile of such an innovation project. Further, they reflect upon the different roles within the society to carry innovation projects forward.

> *We are in the process of designing the next phase, then. And that is extremely exciting, and that will give the answer to a lot of what we think about the future. If it's successful, I see great value and we can potentially see a new industry spinning out of what we are doing. This will attract new talent and resources. We believe so much in this project that we're going in with our own money. And we've done that all the way. We've spent a double-digit number of millions of dollars. We believe that we cannot let – the state can't go in and take all the risk, because they do not have the specific knowledge like we do. And they do not know the strengths and weaknesses (and then you can risk spending money on something that is hopeless). There needs to be someone who will take the risk and say that I want to bet on this. Yes, there is a separate discussion. It's more like . . . So we're going to make an algae factory. It's not going to be done by the university, it's very "on the side" of what the university is going to do . . . So, we're going to do that. Also there will be a licensing fee. Maybe there's a separate company that's going to do – what's owned 50/50 by us and the university.*

For a peripheral university, in an extreme geographical area, with challenges to recruit students and employees, the results of the project are promising. The university especially sees the value in the new knowledge that is being created. Further, this project is an important contribution in addressing current climate challenges and helps position the university as a forward-thinking, solution-oriented knowledge hub.

> *If this is a success, UiT can make money from it, however that's not the highest value for us. And I don't think we should pursue that path, but rather find a niche is unique to us – because there is a great competition internationally for students, for external research funds, and (not least) to keep northern Norway alive. And UiT must build that niche. And I think that this is something new we can build up the education on, and they are. Not only about the algae bit, but also a have a wider impact, socially and environmentally through new technology on the use of CO_2. New products, or purification, or binding it into products in particular (which is what we work on), I think, is a key to solving the world's challenges because that's the way it is. We can't stop producing steel or other products either. Steel in particular, is the most important building material we currently have, and to have steel we have to have ferrosilicon. And we can't just say that we should stop making factories. We have to be part of the development. There is no one who wants to go back to the Stone Age. So . . . then we have to find a sustainable way to do it, and then we can't say that we should just remove – it may also be that steel goes out in a few words like oil – but then we have to, you find new construction methods. Then you have to solve it. Maybe it's not sustainable. It goes on, all the natural resources you extract through geology. Whether it's oil or minerals, it ends sometime, and then you have to hunt for new sustainable methods. It's our domain, there are so many things about this here that I find so fascinating. And it's the right way to go, I think. Man! Have to invest much more heavily in it. And that's because we have a unit that has a world-leading climate and research environment that makes you become sort of, you get it right in the lap. That makes me think that this fits in and is right – and find a solution to this that happens with the ice moving north and the temperature that is rising all the time.*

The researcher finds profound meaning in the results as they represent a culmination of their life's work. The success of the product not only adds significance to their research but also imbues their values with purpose. The researcher advocates for a unique breed of scientists, those who fearlessly venture into uncharted territories to tackle novel challenges. They envision the researcher as a heroic figure, raising questions about how to create an environment conducive to nurturing such individuals.

> *There are many ways to conduct research. One way is to sit down in the office and do something mediocre. And then a mediocre publication comes out every two years which raises the salary, but there are no other ambitions. Another method is leaning heavily on others and putting yourself in line behind someone else who leads the way. And that can be a method, but it's not that challenging. But the third method way is figuring out new things.*

> *Right? And the paradox of new things is, after all, that it's not yet described in the publications. It's not in textbooks. It is not lectured at a solemn scientific seminar by a person who has great expertise and reverence. And that's true research that has driven societies forward! Finally, you must have people around you who share the enthusiasm and who think, that here it sounds captivating, wonderful, and the university management thinks that this might be worth trying, even if they thought it was crazy.*

Findings and discussion: the role of the universities as a CO_2 catalyst

The Finnfjord story can be understood as a responsible innovation project where the university cooperated with industry to develop new knowledge that may answer one of the humanities pressing challenges: how to tackle the climate crises through mitigating CO_2. There are many learning points to this story. Three main disclosures of this study have been generated: (1) the organisation of research, (2) the synergies of the university–industry relation, and (3) the governing institutions. The Finnfjord project throws light on several vital aspects of the university's unique context.

The organisation of research

Historically, the creation of UiT Arctic was driven by leadership at national and local political levels, which paved the way for influential figures from diverse scientific disciplines. The development of the university hinged crucially on (1) the ability of local leadership to identify and nurture regional potential, and (2) the drive to create unique expertise rooted in the region's natural resources. The university's strong focus on its geographical and natural context sets it apart from its counterparts, shaping its integral role in this project. There was a desire to contribute to the recognition and respect for the region's cultural heritage (notably the Saami culture and the traditional fisheries), located in the periphery and undergoing strong "Norwegianisation" policies the previous hundred years. There was a strong regional vision for *knowledge-based* development after many years of failed centralisation policies due to a lack of knowledge about this huge region with its significant geographical, economic, and cultural variations (Jensen, 2014: 6–10) However, other factors have also played essential roles, such as basic research, interdisciplinarity, and the importance of a strong researcher role. The ideals of interdisciplinarity and problem orientation were given priority, to the detriment of the classical, disciplinary organisation that was characteristic of other universities (ibid., 11). In fact, in the early years of the UiT, fishery science was organised as a "section" across two main departments at the University: the department of social science (including philosophy) and the department of biology and geology. This transdisciplinary research environment characterised a common, strong research interest in the sustainable management of natural resources, notably the management of the coastal commons and the reindeer pasture commons of the Saami population. Take this local-to-regional focus on cultural practices of research management and add the *praxeological* research of a pioneer of the new university, the philosopher Jakob Meløe, reconstructing and describing (from the point of view of the actor) the often tacit and non-articulated knowledge and knowledge systems inherent in local practices governing the resource commons.[3] The researcher often returns to the fruitful conversations with the philosophers when the organised fishery sciences were still in infancy. Interestingly, history seems to recur when, 40 years later and having a vision of an interdisciplinary research project on biological carbon capture and utilisation (the project case of this book), the researcher again crosses the disciplinary boundaries and, when building a research team, begins by with inviting an environmental philosopher.

The project highlights the crucial importance of basic research, which is often overlooked in university–industry collaborations that typify applied research (Geuna & Muscio, 2009; Perkmann et al., 2013). Basic research breeds new ideas with unforeseen applications, often made freely accessible, and not monetised. Further, basic research is a prerequisite for responsible innovation. It requires transparency, accountability, and truth seeking. Despite its value, it can be challenging to convey its importance to the public, and the past 20 years have seen a decrease in funding for basic research in Norway (Tønnessen et al., 2022). The Finnfjord case underscores that basic research can establish a knowledge base that leads to more tangible, utilisable, and monetisable results.

The importance of an interdisciplinary approach when tackling today's significant global challenges is emphasised in this case (Aboelela et al., 2007; Lowe & Phillipson, 2006). The Finnfjord project demonstrates that the unique context of interdisciplinarity was integral for the researcher in developing ideas and broadening perspectives. It underscored the knowledge spillover that can occur between philosophers, social scientists, and natural scientists within the context of the interdisciplinary carbon capture and utilisation (iCCU) group. Note that this reflects the demands of a science for a post-normal age referred to in the Introduction – a science appropriate to new post-normal conditions based on the assumptions of unpredictability, incomplete control, and a *plurality of legitimate perspectives*.

At the same time, the researcher's crucial role is highlighted within the context of the Finnfjord project, a perspective grounded in the philosophies of Aristotle and Descartes. Both these philosophers underscored the solitary academic, whether an empiricist or a theorist, as the beacon of knowledge (Jong & Betti, 2010; Burk, 2007). This tradition exalts the investigator as a lone entity interacting with the study subject, striving for comprehension and interpretation. However, there has been a shift in contemporary research paradigms, transitioning towards a more collective approach and emphasising the value of teamwork (Sandberg & Ibarra Rojas, 2021).

While the Finnfjord project accentuates the significance of a strong researcher role, it doesn't undermine the supportive ecosystem enveloping the researcher. For instance, the researcher commended the collaborative efforts during the university's foundational year, where various disciplines intertwined. It was a period of building relationships and learning from errors. They speak about a culture for performing transdisciplinary and cutting-edge research. One can argue that a balance was struck between the independent researcher and their surrounding academic community.

In addition, several philosophical concepts play a role in the research process, as highlighted by the researcher. The researchers look to concepts such serendipity, synchronicity, and the Occam's razor. Serendipity is often an overlooked factor in scientific reports, but it is integral to significant discoveries (Merton & Barber, 2011). Researchers must nurture a mindset that is open, flexible, and curious to leverage serendipitous findings (Mitchell et al., 1999; Verhoeven, 2016). Synchronicity, as defined by Carl Jung (1960), signifies meaningful coincidences with no evident cause. These occurrences can alert the researcher's subconscious, leading to leaps in data understanding (Rescher, 2001; Roberts, 1989). Finally, Occam's Razor, a principle of simplicity, emphasises that the simplest answer to a complex question is often the best. This principle helps avoid overfitting empirical data into models (Tornay, 1938). The researcher makes a point that a strong researcher role, academic freedom and flexibility, extensive research experience, and a long-term focus, facilitates these philosophical tools to come into play. However, this approach can be compromised by external pressures, such as economic constraints or ignorance from the public or industry.

University–industry linkages

The Finnfjord case presents a story of cooperation between university and industry, a relational model that has been promoted over time (Muscio & Vallanti, 2014). Many studies of university–industry collaborations for innovative projects have concentrated on patenting, licensing, and formation of start-up companies as the main contributions of universities to technology diffusion. However, as several authors have noted, university–industry links embrace a much broader spectrum of activities than commercialisation of IPR (Agrawal & Henderson, 2002). In the Finnfjord project, we see a clear work divide, where the university focuses on the research and the company focuses on scaling up the commercial value. This project particularly showcases the synergistic qualities of such cooperation – leading us to explore three paradoxical challenges we observe in responsible innovation with industry-academic cooperation: **time focus, value and knowledge,** and **ethics**.

Time focus

Both university stakeholders (Meyer-Krahmer & Schmoch, 1998) and their industry counterparts (Bruneel et al., 2010) have identified that the most prominent hurdle to fruitful collaboration between academia and industry lies in their differing time frames and expectations. Fundamental research is inherently a slow process, necessitating numerous tests, experiments, and time for novel ideas to fully develop. Yet, this period of seeming inactivity should not be construed as resource wastage, as it generates knowledge and experience.

On the other hand, time is a precious commodity in the industrial sector. The academic timeframe is dictated by the demands of lab work, repeated testing, the process of publishing in academic journals, and dissertation completion (Niedergassel et al., 2011). In contrast, the industrial time frame is propelled by the need for speedy market response in a competitive environment (Bjerregaard, 2010). In the Finnfjord project, our stakeholders reflect on this challenge. Here we see that the CEO of Finnfjord is aware of future challenges and is willing to make such necessary investment for long-term success, particularly in terms of accommodating the research to address academic needs over time. This willingness is rooted in his company's embeddedness in the region, being a family firm, and the desire to protect the region for future generations. At the same time, the research has imposed certain setbacks that are real, and the company is also dependent on short-term financial gain.

Further, when focusing on innovation processes the initial phase, dubbed "the fuzzy front-end stage" is characterised by high risk and uncertainty. This stage is crucial to the development process, as it can prevent companies from wasting substantial time and money on developing a product destined to fail (Kutvonen & Torkkeli, 2009). As managers frequently identify the front end as a weak link in product innovation (Khurana & Rosenthal, 1997), universities can leverage these fuzzy front ends to generate diverse forms of new knowledge. Finnfjord's CEO particularly underscored that industries seek ready-made solutions and "quick fixes" and that risk is incurred when researchers are invited to work on a long-term project.

Value and knowledge

The strategies for value creation distinctly vary between academia and industry. Academia places emphasis on the generation of new knowledge and considers the process itself as valuable. In contrast, the industry sector is primarily concerned with transforming this knowledge into a tangible product that can bring economic gains. Specifically, universities have a unique responsibility in managing environmental and social commons, and should serve humanity at large (Waas et al., 2010; UNESCO, 1999, 2020), thus focusing on producing new knowledge vital for value creation in these areas. The importance of research, including that conducted within universities, as a conduit for new knowledge essential for sustainable development, is widely recognised.

At the same time, our data show that while industry and academia may differ in terms of the ends they seek – collaboration does support other shared values, sometimes in unique ways. Both perspectives acknowledge the value of university–industry linkages in driving innovation and addressing complex challenges. They recognise that overcoming barriers to collaboration is essential to unlock the potential benefits of joint research and innovation efforts. Both perspectives implicitly recognise the value of knowledge transfer and expertise exchange between academia and industry to foster innovation and sustainable development. The differences in perspectives may reflect differing values placed on immediate returns on investment versus the long-term benefits of collaboration and innovation. The emphasis on time and patience aligns with the value of long-term investment in research and development, which may be characteristic of academic institutions. On the other hand, the factory owners' perspective may reflect the value placed on efficiency and cost-effectiveness, which are often critical factors for industries when making investment decisions (Pisano, 2019)."

Ethics

The basic ethics of academia and industry also differs. In industry, there is a focus on respect for property rights and ownership. This differs from sciences which follow the Mertonian principles of CUDOS, the first being *communism:* a common ownership of scientific goods (intellectual property), to promote collective collaboration. The second principle of CUDOS is *universalism:* where scientific validity is independent from the context it is set in, and it should reflect some generalisable characteristics. In the Finnfjord case, the value they create is specifically local and their aim is to contribute to the local community. However, their market and the knowledge they produce would have universal application and benefit. Further, industry does not discriminate on socio-political of geographical status if it brings economic value. As such, also the industry may claim universalism, but not perhaps to such an extent as academia. The third point in the academic ethic code is *disinterestedness*, meaning that scientific institutions act for the benefit of a common scientific enterprise, rather than for the personal gain of individuals within them. This is significantly different than business ethics, where the gain should be for organisational unit and its investors. Finally, academia touts the concept of *organised scepticism*, where scientific claims should be exposed to critical scrutiny before being accepted: both in methodology and institutional codes of conduct. Therefore, multiple studies and tests must be performed before any strong claims are made. The industry has a more pragmatic approach and will conform to market pressures.

Institutions

This research also offers insights into the institutional drivers behind this project. All three dimensions of institutions proposed by Scott are evident, shaping the perspectives and actions of the industry, the university, and the researcher. For the industry (Finnfjord), the regulative dimension plays a significant role, as the company is driven by the need to survive as a business and navigate within the regulatory frameworks of the energy and environmental sectors. Economic drivers, such as carbon quotas and taxes, influence their decisions to explore environmentally friendly solutions like CO_2 capture. Additionally, the normative dimension comes into play as they take on a leadership role inspired by a visionary perspective to address CO_2 capture and potentially create a new industry. The company also reflects on its responsibility as a knowledgeable private actor in interpreting the risk profile of such an innovative project.

For the university's involvement in the project, the regulative dimension comes into play as they seek to develop unique competence in global topics like CO_2 capture and contribute to the climate debate. However, it is the normative dimension that is the strongest as the university focuses on the greater good of the project and sees the value in the new knowledge being created, positioning themselves as a forward-thinking, solution-oriented knowledge hub. The cultural-cognitive dimension is evident as they view the success of the project as contributing to the greater social and environmental challenges of the world and seek sustainable ways to address them through interdisciplinary collaboration.

For the researcher, the regulative aspect is observed as the researcher adheres to research protocols and ethical guidelines in their work with algae growth and CO_2 capture. Normatively, the researcher places a strong emphasis on conducting pioneering research, believing that true innovation involves breaking new ground and taking on challenges that may not be immediately understood by others. The cultural-cognitive dimension is, however, the most pronounced, as the researcher sees their work as a heroic endeavour, pushing the boundaries of knowledge and contributing to societal progress.

In summary, the Finnfjord case illustrates how institutions' regulative, normative, and cultural-cognitive dimensions influence the perspectives and actions of the industry, university, and researcher involved. Each dimension plays a distinct role in shaping their motivations, decision-making, and approach towards responsible innovation in the context of CO_2 capture and utilisation. The dynamic interplay between the university and the firm is summarised in Table 5.1.

Table 5.1 Comparison of the university, researcher, and firm voices.

	University	*Researcher*	*Firm*
Time focus	*Long term*	*Long term*	*Short time*
Value	Contribution to research and society	Contribution to knowledge	Value spreading + developing
Research focus	Focus on basic research	Focus on basic research	Focus on applied research
Ethics	CUDOS/normative foundation of science	CUDOS/normative foundation of science	Business ethics, normative positive and practical, Maxim Storchevoy
RI incentives	High	High	Low
The role research	Focus on basic research to develop unique knowledge	Focus on long-term basic research with potential solve "real-world" problems	Focus on applied research and transforming knowledge into tangible products for economic gains
Organisation of research	Administrative oversight, coordination, collaboration	Faculty cultures and friendship, interdisciplinarity, strong researcher role	Cooperation, openness, differentiation between research and day-to-day business
Institutional drivers	Normative	Cognitive	Regulative

Conclusion

This chapter explores the Finnfjord algae project and the distinct roles that the university, the researcher, and the firm, can play when collaborating on responsible innovation to address grand challenges, such as climate change through CO_2 mitigation. While recognising the limitations of a single case project, we find several theoretical and practical implications of our research:

One key implication is the recognition of the value of basic research in generating ideas with unforeseen applications. The project challenges the prevailing focus on applied research in university–industry collaborations and advocates for a more balanced approach to foster innovation. Moreover, the Finnfjord project underscores the importance of interdisciplinary collaboration in addressing global challenges such as climate change. By promoting knowledge spillover between different disciplines, it facilitates the development of innovative and holistic solutions. Furthermore, the case accentuates the active role played, not only by the lone researcher but also by the supportive team and surroundings in driving innovation. It underscores the importance of a collective approach to research, promoting collaboration and teamwork – while it acknowledges the influential role of the individual researcher as a driving force. Interestingly, the introduction of philosophical concepts like serendipity, synchronicity, and Occam's Razor into the research process highlights the need for ample flexibility, experience, and fellowship – in addition to an open and curious mindset among participants in research activities. This approach can lead to valuable discoveries and push the boundaries of knowledge. (In this particular case, the result has potential to impact the recapture of CO_2 worldwide, which is considered one of the most premier global problems of the current era.) Further, the project describes the differing perspectives of academia and industry in their values in time focus, value and knowledge, and ethics. Understanding and navigating these differences are crucial to facilitate effective collaboration and find common ground for joint projects. Lastly, the Finnfjord project provides insights into how different institutional factors influence the actions of industry, university management, and researchers. Policymakers can use these insights to create an environment that more readily enables collaborations between universities and industries in responsible innovation projects.

In practical terms, this case strongly advocates collaborations between academia and industry in the pursuit of responsible innovation. Here, the challenge is to divide the tasks so that each of the units can maximise their resources, rather than pressuring one other inappropriately as might arise from differing perspectives. As such, it is a warning sign to politicians and bureaucrats to not attempt to manage research too rigidly, including cooperations between academia and industry – but rather to facilitate it and afford incentives. Finally, this case shows that focusing on responsible innovation exceeds the pursuit of simple (and perhaps short-sighted) economic value; it is a means to alleviate the pressure on the commons and contribute to the betterment of society as a whole.

Notes

1 Lund University's Biodiversity and Ecosystem services in a Changing Climate (BECC) describe three Grand Challenges facing the global community: "issues where gaps in scientific understanding constrain the ability to make informed decisions on issues of pressing concern for the well-being of people and the environment, in a world affected by continued global change." First, effective and biologically meaningful biodiversity conservation strategies across scales under global change; second, the carbon cycle response to anthropogenic and biophysical drivers; and third, ecosystem services under global change.
2 A Norwegian oil company.
3 Meløe (1997).

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6 IoT expectations and challenges in monitoring the bioreactors

Roopam Bamal, Daniel Bamal, and Singara Singh Kasana

Introduction

The biological carbon capture and utilisation (bio-CCU) project aims to incorporate responsible and sustainable innovation by utilising CO_2 capture and promoting the use of algae-based products. To achieve this, the project employs several large reactors for algae production and smaller reactors for conducting experiments on different algae types and control parameters. In line with environmental ethics and the principles of a circular economy, the project explores the potential of Internet of Things (IoT) technologies as a cost-effective and scalable alternative to traditional supervisory control and data acquisition (SCADA) systems. By leveraging IoT, the project can utilise affordable off-the-shelf sensors, computers, and communication, thereby reducing costs and enabling redundancy through the deployment of multiple sensors.

This chapter provides an insightful overview of the application of IoT technologies in similar environments, such as during pandemics like COVID-19 and in the context of fish farms. The chapter highlights the advantage of using multiple bioreactors, not only to achieve the necessary scale for production but also to conduct independent research experiments and optimise output. Furthermore, the utilisation of multiple bioreactors enhances robustness, ensuring that issues in one bioreactor do not impact others. The challenges associated with implementing IoT in the bio-CCU use case are also thoroughly examined.

In order to align with the vision of a sustainable future and CO_2 capture in bioreactors, a distributed architecture is proposed. This architecture emphasises the use of edge computing, enabling data processing to occur in close proximity to the sensors. This approach enhances robustness by allowing each bioreactor to independently observe, analyse, and control its local environment. A demonstration prototype is described in detail, along with its impressive results.

It is worth noting that this project strongly supports the achievement of the United Nations' Sustainable Development Goals and promotes collaboration both between and within universities, fostering university cooperation for impactful research and development in the field of sustainable and responsible CO_2 capture and utilisation.

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IoT

The phrase “Internet of Things (IoT)” refers to the network that connects and enables data exchange among physical objects, devices, and systems over the Internet (Ashton et al., 2009) Over the past decade, our society, economy, and survival have become increasingly reliant on technology rather than solely on information and ideas. The ability of computers to autonomously gather data and acquire knowledge about the physical world’s “things” has the potential to reduce costs, time, waste, and losses. Our environment now seamlessly integrates information and communication systems, as emerging technologies such as radio frequency identification (RFID) and sensor networks rise to meet this new challenge (Gubbi et al., 2013).

To establish effective IoT systems, there is a need for shared knowledge among users, appliances, software architectures, and pervasive communication networks. Additionally, analytics tools are essential to enable autonomous and intelligent behaviour within the IoT ecosystem.

The IoT architecture consists of six layers: coding, perception, network, middleware, application, and business. These layers encompass various functionalities, including addressing security risks such as eavesdropping at the network and perception layers. Key aspects of IoT communication (Borgia, 2014) include abstraction of underlying networks, support for different communication modes, handling massive simultaneous device transmissions, high connection reliability, enhanced access priority management, optimised path selection, dynamic metric selection, communication management, energy consumption, traffic profile management, time-dependent traffic management, location detection, and security.

Connectivity stands out as the most critical feature, as seamless communication among interconnected components is indispensable for the execution of IoT-based systems. The interconnectivity of IoT devices facilitates seamless communication, data sharing, and collaboration, promoting efficient and automated operations across sensors, applications, industry, and university settings. Another crucial aspect of an efficient IoT system is ensuring energy efficiency and conservation, aligning with the broader goals of sustainability and minimising environmental impact. An ideal IoT system should be capable of understanding and analysing past experiences, akin to human sensing, to derive meaningful insights. Machine-learning and deep-learning models are commonly applied to vast amounts of data in various IoT use cases to gather valuable insights. IoT users benefit from the integration of cross-domain models, striking an ideal balance between cost efficiency and infrastructure (Gubbi et al., 2013). Cloud computing and blockchain technologies are often utilised to foster active engagements among IoT components. One advantage of IoT devices and applications is their scalability, enabling them to adapt based on specific requirements. For example, a temperature sensor may adjust its input based on location, weather conditions, and other factors. Yet another crucial requirement for an IoT system is security – as misuse, manipulation, or compromise of any component can potentially disrupt the entire pipeline.

IoT with UWSN

The Earth's surface consists of approximately 71% water and 29% landmass in the form of islands or continents (Nayyar et al., 2018). Advancements in technology have long facilitated the exploration of the oceans and aquatic life. Within this context, research in wireless transmissions and ocean observation systems has led to the emergence of technologies like the underwater sensor network (UWSN) and the IoT-enabled UWSN, known as IoUT (Nayyar et al., 2018). A novel working prototype, named Smart IoUT 1.0, has been proposed for underwater sensing and data collection. Smart IoUT 1.0 comprises two sensing nodes equipped with four sensors: dissolved oxygen, temperature, pH analogue, and water turbidity sensors. This innovative system acquires real-time data and provides access to the collected information from anywhere in the world through the Internet, utilising Thingspeak.com (Nayyar et al., 2018).

IoUT inherits challenges from both IoT and UWSN domains. However, it also opens up numerous possibilities for monitoring and managing data from ocean observation systems, ushering in new opportunities for research and exploration.

IoUT

Figure 6.1 depicts the basic setup for integrating UWSN and IoT. Multiple UWSN setups, ranging from UWSN-1 to UWSN-N, are connected to the IoT cloud through a standard gateway. The IoT cloud, in turn, establishes connectivity with servers accessible by Internet users. Achieving integration between UWSN and IoT begins with ensuring connectivity, which can be approached in three ways.

The first approach is the front-end proxy method (Kundaliya, 2020), which involves the Internet user, base station, and sensor nodes. The base station serves as an intermediary to collect and process data, and facilitate bidirectional communication between specific sensor nodes and users.

The second approach is the gateway method (Kundaliya, 2020), where the base station functions as an application layer gateway. In this approach, the data above

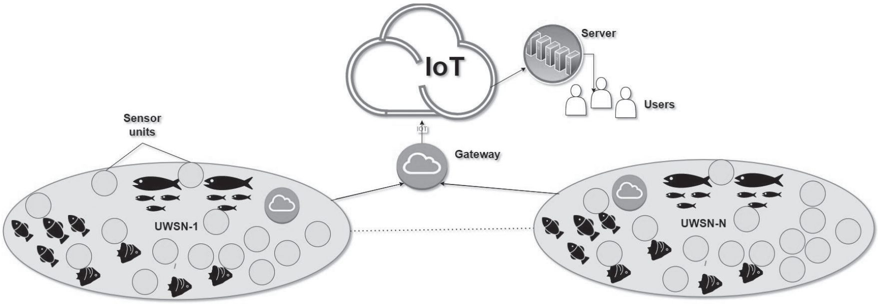

Figure 6.1 Basic structure representation of IoUT.

Source: Kundaliya (2020).

the transmission control protocol/Internet protocol (TCP/IP) layer becomes a common element between the sensor nodes and Internet users, eliminating individuality or node specification in the transmitted data.

The third approach is the TCP-IP overlay method (Kundaliya, 2020), which enables direct communication between specific sensor nodes and Internet users using the TCP-IP protocol. In this case, the sensor nodes must have implemented the required protocols and algorithms used by the setup. Beyond the media access control (MAC) layer, there is no distinction between UWSN and IoT data.

These approaches enable seamless connectivity which facilitates efficient communication among sensor nodes, gateways, Internet sources, internet users, and base station units.

Components of IoUT

A basic IoT system consists of several components, including sensor nodes, actor nodes, relay nodes, cluster heads, gateway, IoT cloud, servers, and a base station.

1. *Sensor nodes* can be either floating (mobile) or fixed, depending on the specific setup requirements. They process data to some extent, collect data, and communicate with other associated nodes in the network. An example of such a sensor node is the HydroNode (Pinto et al., 2012), which possesses essential capabilities such as energy efficiency, versatility, compatibility with different analogue and digital sensors, long underwater communication range, an open design platform, and affordability.
2. *Actor nodes* are high-end devices used to store data, perform complex operations, and make decisions based on the requirements of the UWSN setup. Typically fixed on the shore, they have access to necessary resources such as high-speed Internet for transmission, uninterrupted power supply, and high-quality processing capabilities.
3. *Relay nodes* in the setup are not mandatory, but can enhance the reliability of the network. They act as intermediary nodes to communicate with neighbouring nodes and periodically collect data. Autonomous underwater vehicles (AUVs) can serve as relay nodes in certain cases.
4. *Cluster heads* are usually sensor nodes with high-bandwidth capabilities which can perform tasks like data aggregation and data fusion within the UWSN. The number of nodes acting as cluster heads depends on the system requirements.
5. A *Gateway* serves as an interface between the sensor field (consisting of a cluster of sensor nodes) and external networks. In an IoUT, each UWSN or cluster has its own gateway, which connects to an external gateway for transmitting data to the IoT cloud (as shown in Figure 6.1). An IoT gateway is a crucial component that can handle different communication protocols and data formats, ensuring seamless connectivity and data parsing.
6. The *IoT cloud* is composed of platforms such as Amazon Web Services (AWS), Microsoft Azure, Google Cloud Platform (GCP), and similar platforms that collect, process, and analyse data.

7 The *Base station* is a specialised node with higher configuration compared to other sensor nodes, offering enhanced processing capability and computational energy.

By incorporating these components into the IoT system, efficient data collection, processing, and analysis can be achieved, leading to improved functionality and decision-making.

Impact of Russo-Ukrainian war on cyber technology

In today's interconnected world, the Internet has brought nations closer, but major events like the Russo-Ukraine War can have a significant impact on cybersecurity. Ukraine has faced approximately 800 cyber-attacks (Juutilainen, 2022), highlighting the need for data leakage prevention in the transportation layer and application security in the IoT sensing layer (Phommasan et al., 2019). However, IoT applications relying on the cloud introduce vulnerabilities – public cloud being vulnerable to reliability and security issues, while private cloud faces high costs and resource requirements, and hybrid cloud environments face challenges with data integration and visibility (Tabrizchi & Rafsanjani, 2020).

Ensuring cloud security requires the collaboration of both internal and external service providers. Dependence solely on data servers located in a specific country, such as Mexico, could pose a significant risk in case of geopolitical conflicts like the Russo-Ukrainian war. To avoid a single point of failure scenario, it is crucial to explore alternatives such as open-source data, avoiding vendor lock in, and running everything on site. This approach eliminates dependency on servers from companies like Microsoft, Google, or Apple, which may lack adequate encryption for data confidentiality.

Various solutions can enhance privacy and protection in IoT systems, including routing protocol methods and anonymisation processing for location privacy and data privacy (Phommasan et al., 2019). Implementing mechanisms like secure socket layer and data encryption, coupled with statistical anomaly-based and signature-based intrusion detection systems, can strengthen overall security (Tabrizchi & Rafsanjani, 2020). These solutions should be considered as beneficial inputs when scaling up the bio-CCU project at the Finnfjord smelter plant in the future.

IoT with fish farming

An IoT-based automation system proves valuable in the continuous monitoring, tracking, and control of critical parameters within a fish farm. Parameters such as water level, pH, temperature, and dissolved oxygen play a significant role in decision-making and long-term analysis. By collecting data from such systems, resource utilisation can be optimised, water quality can be effectively treated, and profits can be maximised through methods like forecasting. This automation system contributes to the seamless selling of freshwater fish, maintenance of water quality, and automated tracking of fish breeding.

In the context of fishpond management, Gao et al. (2019) propose water quality indicator forecasting methods as part of an intelligent management module. The module utilises the local outlier factor (LOF) algorithm to identify and eliminate abnormal data, while the model tree algorithm is employed for data analysis, modelling, and prediction. The authors present this system as an IoT-based intelligent solution capable of accurately forecasting key data for water quality maintenance.

Another study (Hapsari et al., 2020) presents a practical working system that incorporates a sensor and monitoring module for fish farm management. IoT technology is employed to monitor salinity levels and control/monitor pH values through sensors. The collected data is continuously stored and updated on a host website, facilitating remote access and monitoring.

IoT for bio-CCU project

To fulfil its requirements and expectations, the project opts for IoUT (Internet of Underwater Things). As illustrated in Figure 6.2, the project utilises CO_2 captured from factory smoke as an input for the tanks. The bio-CCU project incorporates a range of large tanks with varying sizes, starting from 14,000 L (~3698.41 gal) and scaling up to 5 million litres (~1,320,860 gal), to facilitate the process. These tanks are equipped with numerous sensors to monitor and regulate the tank conditions effectively. The outcome of this process is biomass, which serves as the final product and can be sold as fish food.

Currently, the monitoring of several reactors in the bio-CCU project is done using SCADA technologies. However, SCADA has certain drawbacks, especially

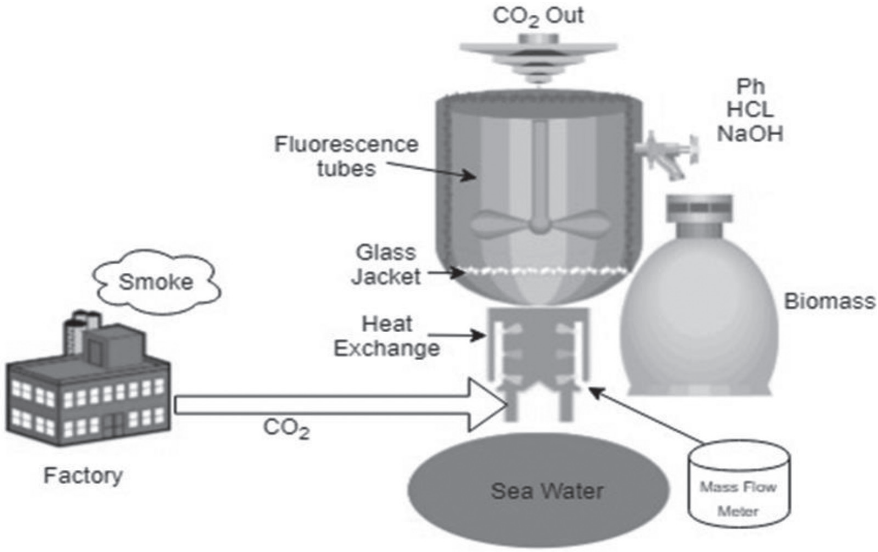

Figure 6.2 Conclusive pictorial representation of the project.

when the project scales up. The increased remote accessibility and interconnectivity make the network more vulnerable to potential attacks. This vulnerability extends to the protocol level, network configuration level, and embedded system level (Upadhyay & Sampalli, 2020). To address these challenges, Internet of Underwater Things (IoUT) emerges as an optimal solution for the bio-CCU use case. It offers a centralised and scalable monitoring system, reducing the need for extensive wiring. Through a centralised monitoring system, access to the IoUT setup is facilitated, ensuring scalability as the project expands. Figure 6.2 provides a visual representation of the bio-CCU use case, showcasing large bioreactors filled with biomass and seawater, along with multiple sensor units. The implementation of an IoUT system becomes crucial for effectively regulating and controlling the conditions within the bioreactors.

Challenges of UWSN, UWSN with IoT, and the bio-CCU project

Underwater environment

The underwater environment poses significant challenges for deploying sensor units in the ocean/sea. It is characterised by extreme unpredictability, including unpredictable underwater activities, varying depths, and continuously changing water pressure. These factors make it challenging to design and maintain sensor units and systems in such environments.

In the case of the bio-CCU bioreactors, the conditions differ from those found in the open sea. Bioreactor turbines rotate the biomass continuously, creating a specific range of pressure. This unique aspect of the bio-CCU use case gives it an advantage over IoUT implementations in the open sea.

Communication

Communication is a significant challenge in the context of IoUT and underwater sensor nodes. These nodes constantly move in the seawater, resulting in different network topologies each time. While some Internet devices may be fixed, establishing communication between sensor nodes within an UWSN presents its own difficulties. Wireless nodes with limited battery life make it even more challenging.

IoUT systems need to be capable of handling dynamic network topologies. In the event of a dead node or resource failure, it is crucial for the gateway node or base station to be immediately alerted. Sensor nodes in IoUT have dual communication capabilities (Bölöni et al., 2013). The primary mode involves using an acoustic modem to transmit data to a resource located on shore for storage. The secondary mode utilises an AUV for data collection. The AUV moves in the seawater within the desired sensor field and downloads data from the sensor nodes it encounters using high-speed and short-distance optical communication.

While fixed nodes may have abundant bandwidth accessibility, the connection reliability is inversely proportional to the number of sensors and the coverage area. On the other hand, high bandwidth is directly proportional to latency. Floating sensor nodes in the bioreactors face similar challenges as those in the open sea. Managing latency is important to prevent inaccuracies in large data transfers. Additionally, the limited spectral resources of IoT pose a significant disadvantage.

Limited resources

Limited resources pose a significant challenge in IoUT systems. The network topology constantly changes as nodes become active or enter sleep mode to conserve energy. This dynamic behaviour necessitates the activation or deactivation of different resources at different times. The mobility of nodes within the sensor field further adds complexity to resource management. Cooperation among the base station, gateway node, and sink nodes becomes crucial due to the heterogeneity of the sensor nodes. These nodes have varying capabilities and resource requirements, requiring coordination for efficient operation.

In the context of the bio-CCU bioreactors, the presence of constantly rotating biomass turbines introduces another dimension of limited resources. The floating nodes are affected by the rotational motion, which can impact their functionality and resource availability. Managing and optimising the utilisation of limited resources is vital for the successful operation of IoUT systems. Efficient resource allocation and coordination strategies are necessary to ensure optimal performance and reliability.

Protocols

The choice of communication protocols in IoUT systems is crucial and depends on the specific requirements and challenges of underwater environments. Acoustic signals are commonly used for long-distance communication underwater, while radio signals are suitable for short-distance communication (Akyildiz et al., 2005). Radio signals, when used for long stretches, especially at lower frequencies, can consume high transmission power and require large antennas, which can adversely affect the network lifetime of UWSN. Additionally, radio signals may introduce significant propagation delay. However, radio frequency communication offers advantages such as tactile nature, portability, ease of deployment, and cost-effectiveness. Conventional protocols may not be well suited for UWSN due to the unique characteristics of underwater environments. Therefore, there is a need for novel protocols that can fulfil the specific requirements of IoUT use cases. Acoustic signals, although they have lower bandwidth, are often used for transmitting low-fidelity information in underwater scenarios (Lloret et al., 2011). However, transmitting sensor data, especially in cases involving the detection of pollution underwater due to fish farming or other activities, can be time-consuming.

Floating nodes in the bioreactors of the bio-CCU project will likely encounter similar challenges with communication protocols. Ensuring efficient and reliable data transmission in such environments requires careful consideration of the available protocols and their limitations.

Energy efficiency

Energy efficiency is a critical aspect of wireless networks. Efficient utilisation of energy is crucial to extend the network's lifespan and ensure sustainable operation. Several energy-efficient routing protocols have been developed specifically for wireless networks, including those used in IoUT (Machado et al., 2013). However, due to the unique challenges and requirements of underwater environments, there is no reliable and effective generic protocol that can be universally applied to IoUT. To improve energy efficiency in IoUT, researchers have proposed various mechanisms. One such mechanism is the implementation of sleep mode in sensor units (Xia & Li, 2013). By strategically putting sensor units into sleep mode when not actively required, energy consumption can be minimised. Additionally, integrating renewable energy devices (Li et al., 2014) and employing load-balancing strategies can further optimise energy usage in IoUT systems. While wireless charging approaches have been explored for large-scale heterogeneous IoT networks (Le Cadre & Bedo, 2016), they may present challenges when applied to IoUT due to the nature of underwater environments.

The energy requirements for fixed nodes are not limited, as they can rely on continuous power sources. However, floating nodes, similar to those deployed in the open sea, face energy limitations and require careful management. As the scalability of the IoUT system increases, the energy requirements also tend to rise proportionally. Efforts to improve energy efficiency in IoUT systems are ongoing, and researchers are exploring innovative solutions tailored to the unique characteristics and challenges of underwater environments.

Quality of Service

Quality of Service (QoS) is an important aspect of IoUT systems. QoS refers to the level of performance and reliability that the system can deliver to meet specific requirements and expectations. In the context of IoUT, achieving the desired QoS involves ensuring that the system operates efficiently, reliably, and with minimal delay. It encompasses various factors such as network availability, data accuracy, latency, throughput, and reliability. To maintain QoS in IoUT, several considerations should be taken into account. These include the following:

- *Efficient resource allocation*: By effectively utilising resources such as bandwidth, energy, and processing capacity, the system can maintain a high QoS while minimising resource wastage.
- *Network reliability:* Reliable communication links and protocols are essential to ensure data delivery with minimal loss or disruption. This is particularly important in underwater environments where signal attenuation and interference can occur.
- *Data accuracy and integrity:* Ensuring the accuracy and integrity of the collected data is crucial for decision-making and analysis. This involves employing data validation and error correction techniques to minimise errors and maintain data quality.

- *Security and privacy:* Protecting the confidentiality, integrity, and availability of data is vital in IoUT systems. Implementing robust security measures, encryption, and access control mechanisms help maintain QoS by mitigating the risk of unauthorised access or data breaches.

By addressing these aspects, IoUT systems, including the bio-CCU project, can strive to deliver the desired QoS levels, ensuring reliable and efficient operation to meet the project's objectives.

Availability

Availability is a critical aspect of IoUT systems, including various use cases such as the bio-CCU project. It refers to the availability of both data and sensor nodes within the network. In terms of data availability, it is important to ensure that sensor nodes are capable of collecting and transmitting data reliably. However, in IoUT, where sensor nodes can be mobile or have limited energy resources, ensuring continuous data availability can be challenging. Mobile sensor nodes often have sleep states to conserve energy, which means they may not be continuously available for data collection. This can impact the overall availability of data within the network.

To address this issue, mechanisms can be implemented to manage the availability of sensor nodes and optimise data collection. This may involve techniques such as scheduling data collection based on the availability of mobile nodes, optimising energy consumption to extend node uptime, or implementing redundancy in the network to ensure alternative paths for data transmission.

Additionally, the availability of nodes themselves is crucial for maintaining network connectivity and ensuring seamless data communication. In IoUT systems, sink nodes or master nodes typically travel through the sensor field to collect data. Therefore, the availability of other nodes for data collection becomes necessary to establish reliable communication links.

Overall, managing the availability of both data and nodes is a key consideration in IoUT systems. By implementing efficient scheduling, energy optimisation, and redundancy strategies, the availability of data and the accessibility of nodes can be improved, enhancing the overall performance and reliability of the system.

Vulnerability

Vulnerability is a significant concern in IoUT systems, regardless of the specific use case. Nodes can be susceptible to various vulnerabilities, leading to node failure or becoming dead nodes within the network. In both fixed and mobile sensor nodes, vulnerabilities can arise due to factors such as hardware failures, connectivity issues, or being in a permanent sleeping mode to conserve energy. In the case of mobile sensor nodes in UWSN, nodes can also be lost in the sea, further contributing to the vulnerability of the network.

The failure or loss of sensor nodes can have adverse effects on the overall functionality and performance of the IoUT system. It can lead to gaps in data collection, disrupted communication, or compromised network coverage. To mitigate vulnerability and address node failures, several strategies can be employed. This includes implementing redundancy and fault–tolerant mechanisms, where multiple nodes can serve as backups or alternative communication paths. Regular maintenance and monitoring of sensor nodes can also help identify and address potential issues before they escalate into complete node failures.

Furthermore, incorporating robust security measures is crucial to protect against potential attacks or unauthorised access that can compromise the integrity and availability of the sensor nodes and the overall IoUT system. By proactively identifying vulnerabilities, implementing appropriate measures, and ensuring proper maintenance, the impact of node failures and vulnerabilities can be minimised, enhancing the reliability and resilience of the IoUT system.

Scalability and independence

Scalability and independence are crucial considerations in IoUT systems. The system should be capable of accommodating a large number of sensor nodes in a UWSN, providing affordable scalability without the need for a centralised control system. By allowing scalability, the IoUT system can expand and adapt to the requirements of the environment or specific use cases. It should be able to handle the addition or removal of sensor nodes without compromising the overall functionality and performance. This flexibility is particularly important in underwater environments, where the area to be covered can be extensive.

Independence is also a key aspect, ensuring that each sensor node in the network operates autonomously and can function without relying on a centralised control system. This approach helps avoid a single point of failure and enhances the robustness and resilience of the system. If one sensor node fails or loses connectivity, it should not affect the operation of the entire network. Traditional technologies may not be suitable for achieving scalability and independence in underwater environments due to factors such as high-cost underwater devices and limitations of underwater sensor network technologies. Therefore, the bio-CCU project, as a specific use case, would also need to consider these challenges and find suitable solutions to ensure scalability while maintaining independence among the sensor nodes. Overall, scalability and independence are essential factors for the success and effectiveness of IoUT systems, allowing them to adapt to changing requirements, cover larger areas, and operate reliably in challenging underwater environments.

Fault tolerance

Fault tolerance is a critical aspect of IoUT systems, ensuring the continued operation and functionality of the setup even in the presence of node or resource failures. System failures can occur due to various reasons, including hardware damage, environmental hazards, energy loss, or other unforeseen circumstances.

To address fault tolerance in IoUT, robust protocols and mechanisms should be employed. These protocols should be capable of detecting errors or failures in the system and taking appropriate actions to mitigate their impact. For example, mechanisms such as error detection codes, redundancy, and error correction techniques can be implemented to ensure data integrity and reliability. In the context of fault tolerance, it is important to define the required limits and performance expectations for the system. These limits may vary depending on the specific use cases and the criticality of the application. For instance, in safety-critical applications, stricter fault tolerance measures may be necessary compared to non-critical applications.

The bio-CCU project, as a specific use case, would need to consider fault tolerance requirements to ensure the continuous and reliable operation of the system. By incorporating fault detection and correction mechanisms into the design and implementation of the IoUT infrastructure, the project can enhance its resilience and ability to withstand node or resource failures. Overall, fault tolerance is an important consideration in IoUT systems, aiming to maintain system functionality and performance in the presence of failures. By employing robust protocols and mechanisms, the setup can detect and correct errors within the defined limits, ensuring the reliability and integrity of the system.

Data freshness

In IoUT systems, ensuring data freshness and synchronisation among nodes is crucial, particularly in extreme underwater sea conditions. The actor nodes, relay nodes, and gateways play a key role in collecting and processing sensor data, and it is essential for them to have access to the most up-to-date information for all use cases. Achieving data freshness requires establishing efficient communication and synchronisation mechanisms within the network. This involves timely and accurate data transmission, as well as synchronisation protocols that enable nodes to align their local clocks and maintain a consistent view of time.

In the context of underwater environments, where communication conditions can be challenging, ensuring data freshness becomes even more critical. The reliability and efficiency of data transmission must be optimised to overcome limitations such as limited bandwidth, high latency, and intermittent connectivity. Various techniques can be employed to address data freshness in IoUT systems. These may include data aggregation and fusion techniques, adaptive sampling strategies, efficient data routing protocols, and synchronisation algorithms tailored to the specific characteristics of underwater environments.

For the bio-CCU project, data freshness would be of paramount importance, given the need for accurate and timely information about the bioreactors' conditions. The actor nodes, relay nodes, and gateways involved in the project would require synchronised access to the latest sensor data to make informed decisions and ensure effective monitoring and control. By implementing robust synchronisation mechanisms and optimising data transmission strategies, IoUT systems can enhance data freshness and enable reliable and up-to-date information exchange among nodes. This contributes to the overall effectiveness and performance of the system, supporting real-time monitoring, decision-making, and control in various underwater use cases.

Privacy and security

Privacy and security are significant concerns in UWSN and the broader context of IoT. UWSN nodes are inherently vulnerable to various attacks, and IoT systems are exposed to external threats (Butun, 2019). Addressing privacy and security challenges is crucial to ensure the integrity, confidentiality, and availability of data in IoUT systems.

There are several types of attacks that can compromise the privacy and security of IoUT systems. These include software attacks, physical attacks, encryption attacks, and network attacks. Malicious nodes can be created to gain unauthorised access to sensitive data or modify it. Attackers can exploit vulnerabilities in the software system, insert malicious code, or perform node capture attacks to compromise the integrity of the network. Man-in-the-middle attacks, i.e., an unauthorised interception of communication between two parties by an attacker who can eavesdrop or alter the data exchanged can be launched to intercept and modify data by forging sensor data or routing information. Sinkhole attacks involve a malicious node attracting network traffic and consuming significant energy. Backdoor insertion and side-channel attacks can also be used to gain unauthorised access to the system or extract sensitive information (Smith et al., 2006).

To mitigate these risks, robust security measures should be implemented in IoUT systems. Data authentication, identification, authorisation, and integration are essential components of a secure IoUT framework. These measures help prevent various attacks such as reply attacks, false message injection attacks, password discovery attacks, asynchronous attacks, and credential theft attacks. Encryption techniques can be applied to ensure the confidentiality of data during transmission and storage. Secure communication protocols, access control mechanisms, and intrusion detection systems can help detect and prevent unauthorised access and intrusion attempts.

In the context of the bio-CCU project, privacy and security measures are critical to protect the integrity of the data collected from the bioreactors and ensure the reliability of the system. By implementing strong authentication mechanisms, encryption protocols, and intrusion detection systems, the bio-CCU project can enhance the privacy and security of its IoUT infrastructure. It’s important to continuously monitor and update security measures as new threats and vulnerabilities emerge. Regular security audits, vulnerability assessments, and adherence to best practices in privacy and security can help maintain a robust and secure IoUT system.

Cost

Cost is indeed a significant consideration when deploying and maintaining an IoUT system. The unique challenges of underwater environments and the need for specialised hardware and sensor units contribute to the overall cost. Several factors contribute to the cost of IoUT systems. First, the hardware components, including the sensor nodes, communication modules, and underwater devices, can be expensive. The development and manufacturing of reliable and durable sensor nodes that can withstand the harsh underwater conditions and have sufficient battery life can drive up the cost. Additionally, the need for regular replacement of sensor units due to factors like salt accumulation, algae collection, or hardware damage caused by high currents can increase the operational expenses.

The scale of the project, as in the case of the bio-CCU project, with hundreds of sensor nodes in multiple bioreactors, also adds to the cost. Each additional sensor node increases the hardware and maintenance expenses, including battery replacement and sensor recalibration. To address these cost challenges, there is a need for cost-effective solutions in IoUT. Research and development efforts are focused on developing affordable sensor nodes and communication modules specifically designed for underwater environments. Low-cost materials, efficient manufacturing processes, and optimised energy consumption can help reduce the overall cost of deploying and maintaining IoUT systems.

Moreover, considering the bio-CCU project's requirements, efforts can be made to identify and select sensor nodes that provide the required functionality at a lower cost. Balancing cost and performance is crucial in selecting the appropriate sensor nodes for the project. It's worth noting that, as technology advances and more research is conducted in the field of IoUT, the cost of deploying and maintaining such systems is expected to decrease over time. Economies of scale, technological innovations, and improved manufacturing processes can contribute to cost reduction in the long run. Overall, managing the cost of deploying and maintaining IoUT systems, including in the bio-CCU project, is a significant consideration. By exploring cost-effective solutions, selecting appropriate sensor nodes, and leveraging technological advancements, it is possible to optimise the cost while maintaining the required functionality and performance of the system.

IoT with COVID-19 and bio-CCU

The usage of IoT in healthcare has experienced significant growth, particularly during the COVID-19 pandemic (Yousif et al., 2021). IoT applications in healthcare have the potential to revolutionise patient monitoring, remote care, and data analysis, leading to improved healthcare outcomes. In healthcare IoT applications, various devices equipped with sensors are used to monitor and regulate different health parameters of the human body. These devices collect data from sensors located at different locations and transmit the data to a gateway (Kumar et al., 2020), which then forwards it to the cloud for storage and analysis. Machine-learning techniques are often applied to analyse the collected data, providing valuable insights for patients, doctors, and experts.

The devices in healthcare IoT applications are connected to the Internet through different communication technologies such as Wi-Fi, 3G, 4G, and LTE. This connectivity enables real-time data transmission and feedback to healthcare professionals and patients. When designing these devices, factors such as efficiency, energy efficiency, and lightweight design (Ndiaye et al., 2020) are taken into consideration to ensure optimal performance and user experience. In terms of data security and privacy, blockchain technology has been proposed as a solution for data logging and retrieval in healthcare IoT applications. By utilising blockchain (Garg et al., 2020), data integrity and security can be enhanced, providing a trustworthy and transparent system for storing and accessing healthcare data.

The challenges faced by healthcare IoT applications, including those in the bio-CCU project, are similar in terms of device robustness, edge computing capabilities, real-time alerts, and user-friendly interfaces. State-of-the-art technologies developed for healthcare IoT can be directly applied to the bio-CCU use case to address these challenges and ensure the efficient operation of the system. Overall, the widespread adoption of IoT in healthcare has brought numerous benefits, and the challenges faced by healthcare IoT applications align with those encountered in the bio-CCU project in terms of QoS, availability, vulnerability, privacy, and security. Leveraging advancements in technology and drawing from the experiences of healthcare IoT applications can contribute to the successful implementation of IoUT in the bio-CCU project and other relevant use cases.

Vision of IoUT for bio-CCU

The vision for IoUT in the bio-CCU project involves the implementation of a cyber-physical distributed system that utilises the network architecture as shown in Figure 6.3. This architecture can be applied to multiple bioreactors within the project. In this

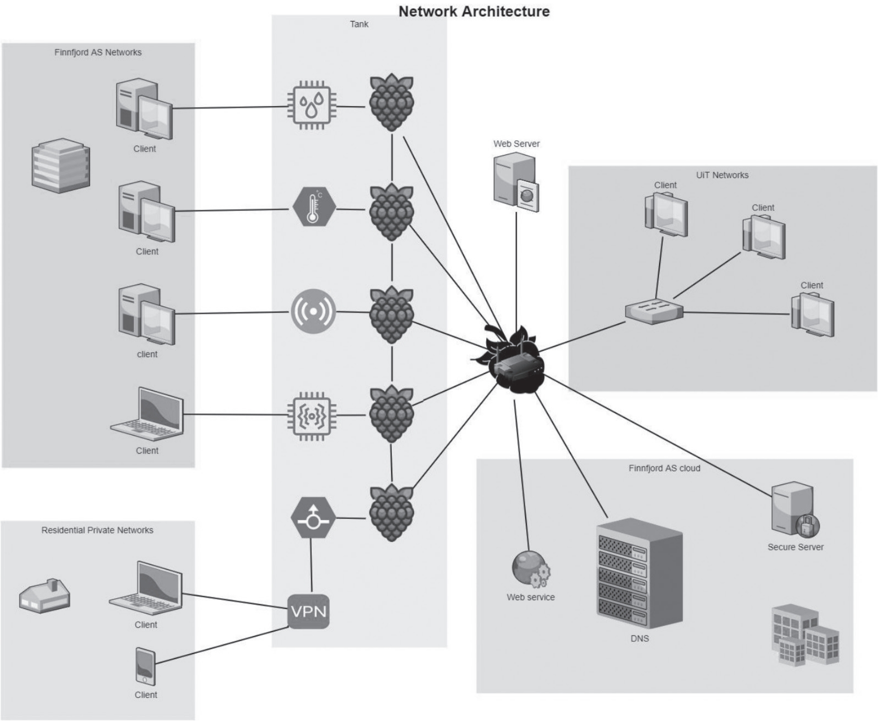

Figure 6.3 Feasible network architecture of a single bio-reactor for bio-CCU project.

vision, each bioreactor consists of several sensors that are connected to a computing device such as a Raspberry Pi or Arduino. These computing devices, referred to as observational units (OUs), play a crucial role in collecting and processing data from the sensors. The OUs are also connected to the devices present in the Finnfjord AS facility's network, allowing for seamless integration and data exchange.

To ensure remote access and secure communication, the OUs can be accessed from any private residential network through a virtual private network (VPN). This enables authorised personnel to monitor and control the bioreactors remotely while maintaining data privacy and security. The OUs are equipped with edge-computing capabilities, which enables local data processing and analysis tasks, and reduces the need for constant data transmission to external servers. This distributed approach helps minimise latency, enhances real-time decision-making, and reduces the dependence on a single point of failure. The data collected by the OUs can be transmitted to multiple destinations, including web servers, on-site web services, the cloud infrastructure of Finnfjord AS, and servers at UiT (UiT – The Arctic University of Norway). This distribution of data storage and processing further improves system reliability and fault tolerance.

Adopting this vision of IoUT for the bio-CCU project establishes a resilient, efficient monitoring, and control system. The combination of cyber-physical integration, edge computing, secure remote access, and distributed data storage ensures the effective management of multiple bioreactors while addressing the challenges associated with IoUT deployment.

Machine learning on the cloud for data analysis

In the bio-CCU project, machine learning can be employed for data analysis in the cloud. Machine learning is a branch of artificial intelligence that utilises algorithms and statistical models to analyse data and uncover patterns or make predictions (Mahdavinejad et al., 2018). It has become a prominent field in computer science and has the potential to extract valuable insights from the large amount of data generated by the observational units (OUs).

The OUs collect data from various sensors within the bioreactors, and this data can be utilised to train machine learning algorithms. By feeding the historical data into these algorithms, the models can learn and identify hidden patterns or relationships within the data. This allows for accurate analysis and prediction without requiring explicit programming or domain-specific expertise. Handling large volumes of data can be challenging, but with the advancements in computer systems and cloud storage, computational power and storage capacity are readily available (Dai & Gao, 2013). Cloud-based platforms provide the necessary infrastructure to process and store the data efficiently, making it feasible to perform machine learning tasks on a large scale.

By leveraging machine learning in the cloud, the bio-CCU project can benefit from advanced data analysis techniques. The machine-learning models can provide valuable insights into the performance of the bioreactors, identify trends, detect anomalies, and optimise operational parameters. This information can assist in making informed decisions, improving efficiency, and maximising the overall effectiveness of the bio-CCU system.

Overall, machine learning in the cloud offers a powerful approach to analyse the vast amount of data generated by the OUs in the bio-CCU project, enabling data-driven decision-making and enhancing the understanding of the bio-reactor's behaviour.

Edge computing with OUs

Edge computing has emerged as a significant research focus in the field of computer science. It offers a distributed computing paradigm that brings computational capabilities closer to the data source, enables real-time data processing, and reduces the need for extensive data transmission to a centralised cloud.

In the context of the bio-CCU project, edge computing can be applied to the OUs within the bioreactors. By deploying computational resources at the edge, closer to the sensors and data collection points, data processing can be performed locally, optimising the data before transmitting it to the cloud for further analysis. This approach offers several advantages.

First, edge computing enables low-latency processing. With the computational capabilities available at the edge, data can be processed immediately without the need for round-trip communication to a distant cloud server. This is particularly crucial in time-sensitive applications where real-time monitoring and decision-making are required.

Second, edge computing enhances scalability and node location (Liang et al., 2020). By distributing computational tasks across multiple edge nodes, the system can handle a larger number of OUs and scale more effectively. Additionally, edge nodes can be strategically placed to minimise communication distance and optimise network performance.

Third, edge computing improves reliability. By processing data at the edge, the system becomes less dependent on continuous network connectivity. Even in situations where the network connection may be intermittent or unreliable, the edge nodes can continue performing localised computations, ensuring continuous monitoring and control of the bioreactors.

Furthermore, edge computing helps reduce network bandwidth usage. By performing data processing and filtering at the edge, only the relevant and summarised data needs to be transmitted to the central Finnfjord system, on-site services, UiT servers, and the cloud. This reduces the amount of data transmitted over the network, conserving bandwidth and improving overall system efficiency.

By leveraging edge computing features, the bio-CCU project can benefit from faster data processing and analysis, energy-efficient OUs, and reduced network bandwidth requirements. The combination of edge computing and cloud-based data analysis allows for a robust and efficient system architecture, enabling real-time insights and decision-making in the bioreactors filled with biomass.

In summary, edge computing offers significant advantages in terms of low latency, scalability, node location, reliability, and reduced network bandwidth for the bio-CCU project. By bringing computational capabilities closer to the data source, edge computing enhances the overall performance and efficiency of the system.

Appropriate approach for IoUT

Employing edge computing on the observational units (OUs) within the IoUT system can indeed enhance the data analysis approach. By utilising edge computing, the initial processing of data can be performed on the OUs themselves, reducing the need to upload raw data to the cloud. The processed data can then be uploaded to the cloud for further analysis using machine-learning techniques.

This approach offers several benefits. First, by processing the data locally on the OUs, the amount of data that needs to be transmitted over the network is reduced. This helps conserve network bandwidth and reduces latency, as only the relevant and summarised data is transmitted to the cloud.

Second, performing initial processing on the OUs allows for faster insights and decision-making. The edge-computing capabilities enable real-time processing and analysis, enabling timely responses to changing conditions or events within the IoUT system.

Once the processed data is uploaded to the cloud, machine-learning models can be applied for more in-depth analysis. The cloud provides the computational power and storage capacity needed to train and run complex machine-learning algorithms on the collected data. This enables the extraction of valuable insights, patterns, and predictions from the data that can further enhance the monitoring and control of the bio-CCU project.

Figure 6.4 illustrates the data flow with the integration of edge computing and machine learning. The data originates from the OUs, where initial processing

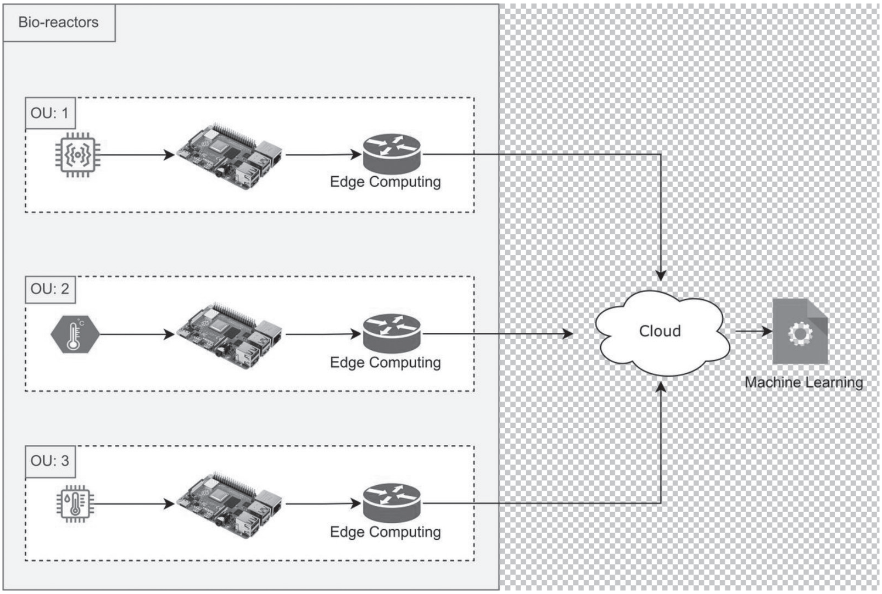

Figure 6.4 Appropriate approach for IoUT.

takes place through edge computing. The processed data is then transmitted to the cloud, where machine-learning algorithms can be applied for comprehensive data analysis and generating meaningful outcomes. Through the integration of edge computing and machine learning, the IoUT system can optimise data processing, minimise network bandwidth usage, and enhance analytical prowess in the cloud. This approach ensures a balance between local processing for real-time insights and cloud-based analysis for more advanced data exploration and decision-making within the bio-CCU project.

Practical implementation

OUs could be stationary or floating in the bioreactors. A demo floating OU is created with the following:

1 Artemis Nano with cost 15€: programmed with the Arduino Integrated Development Environment (IDE).
2 Temperature sensor DS18B20 with cost 1€.
3 Photocell with 1€: in daylight, the resistance is approximately 5–10 KO, and it goes up to approximately 200 KO in darkness.
4 Motion processing unit (MPU) MPU 9250 with cost 4.5€: contains Gyroscope, Accelerometer, and Magnetometer.

The outer body of the OU was designed and 3D printed to meet the project's specific parameters. Figure 6.5 shows the hardware setup, final look, and the data collected from the demo prototype. The final look has a temperature sensor and photocell at both ends of the oval-shaped OU. When the unit is floating, the temperature sensor is submerged, and the photocell is visible on top of the water. LED on the photocell indicates whether the OU is dead, asleep, or alive. Providing the OUs with a sleep cycle increases energy efficiency. Figure 6.6 shows the average variation of light (lumens m^{-2}) in a demo tank of 100 L for 3 days.

This demo floating prototype is not ideal for the actual working bioreactors. But, as the turbines run constantly to rotate the biomass, the location of the floating OUs and the leakproof design are important. Several expectations (including security and data analysis) are lacking in this demo prototype. Yet the prototype is very cost-efficient, meaning hundreds of such OUs could float in the bioreactors and be easily replaced as needed.

Conclusion

IoUT presents a complex set of challenges and issues that need to be addressed for successful implementation. These challenges include dynamic topology, limited resources, power supply constraints, unreliable communication, and data transfer. However, despite these challenges, IoUT holds great potential to provide solutions for applications such as the bio-CCU project. The bio-CCU project, with its focus on underwater sensing within bioreactors, can greatly benefit from IoUT and

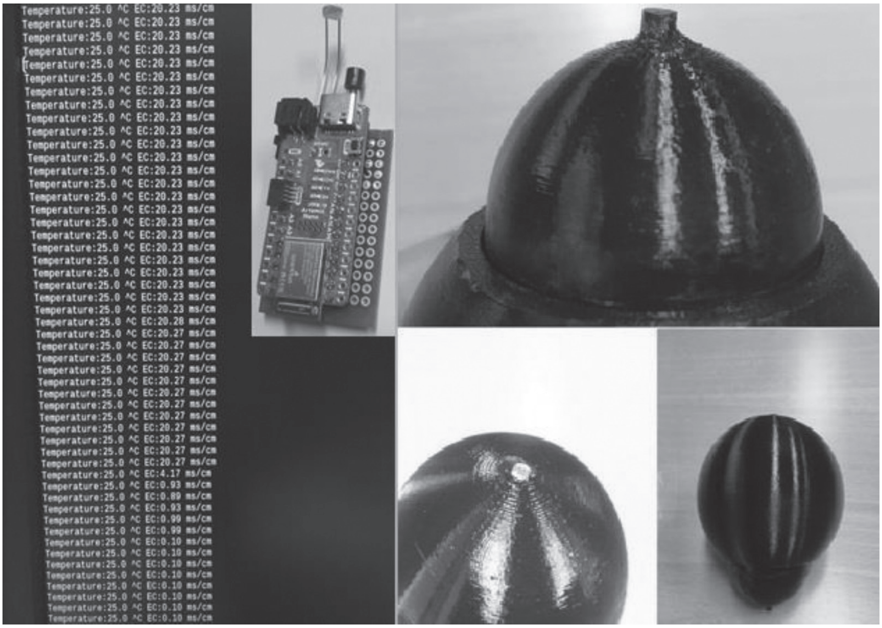

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Figure 6.5 Demo prototype of floating OU.

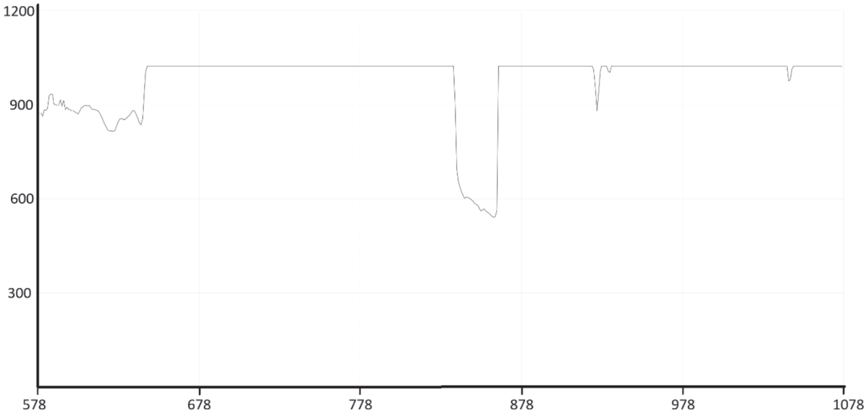

Figure 6.6 Average variation of 3 days for Light (lumens m^{-2} on x-axis and time in seconds on y-axis) in 100lt. tank with cheap sensor.

state-of-the-art technologies that have been introduced in applications related to monitoring and controlling sensors, particularly in the context of COVID-19. By leveraging best practices and techniques, such as edge computing on the sensor nodes, and utilising artificial intelligence and machine learning for data analysis, the bio-CCU project can overcome many of the challenges associated with IoUT.

Hardware design for the mobile sensor node units is crucial, considering factors like battery replacement or recharging to ensure uninterrupted operation. Synchronisation between nodes is also a critical aspect that needs to be addressed to ensure reliable and accurate data collection and analysis. The proposed system should be open to further development to enhance compatibility with additional IoT protocols, support different data types, and integrate with various analytic tools. It should also be designed to be compatible with commonly used server platforms and cloud technologies, ensuring scalability and interoperability. By incorporating the advancements in edge computing, data analysis with artificial intelligence, and machine learning, the proposed IoUT architecture can enable efficient monitoring and control of the bio-CCU project. This will lead to improved resource management, better decision-making, and enhanced overall performance. IoUT, when combined with state-of-the-art technologies, holds great potential for addressing the unique challenges of the bio-CCU project and other similar applications. With careful consideration of the specific requirements and the integration of best practices, IoUT can revolutionise the monitoring and control of underwater environments, enabling sustainable and efficient operations.

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7 From CCS to CCU and CCUS – the pitfalls of utilisation and storage

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This chapter engages critically with carbon capture and storage (CCS), carbon capture and utilisation (CCU), and carbon capture utilisation and storage (CCUS). Beginning with a brief history of the development of CCS and the more recent move towards focusing on CCU and CCUS, it outlines some of the key controversies and debates surrounding these technologies. These reasonings are linked to different worldviews and key strategic choices that cohere with diverse perspectives on the role of technology, its impact on various lifestyles and the changes it may induce, the possibility of reducing fossil fuels, and ultimately, on how to meet the challenge of living within planetary boundaries. Thereafter, we bring this analytical entry point to bear on the ferrosilicon plant of Finnfjord Limited, and specifically address whether CO_2 can or should be seen as a valuable resource. In doing so, we problematise where the carbon in focus comes from and where it goes. In light of this analysis, we reflect upon the extent to which utilisation, the "U" in CCU(S), is fit for purpose in sustainable development.

CCS and the move to CCUS

The idea of capturing CO_2 from fossil fuel combustion and storing it in the ocean or underground started in the 1970s (Marchetti, 1977), but it was only in the mid-1980s, when climate change was put on the international policy agenda, that the interest in CCS became emergent. The International Energy Agency (IEA) played an important role in stimulating research around CCS through its Greenhouse Gas Research and Development Program (Meadowcroft & Langhelle, 2009). The first major international conferences on CCS were held in 1992 and 1993. Throughout the 1990s, actors in industry, academia, and government pushed the CCS agenda, with major fossil fuel producers and governments sponsoring research on technologies for capture and transport, storage potential, and the modelling of costs. In 1996, the first large-scale storage project started at Sleipner in Norway, separating CO_2 from natural gas and re-injecting it into geologic strata under the North Sea (Tjernshaugen & Langhelle, 2009). Today Sleipner is still in operation, storing approximately one million tonnes of CO_2 each year.

It took some time before the Intergovernmental Panel on Climate Change (IPCC) recognised CCS as a potentially legitimate, viable, and appropriate mitigation

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option. It was not listed among the recommended mitigation options in the IPCC Second Assessment Report (AR2) (1995) and received little attention also in the Third Assessment Report (AR3) in 2001 (IPCC, 2005; Meadowcroft & Langhelle, 2009). In 2005, however, the IPCC launched a special report on CCS written by more than 100 experts, which had a major impact on the policy discourse. It presented a comprehensive review of the technical and economic potential of CCS as a viable and important mitigation option, and began the work of mainstreaming it within the wider discourse on climate change (Meadowcroft & Langhelle, 2009). CCS has subsequently become one of the most integral parts of the IPCC's Assessment Reports and Emissions Scenarios. The report from the IPCC argued that CCS could be applied to large point sources, including "large fossil fuel or biomass energy facilities, major CO_2-emitting industries, natural gas production, synthetic fuel plants and fossil fuel-based hydrogen production plants" (IPCC, 2005, p. 3). Several CCS initiatives were launched around this time, but the terminology was still CCS, not CCUS. In Norway, CCS gained traction as gas-fired generation was added to the erstwhile emissions-free hydropower-fed electricity grid, rendering it a compromise of sorts (Tjernshaugen, 2011).

According to Endres et al. (2016), an important move from CCS to CCUS among the CCS-oriented science and engineering professional took place in May 2012 at the 11th Annual Conference on Carbon Capture, *Utilisation*, and Sequestration. Here, the term "utilisation" appeared "in all of the on-site conference materials including welcome signs, name badges, conference programs, and plenary session presentation titles" (Endres et al., 2016, p. 363). The same month, 1 May 2012, the US Department of Energy stated that it was "strategically focusing the program's R&D toward the economic 'utilization' of captured carbon dioxide (CO_2) for commercial purposes, evolving from CCS to Carbon Capture, Utilization and Storage, or CCUS." By putting the captured CO_2 to use, it was argued that "CCUS provides an additional business and market case for companies or organizations to pursue the environmental benefits of CCS" (US Department of Energy, 2012, cited in Bajura & Clemente, 2012, p. 13).

Unsurprisingly, the major near-time opportunity described was in enhanced oil recovery (EOR), where CO_2 is injected into depleted oil wells to recover untapped oil. This was "a well-established and mature technology already providing about 5 percent of U.S. oil production" (US Department of Energy, 2012, p. 1), with the potential to add 60 billion barrels of crude oil to US recoverable resources, three times the current proven reserves. This would help "the US economy, including increased economic activity, improved balance of trade, job creation, and reduced oil imports." The most important, according to the Department of Energy, however, was that "CCUS would benefit the environment by helping reduce atmospheric man-made CO_2" (US Department of Energy, 2012, p. 1).

EOR has, however, for obvious reasons been seriously questioned as a mitigation strategy. As argued by Morrow et al. (2020, p. 9), "the emissions from those extra fossil fuels partly or entirely eliminate any climate benefit from injecting the captured carbon underground." The authors question where the carbon comes from and where it goes, with these responses constituting core markers as to whether any mitigation strategy adds value. Based on this evaluation approach, EOR will never be counted "as carbon removal." We adopt a similar strategy for the analysis in this chapter. In the list of operational commercial CCS facilities and projects from the Global CCS Institute, 29 out of 41 CCS projects in operation are EOR projects (Global CCS Institute, 2023). This demonstrates how the use of CCS to *actually* reduce emissions is at odds with its current and predominant real-world use case.

As for the wider use of the vocabulary of CCUS instead of CCS, this took some more time. The World Energy Outlook's (WEO's) from the IEA illustrate this. In all WEO's up to 2017, there is no mention of CCUS, only CCS. In the 2018 edition, however, CCUS is not only introduced but dominates, present in almost everything.

The re-emergence of CCS/CCUS

The initial experience with CCUS has hardly been promising, as research on for example China's effort shows (Jiang et al., 2020). Yet, its very appearance can be credited to a strong incentive for incumbents to embrace it. The attractiveness of CCUS from a policymaking perspective lies in the ability to mobilise large actors behind it, so that if something does work, there might be "big numbers to show," a need that weighs heavy on the minds of those in charge of rapid climate mitigation, with evidently little success over time. While the real developments and deployment of CCS/CCUS have been meagre, the attention is on the rise. As the IEA (2020, p. 13) puts it, "After years of slow progress and insufficient investment, interest in CCUS is starting to grow." In the overview from the Global CCS Institute, there are 26 facilities under construction. Of these, 20 are projects with dedicated geological storage, and one is yet to be decided. Also for the projects categorised as being in an "advanced development" stage, there is a clear shift towards *geological storage*. Out of 121 projects, only 9 are dedicated to EOR. A further 9 are yet to be decided upon (options are being evaluated). Most of these projects in advanced development are planned to be operational by the mid-2020s and before 2030. In addition, 205 projects in the early development stages are also planned to be operational along a slightly longer timeline. Overall, there are 352 CCS/CCUS projects in operation or planned globally (Global CCS Institute, 2023). Although this represents a substantial increase in planned facilities and capture capacity, the IPCC (2022, p. 32) concludes that the current global rates of CCS deployment "are far below those in modelled pathways limiting global warming to 1.5 °C or 2 °C."

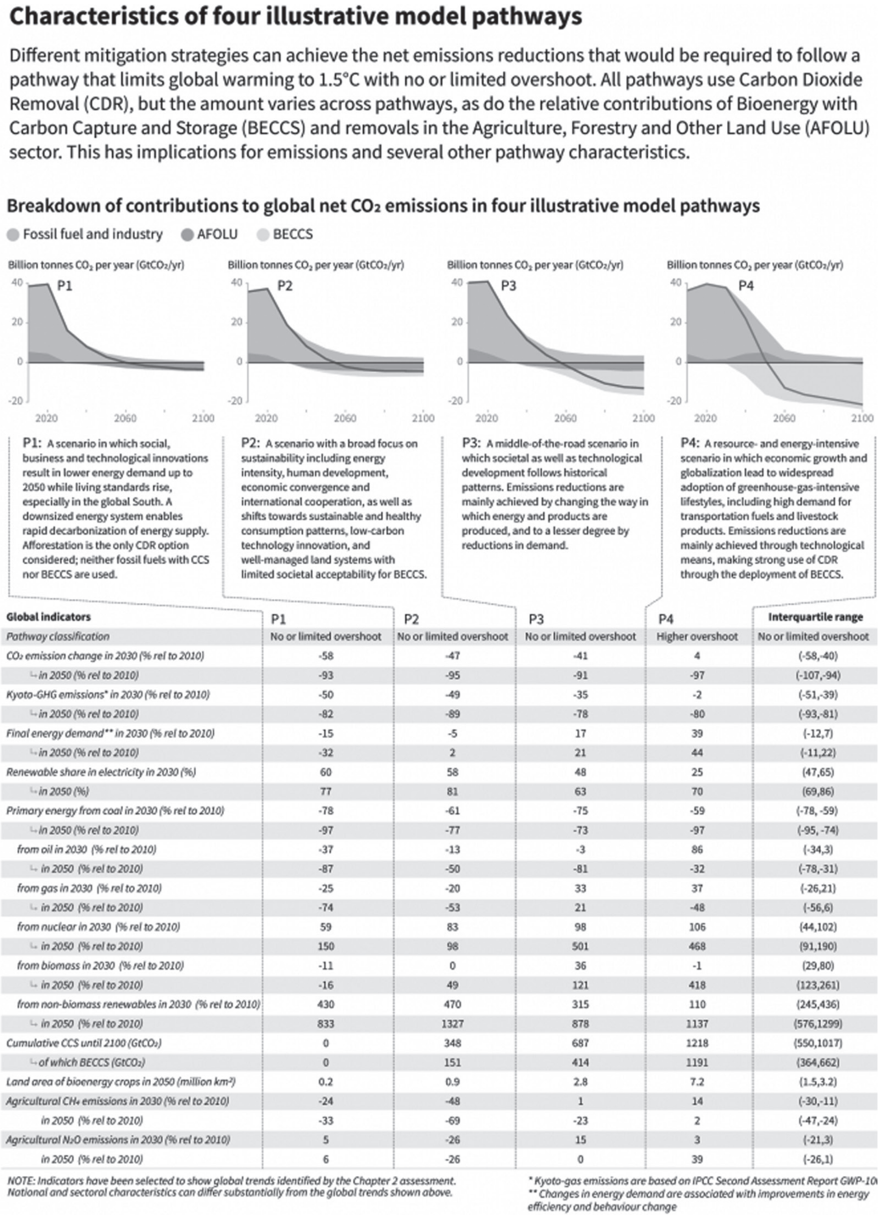
Over the past decade, large-scale CO_2 removal has become an integral part of the mitigation scenarios assessed by the IPCC (Geden & Schenuit, 2020). This is for several reasons. The Paris Agreement represented a breakthrough in the international climate negotiations. In the process leading up to the Conference of the Parties (COP) meeting in Paris, many countries strengthened their climate targets through their Intended Nationally Determined Contributions (INDCs). The inclusion of 1.5 °C in the Paris Agreement target of "Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels" (UN, 2015, p. 3) can be said to have an impact on the need for Carbon Dioxide Removal (CDR) measures.[1]

Further, as pointed out by Geden and Schenuit (2020), Article 4 in the Paris Agreement includes the target "to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century" (UN, 2015, p. 4; IPCC, 2022b, p. 242). Theoretically, this can be achieved with or without large-scale CDR, but excluding this element dramatically reduces the likelihood in line with many popular models in climate science discourse which are circulating at present. Not using CDR would require more ambitious substitutions of fossil fuel sources by upscaling renewable energy uptake. In this sense, CDR can be seen as a legitimation device to prolong business-as-usual emissions.

This became clear in the Special Report from IPCC on global warming of 1.5°C. Importantly, the report "established a new type of target that quickly became 'the benchmark for all climate policy actors in industrialised countries: *net zero emissions* or *greenhouse gas neutrality*'" (Geden & Schenuit, 2020, p. 16).[2] The report argued that in "Emission Pathways and System Transitions Consistent with 1.5 °C Global Warming," global net anthropogenic CO_2 emissions will have to decline by about 45% from 2010 levels by 2030, reaching net zero around 2050 in the model pathways with no or limited overshoot of 1.5 °C (IPCC, 2018, p. 14). Net zero CO_2 emissions would be, by definition "achieved when anthropogenic CO_2 emissions are balanced globally by anthropogenic CO_2 removals over a specified period" (IPCC, 2018, p. 26).

CCS and especially Bio-Energy Carbon Capture and Storage (BECCS) play a central role in many of the scenarios/pathways in which the world warms by or less than 1.5 °C by the end of this century. The Summary for Policymakers included four illustrative pathways (P1 through P4) in which the 1.5 °C target could be reached. As Figure 7.1 shows, these pathways differ dramatically in terms of how emissions reductions are achieved. P1 for example has no use of CCS or BECCS, while P4 relies heavily on CDR and BECCS. This has huge implications for the volume of fossil fuels that can be combusted while remaining within the 1.5 °C target.

These pathways reveal different imaginaries about the future and also the contestations and disputations that are at play politically regarding the direction of emissions mitigation strategies. On the one hand, P1 is the "LowEnergyDemand" (LED) scenario from Grubler et al. (2018). Emissions' reductions in this scenario are achieved without deployment of any CCS, with much of the land being used for afforestation instead of bioenergy crops. In the LED scenario, global primary energy supply drops by 35% by 2030 and is cut in half by 2050 through a combination of changes in consumer behaviour, energy efficiency improvements, electrification, and growth in renewables (Grubler et al., 2018). On the other hand, P4 depicts a very different future. It is a resource- and energy-intensive scenario with high economic growth, with globalisation that leads to the widespread adoption of greenhouse-gas-intensive lifestyles while relying heavily on emissions reductions through technological means. P4 implies a substantial overshoot of greenhouse gas emissions (GHGs). Classified as a "higher-overshoot" scenario, P4 exceeds 1.6 °C but still returns to 1.5 °C by 2100, resulting in higher impacts with various associated challenges compared to pathways that limit global warming to 1.5 °C with no or limited overshoot like P1.



Characteristics of four illustrative model pathways

Different mitigation strategies can achieve the net emissions reductions that would be required to follow a pathway that limits global warming to 1.5°C with no or limited overshoot. All pathways use Carbon Dioxide Removal (CDR), but the amount varies across pathways, as do the relative contributions of Bioenergy with Carbon Capture and Storage (BECCS) and removals in the Agriculture, Forestry and Other Land Use (AFOLU) sector. This has implications for emissions and several other pathway characteristics.

Breakdown of contributions to global net CO₂ emissions in four illustrative model pathways

P1: A scenario in which social, business and technological innovations result in lower energy demand up to 2050 while living standards rise, especially in the global South. A downsized energy system enables rapid decarbonization of energy supply. Afforestation is the only CDR option considered; neither fossil fuels with CCS nor BECCS are used.

P2: A scenario with a broad focus on sustainability including energy intensity, human development, economic convergence and international cooperation, as well as shifts towards sustainable and healthy consumption patterns, low-carbon technology innovation, and well-managed land systems with limited societal acceptability for BECCS.

P3: A middle-of-the-road scenario in which societal as well as technological development follows historical patterns. Emissions reductions are mainly achieved by changing the way in which energy and products are produced, and to a lesser degree by reductions in demand.

P4: A resource- and energy-intensive scenario in which economic growth and globalization lead to widespread adoption of greenhouse-gas-intensive lifestyles, including high demand for transportation fuels and livestock products. Emissions reductions are mainly achieved through technological means, making strong use of CDR through the deployment of BECCS.

Global indicators	P1	P2	P3	P4	**Interquartile range**
Pathway classification	No or limited overshoot	No or limited overshoot	No or limited overshoot	Higher overshoot	No or limited overshoot
CO₂ emission change in 2030 (% rel to 2010)	-58	-47	-41	4	(-58,-40)
↳ in 2050 (% rel to 2010)	-93	-95	-91	-97	(-107,-94)
Kyoto-GHG emissions in 2030 (% rel to 2010)*	-50	-49	-35	-2	(-51,-39)
↳ in 2050 (% rel to 2010)	-82	-89	-78	-80	(-93,-81)
*Final energy demand** in 2030 (% rel to 2010)*	-15	-5	17	39	(-12,7)
↳ in 2050 (% rel to 2010)	-32	2	21	44	(-11,22)
Renewable share in electricity in 2030 (%)	60	58	48	25	(47,65)
↳ in 2050 (%)	77	81	63	70	(69,86)
Primary energy from coal in 2030 (% rel to 2010)	-78	-61	-75	-59	(-78, -59)
↳ in 2050 (% rel to 2010)	-97	-77	-73	-97	(-95, -74)
from oil in 2030 (% rel to 2010)	-37	-13	-3	86	(-34,3)
↳ in 2050 (% rel to 2010)	-87	-50	-81	-32	(-78,-31)
from gas in 2030 (% rel to 2010)	-25	-20	33	37	(-26,21)
↳ in 2050 (% rel to 2010)	-74	-53	21	-48	(-56,6)
from nuclear in 2030 (% rel to 2010)	59	83	98	106	(44,102)
↳ in 2050 (% rel to 2010)	150	98	501	468	(91,190)
from biomass in 2030 (% rel to 2010)	-11	0	36	-1	(29,80)
↳ in 2050 (% rel to 2010)	-16	49	121	418	(123,261)
from non-biomass renewables in 2030 (% rel to 2010)	430	470	315	110	(245,436)
↳ in 2050 (% rel to 2010)	833	1327	878	1137	(576,1299)
Cumulative CCS until 2100 (GtCO₂)	0	348	687	1218	(550,1017)
↳ of which BECCS (GtCO₂)	0	151	414	1191	(364,662)
Land area of bioenergy crops in 2050 (million km²)	0.2	0.9	2.8	7.2	(1.5,3.2)
Agricultural CH₄ emissions in 2030 (% rel to 2010)	-24	-48	1	14	(-30,-11)
in 2050 (% rel to 2010)	-33	-69	-23	2	(-47,-24)
Agricultural N₂O emissions in 2030 (% rel to 2010)	5	-26	15	3	(-21,3)
in 2050 (% rel to 2010)	6	-26	0	39	(-26,1)

NOTE: Indicators have been selected to show global trends identified by the Chapter 2 assessment. National and sectoral characteristics can differ substantially from the global trends shown above.

** Kyoto-gas emissions are based on IPCC Second Assessment Report GWP-10*
*** Changes in energy demand are associated with improvements in energy efficiency and behaviour change*

Figure 7.1 Four illustrative model pathways to limit global warming to 1.5ºC.

Source: IPCC, 2018. Summary for policymakers.

As stated in the AR15 report, “Reversing warming after an overshoot of 0.2°C or larger during this century would require upscaling and deployment of CDR at rates and volumes that might not be achievable given considerable implementation challenges” (IPCC, 2018, p. 18). The same worry is reiterated in IPCC’s Sixth Assessment Report. Overshoot pathways “imply increased climate-related risk and are subject to increased feasibility concerns, and greater social and environmental risks, compared to pathways that limit warming to 1.5 °C (>50%) with no or limited overshoot” (IPCC, 2022, p. 15).[3] Yet while probabilistic scenarios remain relatively niche in their influence over popular discourse, visions of CCS and CCUS have spectacular power to mobilise hope and unleash imaginations, bolstered by the fact that actions, for example, investment, sit well with the general approach of throwing money at any problem.

The difference among CCU, CCS, and CCUS: does it matter?

As Morrow et al. (2020, p. 3) argue, there is much confusion concerning CCU, CCS, CCUS, and Direct Air Capture and Carbon Storage (DACCS, as a specific form of CDR) as technological categories. To understand these approaches, one should focus on the *roles* they can play in climate policy, instead of focusing on technological categories alone. This is a push informed by a classic scholarly insight on the politics of categories themselves: Suchman (1993) argues that categories have a performative aspect which can detract from application. With this in mind, it is clear that Morrow et al. (2020) contend for a consistent focus on climate policy rather than on technical distinctions related to CCUS. This focus on various approaches guides them to ask two essential questions in relation to the *roles* these technologies can play in climate policy: “Where does the carbon come from, and where does it go?”

There are essentially three sources of carbon that define where the carbon comes from: (1) air carbon dioxide that can be captured through direct air capture technology, (2) biocarbon dioxide produced by burning or fermenting biomass, and (3) fossil carbon produced by burning fossil fuels (air carbon can be derived from both fossil and biocarbon). Fossil carbon comes from geological reserves and adds CO_2 to the atmosphere, while biocarbon is part of the natural cycle, absorbing carbon from the air through photosynthesis.

Captured carbon can end up in three different places:

1 Geological storage where carbon is sequestrated in geological reservoirs where the aim is permanent storage of CO_2; an alternative approach is to inject CO_2 into basalt where it is turned into solid minerals (Morrow et al., 2020, p. 3).
2 Long-lived products, for example, low-carbon cement and various polymers. The US National Academy of Sciences defines long-lived products according to “if their production results in carbon being kept out of the atmosphere for at least 100 years” (Morrow et al., 2020, p. 3).
3 Short-lived products that result in the re-emission of CO_2 in less than (a seemingly arbitrarily specified) 100 years such as synthetic fuels and many industrial

> chemicals such as hydrofluorocarbons. One might wonder at the equivalence this accords storage solutions, ranging from a century to as little as a decade or less! Additionally, as Morrow et al. (2020, p. 5) acknowledge, the line between short-lived and long-lived products is somewhat arbitrary, but the longer the CO_2 is kept out of the atmosphere, the better.

From the perspective of climate change mitigation, these three end scenarios for carbon can be seen either as a "captured carbon hierarchy" or as a rule of thumb. Geological storage and long-lived products lead to emission reductions when the carbon comes from the burning of fossil fuels, and carbon removal if it comes from the air or biocarbon. The contribution from CCU in short-lived products is harder to assess in terms of emission reductions, as it depends on the timeframe and what it eventually ends up replacing. As Mac Dowell et al. (2017, p. 248) argue:

> From a commercial and policy perspective, CCU should be encouraged when and only when CO_2 is useful as a cheap feedstock, or when it can [be] robustly and reliably shown that the CO_2-derived product can reasonably displace the incumbent product, that is, deliver the same service at the same price, and also not result in an increase in the emission of CO_2 associated with delivering that service. The driver should be feedstock substitution and the production of materials at a lower cost and with lower fossil carbon content. The primary driver should not be locking up CO_2, as this can never happen at the required magnitude without geological storage.

They also warn against the danger of emphasising and reinforcing the narrative that CO_2 utilisation is key to making CCS profitable in a simplistic commercial sense. If this narrative continues, they argue "it introduces the very real risk that emission mitigation targets will not be met and that CCS through geological storage will not be deployed in any meaningful way" (Mac Dowell et al., 2017, p. 248).

The criticism of CCS

While BECCS and CCS play important roles in most of the IPCC pathways, the latter has been controversial since it was introduced as a mitigation option. As shown by Røttereng (2018), CCS has been driven mainly by petroleum-producing, large, and affluent industrial countries who prefer carbon-sink-based mitigation measures such as CCS and REDD+.[4] Hence, the widely different carbon-sink-based mitigation measures seem to play similar political functions in comparable (petroleum) political contexts, which also partially explains the differences in approaches and enthusiasm for CCS.

Environmental nongovernmental organisations (NGOs) have also been divided in their approach to CCS. It has been seen as an "end of pipe" solution where the main purpose has been to extend the fossil-fuel era, thus delaying the inevitable transition towards a renewable energy economy. It has also been viewed as an expensive and inefficient technology that is risky, increases energy usage instead of reducing it, draws away funding from renewables and energy efficiency, and is essentially a way for the fossil fuel industry to continue with their core business; the burning of fossil fuels. In this respect, it is viewed as a means to prevent transitions towards more sustainable trajectories and hinder alternate sustainable technologies and business practices, to prolong the fossil fuel era despite the urgent need to mitigate climate change.

In 2021, 500 organisations in the United States and Canada published *An Open Letter to US and Canadian Leaders* as an advertisement published in the *Washington Post* and Ottawa's the *Hill Times* newspapers, with the heading "It's Time to End Carbon Capture of Climate Policy," arguing that CCS "is not a climate solution. It is a dangerous distraction driven by the same big polluters who created the climate emergency." The advertisement was paid for by the Center for International Environmental Law (CIEL).[5] Among the arguments were that:

> CCS is unnecessary. Renewable energy sources like solar and wind are cheaper and cleaner than fossil fuels. CCS just makes dirty energy more expensive and more energy-intensive. CCS does not work. CCS projects have systematically overpromised and under-delivered. Despite the billions of taxpayer dollars wasted on CCS to date, the technology has not made a dent in CO_2 emissions. CCS will do little to reduce industrial emissions. Deploying CCS at scale is not economically viable for most heavy-emitting industries, such as plastic or chemical manufacturing. It diverts resources from available and scalable alternatives such as replacing fossil fuels with clean renewable energy sources to supply power and heat, and reusing inputs to reduce the production of virgin material.
>
> (CIEL, 2021, p. 1)

CCS for coal and gas-fired power plants requires additional energy from the construction and maintenance of large-scale infrastructure (e.g., capture facilities, pipelines, and injection sites). It also reduces the overall efficiency of the power plant. To produce the same power output, you need a larger facility, and a greater throughput of materials (e.g., fuel, water, and so on). Hence, increased fuel for a coal plant "would imply more mining and bulk transport, generate additional solid waste, and require more materials for the control of criterion air pollutants" (Meadowcroft & Langhelle, 2009, p. 4). Although improvements in capture technology have the potential to reduce these effects, the technology will ultimately impact the overall efficiency due to the additional energy and capital required to power and install it.

CCS and CCUS are, therefore, seen as technologies that do not address these core drivers of the climate crisis or meaningfully reduce GHGs. As the *Open Letter* puts it, "[we] don't need to fix fossil fuels; we need to ditch them. Instead of capturing carbon to pump it back underground, we should keep fossil fuels in the ground in the first place" (CIEL, 2021, p. 1).[6]

Why we still need CCS/CCUS – the shift to industrial emissions

Despite this, CCS, CCUS, and BECCS all play an important role in the pathways discussed by the IPCC and in the scenarios of the IEA. The energy sector is still seen as a place where CCS must play a role. The focus for CCS, however, seems to have moved *from thermal power* to *industrial emissions*. This is partly because the CO_2 emissions from fuel combustion have been declining in Europe, and coal is supposed to be phased out (sooner or later) as we approach 2050. The quote from the European Commission (2021, p. 1) illustrates this shift:

> While CO_2 emissions from fuel combustion have been declining in Europe, industries like cement, iron and steel, aluminium, pulp and paper, and refineries have inherent CO_2 emissions resulting from energy-intensive industry processes. Carbon capture, use, and storage can provide a key contribution to tackling these sectors' emissions. Furthermore, it can help removing carbon from the atmosphere through carbon removals such as bio-energy carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS) and be a platform for low-carbon hydrogen production.[7]

In addition, the net zero target by 2050 (the benchmark for all climate policy) implies that we cannot emit *anything* if we are to stabilise global temperatures. Hence, as argued by the IPCC:

> The deployment of carbon dioxide removal (CDR) to counterbalance hard-to-abate residual emissions is unavoidable if net zero CO_2 or GHG emissions are to be achieved. The scale and timing of deployment will depend on the trajectories of gross emission reductions in different sectors.
>
> (IPCC, 2022, p. 36)

Further, we need to remove carbon from the atmosphere in general. As argued by Peters (2017, p. 1), this has "rather profound implications" in three main ways:

1. It may be that we cannot remove all emissions from all sectors. Just think about methane from paddy rice, wetlands, or cattle, or nitrogen oxide from fertiliser use, or military, or aid work, or any number of difficult sectors.
2. For equity reasons, we may allow some poor countries to continue emitting for a longer period.
3. We have pretty much emitted too much already, we can't get our act together, and we must undo the emissions of the past.

So, a key argument for CCS and CCUS related to industrial emissions is the fact that these are hard-to-abate sectors without readily available substitutes to meet high global demand (Paltsev et al., 2021). While inherent scepticism is understandable – and warranted for some CCUS projects, notably ones that focus on EOR – there are good reasons to dig deeper into their potential role. In a positive light, this could be different from an attempt to legitimate prolonged fossil fuel production and use, and rather a way of finding optimal solutions amidst a complex range of transition-related problems. Interest in CCUS has in any case been successful at attracting considerable capital investment, and as stated in the *Oxford Principles for Net Zero Aligned Carbon Offsetting* (2020, p. 10), it is "critical that investment in scaling and improving the technologies that enable long-lived storage begins now."

A place for CCU? The case of Finnfjord

What then about CCU? What is the potential of the "U" in terms of mitigation? In principle, a CCU project can be a storage project if the product is long-lived (as, for instance, with mineralisation). But what if the "U" is a short-lived product, as it is in the Finnfjord algae project? What would be a reasonable criteria to assess such a project on? As a large ferrosilicon producer, the company Finnfjord Limited is already one of the most energy-efficient companies in the world. Production is based on renewable electricity in Norway, and they have put in place an energy recovery system that generates 340 gigawatt hours (GWh) of electric power annually. Still, Finnfjord Limited emits 300,000 tonne of CO_2 and 1100 tonne of NO_x annually, and "U"tilising these emissions is part of what its pioneering microalgae project aims to do.

In the project, diatoms are cultivated by using light, CO_2, and NO_x from the factory fume (which is fed directly into the cultivating reactors from the factory baghouse filter), increasing the production of algae and utilising both CO_2 and NO_x in the process. In principle, microalgae are used as "CO_2 sequestration agents," capturing parts of the CO_2 and NO_x with the potential use of algae production for several possible products – as fish fodder, biogas, biofuels, and more (Eilertsen et al., 2022, p. 1).

The project's aim goes beyond this, however, and it should be seen in a broader context as more than just as a CCU project. As stated by Eilertsen et al., the project is

> based on the conviction that a large part of the future's fish feed, nutritious biomass and oil in general will and should be harvested or produced from the lowest trophic level in the marine food web, i.e., from fast growing photoautotrophic organisms. (Eilertsen et al., 2022, p. 23)

Hence, the project addresses the challenges of upscaling mass cultivation of microalgae for industrial purposes, including cost reductions, efficiency, and increases in volume.

It would also be somewhat misaligned to evaluate the Finnfjord algae project from a purely storage perspective. The primary driver in a CCU project is not necessarily to lock up $CO_{2,}$ which according to Mac Dowell et al. (2017, p. 248) "can never happen at the required magnitude without geological storage." So, instead, there are two other criteria that can be used to assess the project, and both make intuitive sense. The first is of course the essential question of *where the carbon* *comes from*. Is it from fossil or renewable sources? The other question is *what impact the project carries* in terms of Scope 1, 2, and 3 emissions.

Where the carbon comes from in the production of ferrosilicon becomes a key question. Production is based on quartz, iron ore, coal, coke, and biocarbon. According to Haque and Norgate (2013, p. 220), "the major difference in greenhouse gas emissions between the various ferroalloys is largely due to their respective amounts of electricity use and coke/coal consumption," and LCA results show "that coke and coal usage contributed close to 60% or more of the total GHG emissions from the various ferroalloy production processes." They, therefore, conclude that there is potential to reduce GHG emissions from ferroalloy production "if fossil fuel-based coal is replaced with biomass based renewable carbon" (Haque & Norgate, 2013, p. 220). Another option is the use of blue or green hydrogen. Hydrogen, however, has the "disadvantages that current production facilities relying on solid reducing agents need to be adjusted. Furthermore, hydrogen reduction of ignoble metals like chromium, manganese, and silicon is only possible at very low H_2O/H_2 partial pressure ratios" (Sommerfeld & Friedrich, 2021, p. 1). Although hydrogen may be something that needs to be further developed, the point here is that replacing fossil fuels with biocarbon or hydrogen addresses both *where the carbon comes* from and potentially Scope 1 emissions from Finnfjord, i.e., emissions that are direct emissions from owned or controlled resources.[8]

Mass cultivation of microalgae for industrial purposes end up in short-lived products. The key, therefore, is to replace fossil fuels with bio-based fuels in the production process. This would potentially move the cultivation of microalgae from one category to another, i.e., from fossil carbon (produced by burning fossil fuels) to (bio)carbon dioxide (produced from renewables). And the "cleaner" the fume, the closer the production of algae gets to carbon neutrality. The project is also capable of capturing large amounts of CO_2. This of course depends on the speed (the lower the speed the higher the uptake of CO_2), and the growth rate of the algae at given moments. In the project, the overall CO_2 transfer rate from injector to fluid and algae was measured/calculated to an approximate mean of 26%. This "is not considered to be a high transfer rate," implying that 74% of the CO_2 is not utilised. The potential capture and utilisation, however, is huge. If 50% of the CO_2 in the fume is captured in the algae production, the project would capture 75,000 tonnes of CO_2 a year (relative to the emitted 300,000 tonnes).

Scope 2 emissions concern indirect GHG emissions from purchased electricity the company consumes. Finnfjord relies 100% on renewable electricity. So, the place where the cultivation of microalgae for industrial purposes can have an impact and make a real difference is within Scope 3, defined as follows:

> Scope 3 is an optional reporting category that allows for the treatment of all other indirect emissions. Scope 3 emissions are a consequence of the activities of the company, but occur from sources not owned or controlled by the company. Some examples of scope 3 activities are extraction and production of purchased materials; transportation of purchased fuels; and use of sold products and services.
>
> (WBCSD/WRI, 2004, p. 25)

Within Scope 3, mass cultivation of microalgae for industrial purposes could replace natural gas and other fossil fuels by producing biogas and biofuels, resulting in direct emission reductions for other companies (Scope 1) and lead to substantial GHG reductions depending on scale. As such, it is in line with Mac Dowell et al.'s (2017) criterion that CCU makes sense when it can be robustly and reliably shown that the CO_2-derived product can displace the incumbent product. It also aligns with the requirement that it does not result in an increase in the emission of CO_2. In fact, to the contrary, the Finnfjord algae project team has done some preliminarily calculations for the mitigation potential of producing fish fodder from algae. They determined that:

> When salmon is fed conventional feed containing 70–80% terrestrial crops (soy, wheat, rapeseed) and 20–30% fish meal/oil, nearly 2 kg CO_2 per kg salmon produced is released into the atmosphere. The large part of this CO_2 is produced during the production of the feed ingredients (land use, harvesting crops, fishing vessels, etc.). On the other hand if "whole" algae feed is applied, 0.76 kg CO_2 is taken up/removed in the production process, simply because production of photoautotrophic algae relies on CO_2 in the factory fume. These figures we are aware can change with feed composition and algae cultivation method, but we are confident in the main findings.
>
> (Eilertsen et al., personal communication)

Producing fish fodder from algae by utilising the fume gas thus has quite a large mitigation potential if it replaces soy, wheat, rapeseed, and fish meal/oil. In addition, the algae-produced feed has lice deterrent properties (Eilertsen et al., 2021) and could therefore also have a positive effect on fish health, improving the sustainability and life of salmon (Eilertsen et al., 2022). This is a major policy issue in Norway that has proved intractable given a strong industrial lobby for farmed salmon.

Mac Dowell et al. (2017, p. 248) argue that CCU should be encouraged when and only when it delivers the same service at the same price with lower emissions. As a criterion for the Finnfjord algae project, however, this is not the main driver. This is a development project, looking at options and ways to reduce costs and optimise production processes, and through that to attempt to produce a large part of future fish feed, nutritious biomass, and oil in general from the lowest trophic level in the marine food web. Both the importance and the challenge of the project are thus contingent on further technological developments. Mass cultivation of microalgae for industrial purposes is expensive and high costs have hampered large-scale production of substantial volumes in the past (Eilertsen et al., 2022). Cost reduction, optimisation, and further developments are, therefore, needed to mitigate this and improve viability. At this point, the hope is that the Finnfjord algae project will contribute to cost reductions, upscaled production, and ultimately the realisation of algae-based production of fish fodder, biogas, biofuels, and more.

Concluding remarks

In this chapter, we have argued in line with Morrow et al. (2020) that the important questions in terms of CCU, CCS, CCUS, and DACCS boil down to two essential aspects in relation to the role these technologies can play in climate policy: "*Where does the carbon come from*, and *where does it go?*" From this, we have argued that the three places captured carbon can end up should be seen as a "captured carbon hierarchy" or only as a rule of thumb. Geological storage and long-lived products lead to emission reductions when the carbon comes from the burning of fossil fuels, and to carbon removal if the carbon comes from air or biocarbon.

The contribution from CCU in short-lived products is, as argued by Mac Dowell et al. (2017), harder to assess in terms of emission reductions, depending on the timeframe and what it eventually replaces. *Where the carbon comes from*, however, is as important as where *does* it go, especially for CCU projects. Even if the Finnfjord algae project and algae products are short-lived products by definition, the key is to utilise CO_2 from biomass. Hence, the cleaner the fume, the higher the mitigation. As a CCU project, the potential for GHG reductions is high, especially with further Scope 1 reductions at Finnfjord and by replacing products based on microalgae production.

Given this, we must, therefore, be careful to not cling too tightly to the current categorisations of various carbon capture projects. Doing so could at best limit situated understandings of the potential and actual benefits of innovative projects, and at worst could actually hinder requisite developments by placing genuine CO_2 removal and utilisation projects amongst a litany of others that do not deliver the negative emissions we truly need to achieve climate targets. Furthermore, we must be equally cautious to monitor the developmental trajectory of these projects to ensure that we adopt a pragmatic approach, adapting definitions when and where appropriate. While many CCS, CCU, CCUS, and DACCS projects currently in operation and planned for the future are rightly treated with scepticism, and compelling arguments are put forth in the Open Letter from CIEL (2021), there is some scope to advance specific forms of CCU that limits the massive emissions linked to hard-to-mitigate industrial activities that are not on the verge of being rapidly phased out within dominant political economic systems.

Notes

1 CDR options include afforestation, soil carbon sequestration, bioenergy with carbon capture and storage (BECCS), wetland restoration, ocean fertilisation, ocean alkalinisation, enhanced terrestrial weathering, and direct air capture and carbon storage (DACCS) (IPCC, 2022b, p. 621).

2 IPCC AR 6 defines *net zero emissions* and *greenhouse gas neutrality* the following way:

> Net zero CO2 emissions' is defined in AR6 as the condition in which anthropogenic CO2 emissions are balanced by anthropogenic CO2 removals over a specified period. Similarly, "net zero GHG emissions" is the condition in which metric-weighted anthropogenic GHG emissions are balanced by metric-weighted anthropogenic GHG removals over a specified period. The quantification of net zero GHG emissions thus depends on the GHG emissions metric chosen to compare emissions of different gases, as well as the time horizon chosen for that metric.
>
> (IPCC, 2022b, p. 242)

3 IPCC's Sixth Assessment Report assessed 1202 scenarios of which 80% became available after SR1.5. They differ to some extent in the following: Global-modelled pathways falling into the lowest temperature category of the assessed literature (C1, Table SPM.2) are on average associated with a higher median peak warming in AR6 compared to pathways

in the same category in SR1.5. In the modelled pathways in AR6, the likelihood of limiting warming to 1.5 °C has on average declined compared to SR1.5. This is because GHG emissions have risen since 2017, and many recent pathways have higher projected emissions by 2030, higher cumulative net CO_2 emissions, and slightly later dates for reaching net zero CO_2 or net zero GHG emissions (IPCC, 2022, p. 21).

4 REDD' stands for "Reducing emissions from deforestation and forest degradation in developing countries. The '+' stands for additional forest-related activities that protect the climate, namely sustainable management of forests and the conservation and enhancement of forest carbon stocks" (UNFCCC, 2024, p. 1). https://unfccc.int/topics/land-use/workstreams/reddplus

5 Centre for International Environmental Law. URL: www.ciel.org/wp-content/uploads/2021/07/CCS-Ad_The-Hill-Times_FINAL.pdf (accessed 27 January 2023).

6 Centre for International Environmental Law. URL: https://below2c.org/2021/07/carbon-capture-and-storage-ccs-a-death-sentence-for-the-planet/ (accessed 27 January 2023).

7 European Commission. https://climate.ec.europa.eu/eu-action/carbon-capture-use-and-storage_en (accessed 13 July 2022).

8 NO_x, however, is not included in Scope 1 but may be reported separately. See the WBCSD/WRI GHG protocol at URL: https://ghgprotocol.org/sites/default/files/standards/ghg-protocol-revised.pdf (accessed 28 August 2023).

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8 Black is the new green

Sustainable diffusion of Innovation

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The Finnfjord algae project has been labelled a carbon capture and utilisation (CCU) project as it holds significant promise in converting CO_2 into biomass. Distinct from carbon capture and storage (CCS), which focuses solely on trapping and storing CO_2 in underground geological formations, CCU goes a step further, presenting an economic incentive through the potential monetisation of products, services, and technologies derived from CO_2 capture (Friedlingstein et al., 2020; Stocker, 2014; Styring et al., 2011). This approach not only helps reduce point source greenhouse gas emissions but also creates value by turning a harmful waste product into a resource. However, a pivotal concern about CCU is its potential to only delay the eventual CO_2 emission, rather than permanently sequestering it. This has raised questions from scholars in different fields about its long-term impact, with a common perspective that the broader environmental implications of deploying CCU at scale still require comprehensive scrutiny (Olfe-Kräutlein, 2020; Roy et al., 2023).

In the realm of CCU, carbon is captured from the end of one value chain and channelled to the beginning of another. In the context of Finnfjord, primarily a ferrosilicon manufacturer for the European market, the carbon is captured at the end of the ferrosilicon manufacturing value chain and then channelled to growing microalgae. In exploring innovations for sustainability transition, the transformation of CO_2 into diverse products via microalgae cultivation emerges (Mobin et al., 2019; Pulz & Gross, 2004). The dried biomass of these algae possesses intriguing potential. These single-celled algae, called diatoms, are unique for their ornate, glass-like silica-based cell walls, often called frustules. With their intricate patterns and uniformly spaced pores, they are suitable for various applications ranging from energy to aquaculture (Eilertsen et al., 2021). As a type of phytoplankton, diatoms not only play a critical role in carbon sequestration but also contribute to the world's oxygen production, underscoring their ecological importance (McQuatters-Gollop et al., 2011; Omar et al., 2023).

While the microalgae project at Finnfjord embodies sustainable innovation, a thorough examination of its broader implications is essential to label its widespread application as sustainable. However, some challenges remain: while microalgae cultivation offers a promising strategy to curb carbon emissions, utilizing the cultivated algae raises questions, particularly regarding its potential benefits and drawbacks, given

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various factors such as environmental impact and resource utilization. Therefore, by outlining the concepts of sustainable innovation and diffusion, this chapter delves deeper into how this innovative effort can be diffused into different products. It provides insights into whether diffusion is sustainable depending on the method through which the diatoms are utilised or rather, on the mitigation potential of the technology.

Sustainable innovation

An innovation is defined as "idea, practice or object that is perceived as new by an individual or other unit of adoption" (Rogers, 1983, p. 11). In today's rapidly evolving technological landscape, the acceleration of technological change has become a hallmark.

Over time, many forms of environmentally friendly behaviours came to be considered as innovations which in turn meant that they could be studied from a diffusion and adoption perspective (Darley & Beniger, 1981). The concept of sustainable innovation shares several terms with the phenomena, including many similarities and minor differences. Prevalent in the discourse, are concepts such as "environmental innovation," "eco-innovation," "circular economy," "sustainability-oriented innovation," and "green innovation" (Adams et al., 2016; Franceschini et al., 2016; Schiederig et al., 2012). These terms collectively represent a multidimensional approach to understanding innovation within the context of sustainability, offering a rich landscape for academic exploration.

For example, Zubeltzu-Jaka et al. (2018) refer to "green innovation," "environmental innovation," and "eco-innovation" as synonymous terms, insinuating that they include activities whose ultimate objective is environmental protection. One of the most referenced definitions of "eco-innovation" is provided by Kemp and Pearson (2007, p. 7) who define eco-innovation as

> the production, assimilation or exploitation of a product, production process, service or management or business method that is novel to the organisation (developing or adopting it) and which results, throughout its life cycle, in a reduction of environmental risk, pollution and other negative impacts of resources use (including energy use) compared to relevant alternatives.

This comprehensive definition, thus, places emphasis on not only the novelty of innovation but also particularly, the inputs, outputs, and life-cycle impacts of the innovation.

It should also be noted that sustainability-oriented innovation is often used synonymously with sustainable innovation (Hansen & Große-Dunker, 2013). Thus, according to Adams et al. (2016) and Hansen and Große-Dunker (2013), sustainability-oriented innovation is best known as the intentional creation or improvement of new products, services, processes, or practices that aim to enhance environmental and/or social benefits in addition to economic returns. In addition, Axtell et al. (2000, p. 266) acknowledge that sustainability-oriented innovation is therefore "a broader and more complex concept."

Furthermore, the concept of sustainable innovation includes ecological improvements but considers into account a firm's economic and social aspirations and goals.

This holistic perspective means that, rather than focusing on short-term profits, stakeholders place expectations on firms to convene at a triple bottom line of environmental, economic, and social value creation (Freudenreich et al., 2020). Fichter (2005, p. 138) provides a concrete definition of sustainable innovation, conceptualising it as:

> the development and implementation of a radically new or significantly improved technical, organisational, business-related, institutional, or social solution that meets a triple bottom line of economic, environmental and social value creation. Sustainable innovation contributes to production and consumption patterns that secure human activity within the earth's carrying capacities.

In addition, Kemp and Pearson (2007, p. 6) argue that the determinant of whether an innovation is an eco-innovation is: "that its use is less environmentally harmful than the use of relevant alternatives."

In conclusion, according to Halila (2007) and Kemp and Pearson (2007), the use of eco-innovation may or may not aim to reduce environmental harm, due to the fact that eco-innovations might be motivated to achieve business goals such as reducing costs or enhancing product quality. However, sustainable innovations have been challenged by greater financial risks, shareholder uncertainty, larger investments, and to have more regulations (Jinzhou, 2011). Most of these innovations also end up in small-market niches (Clausen & Fichter, 2019), therefore, creating additional barriers for consumers and companies to embrace such innovations (Karakaya et al., 2014). Nonetheless, there is more societal pressure on organisations to move in a sustainable direction, therefore, incentivising them to develop and adopt sustainable innovations as a basic requirement to hold legitimacy (H.-C. Li et al., 2017) and secure their social licence to operate (Bräuer-Provasnek & Sentic, 2016). Moreover, innovations focusing on sustainability benefits will produce spillover effects during the diffusion phase potentially generating a greater competitive advantage for organisations (Montalvo, 2006; Rennings, 2000). During the diffusion process, new uses and users may be found and thus the characteristics of the innovation and the way of how it is used might also change (Kemp & Pearson, 2007).

Olfe-Kräutlein (2020) argues that CCU technology can be considered as an example of sustainable innovation with an intention of having scalable positive impacts on the economy, society, and environment. Cultivating diatom algae can be looked at as a CCU initiative, since carbon is used in photosynthesis, thus this chapter accepts novel ways of cultivating and harvesting diatom algae as a sustainable innovation. However, given that the effect of an innovation determines its sustainability position, also the way that the innovation is diffused should be sustainable. This means that the utilisation of the diatom algae is critical.

Sustainability of innovation diffusion

Within the CCU framework, the principles of Rogers' Diffusion of Innovations theory may offer valuable insights (Rogers, 2003). Diffusion, within this framework, encapsulates the journey of CCU technologies from mere conceptualisation to their widespread acceptance and implementation across varied industries and regions (Mac Dowell et al., 2017). This process isn't merely about the technological adoption; it equally emphasises the proliferation of knowledge, fostering awareness, and cultivating a collective recognition of CCU as an essential solution to carbon emissions (Aresta et al., 2013).

Simultaneously, as diffusion strategies ensure CCU technologies gain traction, the focus shifts to utilisation. This is the transformative phase where captured CO_2 transitions from being a waste product to a valuable resource (Sundaram et al., 2023). The actualisation of this phase sees CO_2 being harnessed for the production of chemicals, fuels, and building materials, and even for processes like enhanced oil recovery.

In essence, Rogers' theory paints a landscape where diffusion sets the stage, creating an environment ripe for CCU technologies' acceptance, while utilisation embodies the tangible, beneficial actions stemming from that acceptance (Mac Dowell et al., 2017).

Rogers defines diffusion as the "process by which an innovation is communicated through certain channels, over time among the members of a social system" (Rogers, 1983, p. 5). While Rogers's innovation theory is fundamental when understanding how innovations diffuse, this framework may benefit from a discussion when it comes to investigating the adoption of "sustainable innovations" (Driessen & Hillebrand, 2002; Karakaya et al., 2014).

According to Rogers (1983), five elements determine between 49% and 97% of the variation in diffusion: (1) *relative advantage:* refers to the degree of how much better an innovation is perceived than the idea it replaces. The degree of relative advantage can be measured in several ways, which could include economic terms, convenience, satisfaction, and social prestige factors. With ordinary diffusion of innovation, the perception of advantage is often cantered around economic benefits, convenience, or increased social prestige (Rogers, 2003). However, with sustainable diffusion, it focuses on the knowledge of a product's real and positive environmental impacts (Hargreaves, 2011). This can incentivise adoption among environmentally conscious consumers, although proving and communicating these impacts can be challenging (Hargreaves, 2011). Relative advantage also extends to environmental benefits such as reduced emissions or resource conservation, which may appeal to those valuing sustainability (Klewitz & Hansen, 2014). (2) *Compatibility:* refers to the degree of how an innovation is seen as consistent with existing values, past experiences, and needs of potential adopters. If the innovation or the idea is not compatible with current values or norms within the social system, the adoption process will take longer for the innovation, if compared to one that is compatible. For an incompatible innovation to be adopted, it often requires the adoption of a new value system. Innovations that fit well with potential adopters' existing values and needs are more quickly adopted (Rogers, 2003). With the case of sustainable diffusion of innovations, adoption is potentially slow, as adopters are typically required to embrace new values or behaviours such as environmental responsibility or responsible consumption (Hargreaves, 2011).

(3) *Observability*: refers to the extent to which the benefits and outcomes of an innovation are visible and easily noticeable to potential adopters. In the context of diffusion theory, the more easily an innovation's positive impact can be observed and understood, the more likely it is to be adopted by individuals and organisations (Rogers, 2003). However, when it comes to sustainable innovations, observability can present unique challenges. Many of the benefits of sustainable innovations, such as reductions in carbon emissions or resource conservation, might not be immediately visible or easily quantifiable. The positive environmental impact of a sustainable innovation can be complex, multifaceted, and often occurs over an extended period, making it less observable compared to more immediate traditional benefits (Hargreaves, 2011). This lack of immediate observability can hinder the adoption of sustainable innovations. Potential adopters may struggle to recognise the long-term benefits, especially if these benefits are not directly evident or easily measurable in their everyday experiences. Communicating the long-term environmental and social benefits of sustainable innovations becomes crucial in overcoming the observability challenge (Klewitz & Hansen, 2014). (4) *Complexity*: refers to the degree of how an innovation is seen as difficult to understand and use. Some innovations are widely understood by members of a social system while others are more complex and will be adopted more slowly. New ideas that are easier to understand will in general be adopted more rapidly compared to innovations that require the user to develop new skills or understandings: less complex innovations, or those easily understood by potential adopters, diffuse more quickly (Rogers, 2003). Sustainable innovations may often be perceived as more complex due to unfamiliar technologies or misconceptions sustainability, necessitating educational efforts (Klewitz & Hansen, 2014). (5) *Trialability:* refers to the degree of how an innovation can be tried and experimented with. New ideas will be adopted more rapidly if they can be tried before adoption compared to innovations that cannot. An innovation that is triable reduces the uncertainty for the potential adopter, as it is possible for the individual to learn by doing: innovations that can be experimented with before adoption also spread more quickly (Rogers, 2003). The ability to try sustainable products can reduce uncertainty and encourage adoption, especially since benefits may not be immediately obvious (Klewitz & Hansen, 2014).

The diffusion of innovations, as conceptualised by Rogers, primarily considers how and why certain innovations spread across social systems and why some innovations are adopted while others aren't (Rogers, 2003). However, when integrating this theory with sustainability, additional criteria may become essential to ensure that innovations not only serve functional or efficiency-based needs but also contribute holistically to the well-being of both the environment and society. Sustainable diffusion refers to the dissemination and adoption of practices, technologies, or innovations that strike a balance between utility and the overarching principles of sustainability. To understand this better, other aspects must be taken into consideration. For example, the aspect of (6) *ecological integrity* which considers that sustainable innovations should ideally have a minimal negative impact on the environment and, if possible, provide ecological benefits (Brundtland, 1987). There is also the aspect of (7) *economic viability*: since sustainable innovations should demonstrate long-term economic viability, ensuring that they remain beneficial and feasible in the long run (Elkington, 1997). In addition, (8) *social aspects* are present with an expectation that innovations should be accessible to, and benefit, all sections of society, promoting overall social well-being (Sen, 1999). Additionally, (9) *cultural and ethical values* come into consideration as innovations need to: align with, or at the very least, respect the cultural and ethical values of its potential adopters (Shove, 2010). Given the rapidly changing ecological and social landscapes, innovations that are rigid might become obsolete. Adaptive capacity, thus, ensures that innovations can evolve based on changing circumstances (Adger, 2003). Finally, it is also worth mentioning that sustainable innovations often thrive when they are the result of inclusive participation and collective efforts (Ostrom, 1990).

In the remainder of this chapter, we will discuss several avenues of diffusion for the microalgae cultivated at Finnfjord. We will discuss their properties and the potential products that present a challenge with regard to the sustainable diffusion of this innovation.

Method

This study explores the sustainable diffusion of products derived from diatoms. Rooted in a qualitative research design, our examination is steered by four potential diffusion pathways highlighted by the Finnfjord research group. The foundation of our analysis, however, rests upon a literature review that narrows down on the most interesting areas of application for diatoms.

Data for this study was, as such, sourced from a spectrum of scholarly articles. Key platforms included Google Scholar, Web of Science, and Scopus, complemented by data from authoritative governmental sources. Selection criteria prioritised potential advantages of integrating diatoms into diverse products. Fundamental to our methodology is the understanding of diffusion dynamics. We evaluated each product's relative advantages, compatibility, observability, integration complexity, and trial feasibility. To make sure that diffusion is sustainable, we strived for a complete sustainability lens. The data had to resonate with principles of ecological integrity, economic feasibility, societal welfare, and ethical alignment. An additional layer of scrutiny was applied to assess CO_2 emissions throughout the product's life cycle. Through this multidimensional lens, we strive to unveil the opportunities and obstacles associated with the sustainable propagation of diatom-based products.

Context and background

The study at hand is situated within the collaborative exploration between UiT-The Arctic University of Norway and Finnfjord AS. This partnership has investigated the potential of utilising factory emissions as a resource to cultivate diatoms, with

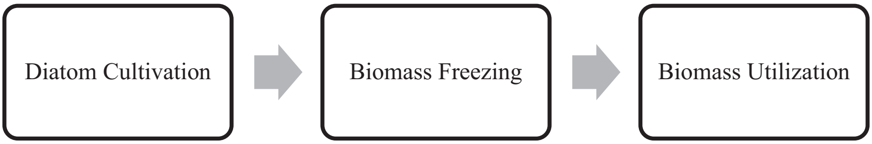

Figure 8.1 General model for production chain of diatom biomass.

the outlined process depicted in Figure 8.1, which delineates the sequential steps in the production chain of diatom biomass.

Diatom cultivation

At its core, the cultivation of diatom algae at Finnfjord operates as a carbon capture initiative. Factory emissions are intentionally channelled through pipes into algae tanks, where photosynthesis takes place (Eilertsen, this publication). The efficacy of CO_2 uptake during this process is contingent on the rate at which emissions are introduced into the tanks; a slower introduction correlates with increased CO_2 uptake. For instance, while test productions have shown a 35% uptake, a more deliberate introduction of emissions can enhance uptake to up to almost 100% (Eilertsen et al., 2022). The goal is absorption of half of the Finnfjord Ferrosilicon Factory CO_2 emission of 300,000 tons. This would significantly contribute to the local CO_2 emission. Furthermore, NO_x emissions, typically regarded as pollutants, have been found to be beneficial for algae, potentially resulting in an annual algae biomass production ranging from 16,500 to 47,000 tonne (Eilertsen et al., 2022).

In their natural form, diatom algae produce 20% of the world's oxygen (McQuatters-Gollop et al., 2011; Omar et al., 2023). Upon their life-cycle completion, diatoms descend to the water body's bottom, effectively sequestering absorbed carbon into the sediment – a process recognised as the "biological pump." Carbon relegated to deep ocean sediments is thus sequestered, distanced from atmospheric interaction for extensive periods ranging from hundreds to thousands of years. This efficient sequestration mechanism, coupled with negligible water footprint, underscores algae cultivation's environmental sustainability (Nagappan et al., 2021). Previous research suggests that water footprints linked to microalgae cultivation could be diminutively reduced by approximately 90% (Pugazhendhi et al., 2020), accentuating its environmentally conscientious water use.

Microalgae cultivation is characterised by its minimal nutrient requirements, permitting growth in various mediums including seawater and wastewater (K. Li et al., 2019). Further, innovative techniques have been used to cultivate algae such as efficiency and reducing the costs associated with the mass cultivation of photoautotrophic microalgae. One significant innovation is in the realm of illumination, which is crucial for the synthesis of biomass. Strategies have been devised to enhance illumination efficiency, leading to a reduction in the energy costs pivotal to algae cultivation (Eilertsen et al., 2023). This research has shown that blue flashing lights not only stimulate the growth of diatoms but also facilitate a biovolume production comparable to that achieved with blue linear light at equivalent maximum intensities (Eilertsen et al., 2023). The use of larger diatom cells was also a novel approach, since the minimise self-shading, which in turn, enables more effective utilisation of light (Eilertsen et al., 2023). The innovation extends to the application of technology designed to optimise microalgae cultivation. By focusing on variables such as algae photosynthetic efficiency, the spectrum and intensity of light, and the absorption and scattering of light in the cultivation medium, novel technological applications and processes are applied. These are anticipated to significantly advance the field of microalgae cultivation. Therefore, innovations in microalgae cultivation techniques not only contribute to economic competitiveness but also hold promise in advancing climate mitigation efforts and promoting a circular economy. By harnessing the potential of microalgae to capture carbon dioxide and generate valuable bio-based products, sustainable innovation in this domain becomes a vital pillar of addressing pressing environmental challenges while simultaneously fostering economic growth.

Biomass freezing

Post-cultivation, the harvested algae are subsequently extracted from the tanks and are subjected to freezing for preservation over extended durations. It is imperative to note that the only CO_2 emissions generated during the freezing process are those associated with electricity consumption. The final consideration, and the primary focus of this paper, pertains to the CO_2 emissions resulting from the eventual utilisation of the biomass.

Biomass utilisation

Biomass utilisation includes processes for converting biomass into products such as foods, fuel, chemicals, and electricity (Ouchida et al., 2016). This chapter focuses on four products; biofuel, battery production, fish feed, and photovoltaics as will be explained next.

Biofuel

The transformation from diatoms to fuel can be achieved through either thermochemical or biochemical processes (Mobin et al., 2019; Zheng et al., 2023). On the one hand, thermochemical conversion leverages heat, producing syngas and subsequently generating fuels, alongside heat and electricity. Common methods within this conversion include gasification, liquefaction, and pyrolysis (K. Mishra et al., 2023). On the other hand, biochemical conversion encompasses a combination of biological and chemical processes, such as anaerobic digestion, fermentation, and esterification (Osman et al., 2021).

Although diatom-based biofuels might witness substantial CO_2 emissions during oil extraction and biodiesel conversion (Saranya & Ramachandra, 2020), on the consumption side, these biofuels are often perceived as carbon-neutral. This

Table 8.1 Biofuel.

Criteria	*Fossil fuels*	*Conventional biofuel production*	*Diatom-based biofuel production*
Resource sustainability	Finite resource; extraction becomes more difficult and environmentally damaging over time	Uses food crops (corn and sugarcane), leading to food versus fuel debate – requires large tracts of arable land, potentially causing deforestation	Diatoms are microalgae that don't compete with food crops for arable land. Can be cultivated in non-arable areas, including wastewater
Water usage	Water is used extensively in the extraction and processing of fossil fuels	Traditional biofuel crops require substantial amounts of water for irrigation	Diatom cultivation can occur in saline or wastewater, reducing freshwater usage
Environmental impact of resource acquisition	Extraction processes (like fracking and drilling) cause significant environmental degradation. Risk of oil spills and other environmental disasters	Use of pesticides and fertilisers in crop cultivation can cause environmental harm. Land-use changes for biofuel crops may result in loss of biodiversity	Minimal use of chemicals in diatom cultivation. No need for significant land-use changes, protecting biodiversity
Carbon footprint	Highest carbon footprint due to high emissions during combustion and release of methane during extraction	The cultivation, harvest, and processing of traditional biofuel crops can be energy intensive. Not all biofuels offer significant carbon emission reductions	Diatoms sequester carbon during growth, potentially offering a lower carbon footprint. Energy-efficient harvesting and processing methods are being developed
Energy return on energy invested (EROEI)	Generally high EROEI, but diminishing as easier-to-access deposits are depleted	EROEI varies but can be low for some biofuel crops	Preliminary studies suggest that diatoms might offer a favourable EROEI, but further research is needed
Waste generation	Produces high amounts of waste, including CO_2, ash, and other pollutants	Crop residues and processing by-products need careful management to minimise environmental impact. Produces similar CO_2 through combustion as fossil fuels	Diatom cultivation may produce less waste, and by-products can potentially be used for other applications. However, combustion delivers CO_2 similar to fossil fuels

(*Continued*)

Table 8.1 (Continued)

Criteria	*Fossil fuels*	*Conventional biofuel production*	*Diatom-based biofuel production*
Land use	Extraction sites can cause large-scale environmental disruption, including habitat destruction	Requires significant amounts of arable land, often leading to land-use conflict and deforestation	Can be produced in ponds, tanks, or bioreactors, being more land effective
Biodiversity impact	Habitats are often destroyed or degraded at extraction sites, negatively impacting biodiversity	Monoculture plantations of biofuel crops can negatively impact biodiversity	Cultivation in controlled environments can mitigate impacts on natural biodiversity
Social impact	Industry jobs are often dangerous and can cause community displacement due to extraction activities	Land acquisition for large plantations might lead to displacement of local communities	Smaller-scale, decentralised diatom cultivation facilities may offer local employment without mass displacement

is because the CO_2 they emit upon combustion is approximately equal to the CO_2 consumed during growth (Chisti, 2007; Searchinger et al., 2008). The CO_2 emissions from diatom-derived biofuels are comparably aligned with fossil fuels (Priya et al., 2022; Sethi et al., 2020). While the utilisation of such biofuels may aid in carbon emission reduction, the production phase remains multifaceted and warrants scrutiny (Sethi et al., 2020). As critics of CCU argue that it merely postpones emissions without offering true mitigation (Markewitz et al., 2012), the perceived carbon-neutral stance of microalgae-derived biofuels thus necessitates an in-depth evaluation (Bradley et al., 2023). It is, therefore, essential to balance the CO_2 intake during microalgal growth against the emissions produced during biofuel processing to achieve a comprehensive understanding of the carbon dynamics associated with these biofuels (Gupta & Hall, 2011; Hall et al., 2014; Khan et al., 2023; Murphy & Hall, 2010; Sundaram et al., 2023).

Battery production

In the evolving landscape of battery production, the incorporation of diatoms presents both potential benefits and challenges. There is a burgeoning global demand for innovative solutions like Li-ion batteries for diverse applications, from electronics to vehicles (Etacheri et al., 2011; Tarascon & Armand, 2001). Traditional carbon coatings in batteries, known for their capacity limitations and stability challenges (Winter et al., 1998), are seeing potential replacements with microalgae, a pioneering approach offering improved performance parameters (Xia et al.,

Table 8.2 Comparison between conventional and diatom-based battery production.

Aspect	*Conventional batteries*	*Diatom-based batteries*
Resource cost	Costs fluctuate due to reliance on graphite and scarce and expensive metals (e.g., lithium, cobalt)	Cultivated, renewable diatoms potentially lead to lower and stable resource costs
Production cost	Well established but can be costly, given the use of expensive materials and energy-intensive processes	Substantial initial costs for further R&D and setting up new production facilities but when cultivated through factory fumes, it is cost-efficient
Operational efficiency	Efficiency and lifespan are often material limited, leading to more frequent replacements	Enhanced efficiency and capacity might result in longer life cycles and less frequent replacements
Waste and recycling	Complex and costly recycling and disposal processes due to toxic materials	Biodegradable and non-toxic diatoms facilitate cost-effective waste management and recycling
Market development	Benefits from established markets, supply chains, and consumer trust	Facts challenge in market acceptance and need investment in consumer education and market development
Complexity in production	Complex and energy-intensive mining and refining processes with established technologies	Less complex cultivation and engineering process but requires new technologies and expertise
Regulatory compliance	Subject to regulations with well-established approval pathways	May face stringent regulatory scrutiny and need extensive testing and certification
Long-term viability	Rising costs of materials and environmental compliance may impact long-term viability	Promising long-term economic benefits due to environmental and operational advantages
Risk and uncertainty	Known risks with established mitigation strategies	Significant risk and uncertainty due to being a new technology

2016). Notably, diatom frustules, subjected to minimal processing, have demonstrated their prowess as efficient anodes in Li-ion batteries, indicating not only enhanced capacity but also reduced electrolyte decomposition issues (Lin et al., 2022). When assessing the environmental footprint during the operational phase, batteries harnessing diatom frustules as anodes don't contribute to direct CO_2 emissions, unlike some traditional counterparts. A holistic life-cycle assessment suggests that the potential environmental merits of diatom-based batteries, especially when considering longevity and performance enhancements, might counterbalance the initial production emissions. Additionally, the opportunity to recycle diatom biomass post-lipid extraction further underscores the sustainability prospects of this approach (X. Li et al., 2009; Zhou et al., 2007).

Fish feed

Microalgae-based products, particularly fish feed, have showcased a significantly reduced carbon footprint relative to their conventional counterparts. Taelman et al. (2013) affirmed that microalgae-sourced fish feed exhibited a substantially diminished carbon footprint when compared to pilot-scale fish feed. These findings are bolstered by the intrinsic capacity of microalgae to sequester carbon dioxide, with evidence indicating a capture rate of up to 1.8 kg of carbon dioxide per kilogram of microalgae (Preedy, 2021). Additionally, the cultivation requirements for microalgae are minimalistic. Given their adaptability to thrive in seawater or wastewater, their water footprint is virtually negligible (K. Li et al., 2019). This assertion aligns with Nagappan et al. (2021), suggesting a near-zero water footprint, and with Pugazhendhi et al. (2020) emphasising the potential to curtail the water footprint of microalgae by 90%. Further, Sánchez et al. (2003) underscored the environmental advantage of microalgae cultivation, elucidating its potential to reduce atmospheric carbon emissions, especially when scaled up.

Using diatom algae in fish feed further could replace the need for soy, which is currently grown in the Amazon rainforest (Eilertsen et al., 2022; Rotabakk et al., 2020). The Amazon rainforest is crucial for the environment for reasons, such as biodiversity, carbon sequestration, and climate regulation, and faces the dual threats of deforestation (Malhi et al., 2008). Diatoms also play a significant role in global oxygen production, with marine phytoplankton, including diatoms, being vital contributors to the world's oxygen through photosynthesis (Field et al., 1998).

The Finnfjord CCU project is noteworthy for its use of algae that can naturally capture CO_2. As a vital CO_2 absorber, this effort helps reduce the pressure on the Amazon. Today, sardine-based maritime oil is a component in fish feed (Lall & Dumas, 2022). However, transporting sardines to Norway releases CO_2 (Johansen et al., 2022). Therefore, using algae for marine products might be a more efficient way of using marine resources (Eilertsen et al., 2022).

Diatom algae serve as a natural nutritional source for marine species such as salmon. Their nutrient profile, enriched with omega 3 and 6 fatty acids, plays a pivotal role in fish development and growth (Eilertsen et al., 2022). A notable observation by Eilertsen et al. (2021) reveals a lower prevalence of salmon lice in specimens fed with diatom algae as opposed to those sustained on traditional feed.

Elaborating on the previously mentioned study by Eilertsen et al. (2021), a detailed analysis of salmon diets incorporated variations like diatom supplements, fish oil, *Calanus* sp. oil, and rapeseed oil. Following an experimental period, salmon from divergent diet groups were exposed to salmon lice copepodites. Remarkably, those on the diatom-enriched regimen exhibited fewer lice infestations. Yet, the underlying cause remained elusive, as the unique fatty and amino acid profiles did not provide a discernible reason. The evidence pivoted toward a potential anti-lice component in diatoms or a diatom-induced deterrent production within the salmon, although the precise mechanism necessitates further exploration (Eilertsen et al., 2021).

Therefore, if algae-based fish feed can significantly replace traditional feed, it might significantly reduce emissions from feed production (Onyeaka et al., 2021; Tham et al., 2023).

Table 8.3 Fish feed.

Criteria	*Conventional fish feed*	*Diatom-based fish feed*
Nutritional content	– Requires addition of various nutrients, which can be synthetic or sourced from fish meal and fish oil – Nutritional content can be inconsistent	– Naturally rich in essential fatty acids, proteins, and other nutrients – Provides a balanced and consistent nutritional profile
Sustainability	– Over-reliance on fish meal and fish oil is unsustainable. Production of synthetic nutrients can be energy intensive	– Diatoms can be sustainably cultivated with a lower environmental impact
Feed conversion ratio (FCR)	– FCR can vary and is often not optimised, leading to waste and inefficiency	– High nutritional content and digestibility of diatoms can improve FCR
Environmental impact	– Production and sourcing contribute to overfishing, habitat destruction, and carbon emission	– Diatom cultivation has a lower environmental footprint and can contribute to carbon sequestration
Cost	– Volatile prices of fish meal and fish oil impact cost. Synthetic additives can also be expensive	– Diatom cultivation systems, once established, can offer a potentially cheaper and steady source of high-quality feed
Health impact on fish	– Might not optimally support fish health and growth, necessitating supplements or medications	– Diatoms support fish health due to their rich nutritional profile, reducing the need for supplements or medications
Disease and parasite management	– Does not inherently contribute to disease or parasite management	– Diatoms might help manage aquaculture challenges like lice infestations in salmon farms
Complexity of production	– Production process can be complex due to the need for various ingredients and nutritional additives – Managing sustainability is also challenging	– Initial setup of diatom cultivation systems can be complex, but the process can be streamlined once established. Complexity also lies in maintaining optimal conditions for diatom growth

Photovoltaics

Diatom frustules, with their unique structures, can scatter light and potentially enhance solar cell performance by improving light absorption and conversion efficiency (Morales et al., 2019). Integrating diatoms into solar cells is still in its nascent stages, with challenges like ensuring diatom durability in solar environments (Uwizeye et al., 2021; Yan et al., 2018). As of 2021, the commercial use of diatoms in photovoltaics remains

Table 8.4. Photovoltaic.

Criteria	*Conventional PV production*	*Diatom-based PV production*
Material efficiency	Uses crystalline silicon, CIGS, or CdTe, requiring resource-intensive processes. Availability and cost of materials can be limiting	Inherent nanostructures of diatoms enhance light absorption without complex fabrication. Abundant and easily harvested, providing a sustainable material source
Energy input	High-energy input needed for silicon PV cells production and installation. Energy payback time (EPBT) is often cited as a drawback	Lower energy needed for material extraction and processing, potentially leading to a shorter EPBT
Toxicity and environmental impact	Some thin-film technologies use toxic materials posing disposal and recycling challenges – Silicon tetrachloride, a by-product, is hazardous	Diatoms are non-toxic, reducing environmental and health risks associated with production and disposal
Light absorption and efficiency	Limitations in light absorption efficiency. Improvements often result in increased costs	Nanostructures of diatoms can trap and utilise light efficiently, potentially increasing energy conversion efficiency without significant additional costs
Manufacturing complexity	Silicon cell manufacturing involves complex processes; thin-film technologies, while simpler, have their own challenges	Diatom-based PV cells might utilise simpler, bio-inspired processes, reducing complexity and costs
Waste and recycling	Contains materials that are challenging to recycle, contributing to e-waste	Potentially more recyclable due to biological origin, reducing e-waste and facilitating circular economy approaches
Material scarcity	Relies on rare or scarce materials, causing sustainability and price volatility concerns	Diatoms are abundant, offering a solution to material scarcity issues
Complexity of production	Production processes are intricate and sophisticated, requiring advanced technology and expertise. Thin-film technologies simplify production but introduce new challenges	Production might be less complex due to the biological nature of diatoms, but optimising their use in PV cells will require specialised knowledge and technical competence

largely experimental (Chen et al., 2022). Diatoms showcase intricate nanostructures surpassing the capabilities of many advanced synthetic procedures (M. Mishra et al., 2017). Growing diatoms requires equipment, water, nutrients, and often artificial light, but they absorb CO_2 during photosynthesis, offsetting some emissions (Najiha Badar et al., 2021). Once grown, extracted silica frustules from diatoms undergo processes like drying and chemical treatment, which consume energy (The Norwegian University of Science and Technology (NTNU), 2012). The incorporation of diatom material into solar cells varies based on the solar technology and integration method (Huang et al., 2015; Jeffryes et al., 2011). Solar cells with diatoms might have CO_2 emissions comparable to conventional solar cells during usage, which is nearly zero, while end-of-life handling could add to emissions (Muteri et al., 2020; Wang et al., 2022). The CO_2 emissions from each stage should be weighed against potential benefits, like increased efficiency (Huang et al., 2015). Leveraging renewable energy and biotech advances can minimise these emissions. Detailed life-cycle analyses are necessary for precise CO_2 emission assessments (Yang et al., 2022).

Discussion

The sustainable diffusion of diatoms across various applications holds significant promise, primarily when evaluated through Rogers' diffusion of innovations theory (Relative Advantage, Compatibility, Observability, Complexity, Trialability) and extended to encompass ecological integrity, economic viability, societal welfare, and cultural and ethical norms.

Relative advantage: One of the key driving forces behind the adoption of an innovation is its relative advantage over existing alternatives. In the four product categories we have examined, the use of diatoms seems to have some advantage over the traditional product. However, a significant critique lies in the domain of carbon neutrality. Biofuels from diatoms, while deemed carbon-neutral, release as much CO_2 upon combustion as fossil fuels. The reasoning behind the "carbon-neutral" label is that the CO_2 released during combustion was originally absorbed from the atmosphere during photosynthesis, creating a closed loop. Yet, it's crucial to understand that diatoms, through photosynthesis, effectively sequester carbon, removing CO_2 permanently and releasing oxygen. This nuanced difference is pivotal for a well-informed discussion. The observable benefits, although real, need a broader context. Further, diatoms may offer solutions to the challenges faced by traditional carbon-coated batteries. Their enhanced performance in terms of capacity and efficiency serves as a clear relative advantage. The advancements in this field are evident, especially when one considers the growing demand for electric vehicles and renewable energy storage solutions.

The unique nanostructures of diatoms can also enhance the performance of solar cells, tapping into the escalating demand for renewable energy. The observable efficiency improvements in diatom-integrated solar cells provide a measurable advantage over conventional systems.

Compatibility: Diatoms, microalgae with intricate silica structures, represent a congruent fit in the global trajectory towards sustainable solutions. Their multifunctional capabilities span from potential contributions to carbon-neutral vehicle propulsion, to the augmentation of battery efficiency, and even as a contender in aquacultural practices. In every product category, they offer an improvement to an already existing product, with established markets and as such, the compatibility is high.

When it comes to complexity, observability, and trialability: The diatom-based products will inevitably be compared with the traditional products considering these factors. Thus, it is important to which degree the diatom-based product can substitute the established products. As such, the diatoms exhibit considerable potential across various applications, yet the intricate processes involved can impede their broader integration. For successful mainstream adoption, it's imperative that such applications are scalable and undergo thorough validation. Emphasising these trials will mitigate scepticism and diminish potential barriers to adoption. Here the concept of substitution might be useful: Can the sustainable product successfully substitute the established product in terms of complexity, observability, and trialability.

Ecological integrity: In terms of carbon cycling, diatoms excel by actively photolyzing CO_2, bolstering their role as environmental custodians. However, when transitioning diatoms into biofuel applications, it's imperative to assess their long-term impact on carbon sequestration. While diatom-derived biofuels offer a commendable alternative to fossil fuels, potential pitfalls in their carbon balance should be critically examined. The exploration into diatom integration in photovoltaics and battery technology demands a comprehensive ecological assessment to fully appreciate any potential environmental trade-offs. Moreover, in the domain of aquaculture, the introduction of diatom algae as fish feed holds promise, especially as an alternative to the established soy-based feed. Cultivating diatoms for this purpose can promote sustainability in the sector, potentially offering an ecologically balanced feed source that aligns with the aspirations of sustainable aquaculture.

Economic viability: The financial feasibility of diatom-based technologies is critical for their mainstream adoption. In the realm of energy, the increasing demand for renewable sources and efficient storage make diatom applications in both biofuel production and battery enhancement promising. However, the energy-intensive process of biofuel generation calls for a thorough cost–benefit analysis. Similarly, leveraging diatoms for photovoltaics aligns with growing renewable energy trends, but its economic viability needs assessment. In aquaculture, diatom algae's potential as sustainable fish feed could provide economic benefits, given the challenges faced in traditional feed sources. Each pathway demands a detailed financial analysis to ensure its economic soundness amidst evolving market demands.

Societal equity and welfare: The broader societal benefits of diatoms are implicit in their potential applications. Healthier fish stocks due to diatom-based feed, for instance, directly contribute to food security and industry stability. Cleaner energy storage solutions and carbon-neutral combustion also align with societal welfare by promoting a cleaner environment.

Cultural and ethical norms: Diatoms resonate with the global narrative of sustainability, climate change mitigation, and eco-consciousness. Their diffusion aligns well with the ethical mandate to combat climate change and adopt environmentally friendly practices

Table 8.5 outlines a summary of findings for various applications of diatoms when evaluated through Rogers' diffusion of innovations theory.

Table 8.5 Summary of findings.

Diatoms used for	*Relative advantage*	*Compatibility*	*Observability*	*Complexity*	*Trialability*	*Ecological integrity*	*Economic viability*	*Societal equity and welfare*	*Cultural and ethical norms*
Biofuel	Perceived carbon neutrality compared to fossil fuels	Directly compatible with current technology	Effectivity of use can be observed and measured	Comparable complexity to fossil fuels	The effectiveness of biofuels can be easily tested and validated	Lower carbon footprint than fossil fuels. However, CO_2 is out in the atmosphere	High economic viability with market demand for alternative fuels	Societal equity remains unaffected	Ethical concerns centre around the fuel-based tech versus electric; societal discussions regarding energy source sustainability are pertinent
Battery	Addresses challenges posed by traditional carbon-coated batteries	Functionally equivalent to ordinary batteries	Efficiency and capacity enhancements are observable and measurable	Specialised knowledge and techniques may be required for optimal usage and maintenance	Diatom-based batteries can be easily tested and validated for efficiency and capacity	Potentially reduced waste due to longer-lasting batteries	Substantial R&D investment needed; long-term economic viability contingent upon optimisation of performance and reliability	Neutral impact on societal equity	Aligns with international sustainability objectives and ethical standards promoting green technology
Photovoltaic	Enhanced solar cell performance	Compatible with the growing demand for alternative energy sources	Observability of efficiency improvements in energy conversion	Specialised knowledge and techniques necessary for installation and maintenance	The efficiency of diatom-based photovoltaic cells can be easily tested and validated	Reduced carbon footprint and environmental impact with sustainable energy conversion	Requires significant R&D investment; economic viability is subject to performance optimisation and market demand	Provision of cheaper, sustainable energy promotes societal welfare	Ethical considerations align with global sustainability goals and the promotion of renewable energy sources
Fish feed	Diatom-based feed aligns more closely with the natural diet of fish	Direct alignment with natural fish diets	Observable reduction in lice infestation and general improvement in fish health	Comparable complexity to traditional feed options	The effectiveness of diatom-based fish feed can be easily tested and validated	Sustainable alternative contributing to the overall health of marine life	Economic viability dependent on market demand for sustainable fish-feed options	Positive impact on societal welfare through the provision of healthier fish	Aligns with ethical standards promoting sustainability and animal welfare

Conclusion

Finnfjord's algae project exemplifies sustainable innovation through advancing the cultivation of diatom algae which captures and photolyze CO_2. The diatom biomass may then be utilised into valuable products.

Upon scrutinising the sustainability aspects of utilising cultivated diatoms, it is imperative to discern its wide array of application. The discussion in this paper has focused on four product categories and shown that the organic biomass from diatom algae can be beneficial to each of them. Among these, some applications stand out for their dual advantage of sustainability and market potential. For instance, the production of fish feed from diatoms not only presents a sustainable feeding source but also one that is similar in the fish natural diets which again offers better fish health (Eilertsen, Ingebrithsen and Striberny, this publication; Elvevoll and xx, this publication). On the other side, production of biofuel from algae may bring up the classic criticism of CCU that it only delays the emission of CO_2, not removing it completely (Langhelle and Sareen, this publication). The production of photovoltaic and batteries, however, are promising, but need more research and development.

It is crucial to recognise that the sustainability of diatom-based products is inherently tied to the modes of their production and utilisation. Each step, from cultivation to product development and market diffusion, needs to be executed with an unwavering commitment to environmental stewardship, economic viability, and societal benefit. While diatoms indeed offer a promising route for CCU, the degree to which they contribute to climate mitigation as compared to conventional CCS depends substantially on the life-cycle analysis of the resulting products and their respective markets.

Nevertheless, this discussion has shown that innovating on microalgae cultivation may augment climate mitigation efforts and advancing the principles of a circular economy (IPCC, 2018; Olfe-Kräutlein, 2020). In addition, it can bolster the provision of new avenues for various techniques, products, and industries (Bhattacharya & Goswami, 2020; Mahmood et al., 2023). Viewing CO_2 as a continuously renewing, low-cost, and non-toxic resource – thanks to its persistent industrial emissions – presents a potential for a paradigm shift in its management (Eilertsen et al., 2021; Gately et al., 2013). As highlighted by Eilertsen et al. (2021) and Sánchez et al. (2003), large-scale diatom cultivation can significantly cut carbon emissions, highlighting its contribution to climate change mitigation efforts.

Limitations and future research

While the prospects of diatoms appear promising, it is essential to address the limitations of our current understanding: (1) *complex processes*: some diatom applications, particularly in biofuel production, are energy intensive, which might offset their environmental advantages to some extent. (2) *economic feasibility*: the cost implications of large-scale diatom integration, especially in sectors that demand high-energy inputs, remain relatively unexplored. (3) *mechanistic ambiguity*:

Finnfjord's algae project epitomises a compelling iteration of CCU, bringing a spotlight to the viability and sustainability of turning captured CO_2 into valuable products, while contrasting itself from traditional CCS approaches. As elucidated in the introduction, while CCS solely focuses on the containment of CO_2, CCU endeavours further, envisioning CO_2 as a pivotal resource. The Finnfjord initiative embraces this ethos, wherein harvested CO_2 is not merely stored but ingeniously converted into microalgae, particularly diatoms.

Upon scrutinising the sustainability aspects of utilising cultivated diatoms, it is imperative to discern that their applications span extensively, from energy to aquaculture, each bearing distinctive sustainability credentials. Among these, some applications stand out for their dual advantage of sustainability and market potential. For instance, the production of biofuels from diatoms not only presents a renewable energy source but also offers a mechanism for long-term carbon sequestration, thereby aligning with global climate mitigation targets. Furthermore, diatoms' utilisation in creating high-value products like nutraceuticals can foster economic sustainability while contributing to health and wellness.

However, it is crucial to recognise that the sustainability of diatom-based products is inherently tied to the modes of their production and utilisation. Each step, from cultivation to product development and market diffusion, needs to be executed with an unwavering commitment to environmental stewardship, economic viability, and societal benefit. While diatoms indeed offer a promising route for CCU, the degree to which they contribute to climate mitigation as compared to conventional CCS depends substantially on the life-cycle analysis of the resulting products and their respective markets.

To delineate, while CCS provides a straightforward approach to reducing atmospheric CO_2 levels, its impact is predominantly environmental. In contrast, CCU, as embodied by the Finnfjord project, promises not only environmental benefits but also economic value, which is integral to the project's long-term viability and success. Nonetheless, for CCU to be genuinely mitigating and sustainable, the end-use of captured carbon, in this case, the diatoms, should be meticulously chosen to maximise the mitigation potential while ensuring economic feasibility.

Thus, as we evaluate the potential widespread application of Finnfjord's innovative approach, a careful and holistic examination of its environmental, economic, and social implications is paramount. By doing so, we can discern the true sustainability of this endeavour, understanding whether and how it contributes to a more sustainable and resilient future. In steering the diffusion of this innovative effort, prioritising applications that are not only economically viable but also environmentally benign and socially beneficial is imperative. Through this lens, diatoms indeed offer a promising horizon, yet the path to realising their full potential requires navigating through complexities with informed and deliberate choices.

Given the limitations and the vast potential of diatoms, the roadmap for future research should be multifaceted: comprehensive research focusing on the complete life-cycle emissions of diatom-based applications will provide clarity on their net environmental impact. Deeper dives into the cost structures and economic implications of diatom applications will be pivotal in understanding their commercial viability. A focus on the biochemical interactions that grant diatoms their unique properties might not only explain observed phenomena but also unveil new applications. As the world moves more assertively towards sustainability, research should also pivot towards understanding the societal and cultural implications of widespread diatom adoption.

In essence, diatoms, with their inherent advantages, present a promising horizon for a sustainable future. While current research has illustrated their potential, the path ahead signals a nuanced, thorough exploration to harness their capabilities for global betterment. In addition, certain observed benefits, such as the deterrence of lice in salmon fed with diatom algae, are yet to be explained at a molecular or chemical level, leaving room for uncertainties.

Note

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9 Attuning our consumption and food production systems

An environmental virtue ethics approach to algae-based carbon capture and utilisation, and feed use in salmon farming

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Introduction

There is now wide recognition that substantial changes are needed in the way humanity shapes industries and consumes natural resources, given how these activities impact the natural environment and all its inhabitants. In the following, I argue that an environmental virtue ethics approach provides a viable framework with suitable tools to conceptualise and realise this change. A virtue-oriented approach is based on a language that most people are familiar with and, thus, ensures a broad societal appeal. My discussion revolves around the case of a ferrosilicon smelter plant in Northern Norway, where researchers and factory owners have teamed up with the aquaculture industry to utilise carbon dioxide from flue gas to grow algae biomass, which in turn will be made into a nutritious and sustainable fish-feed ingredient. Examining this case through the environmental virtue ethics framework will give us a clearer idea of what it takes to attune our industries and our consumption to the environmental reality we are living in. The takeaway point from this chapter should be that substantial change of the food production systems will require a change in perspective for both industry agents and consumers. I discuss various relevant environmental virtues that both industry agents and consumers should cultivate.

Keywords: Environmental Virtue Ethics, Carbon Capture and Utilisation, Attunement, Environmental Ethics, Industry, Salmon Farming, Aquaculture

Problems and solutions in fed aquaculture

While non-fed aquaculture has become more sustainable and, thus, increased in social acceptance, the same cannot be said of fed aquaculture (Costa-Pierce, 2010). While there has been a shift in feed stuff uses, this has largely been a shift from ocean-sourced protein feeds and oils (a practice that has not been conducted in a sustainable way) to sourcing needed protein feeds and oils from land-based agriculture (Costa-Pierce, 2010). This is also largely true for the Norwegian salmon farming industry. According to Aas et al. (2022), it took 1,976,709 tonnes of feed ingredients to produce 1,467,655 tonnes of salmon in Norway in 2020. This feed was made from 22.4% ocean-sourced ingredients, 73.1% land-based agriculture-sourced ingredients, and, of the remaining share, only 0.4% was produced from

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single cell protein, insect meal, fermented products, and, notably in relation to our case, microalgae (Aas et al., 2022).

While the use of microalgae provides a step towards sustainability, the amount currently being used represents only a small fraction in a mix of ingredients that is largely unsustainable. The ability to mass-produce and implement microalgae in fish feed on a large scale, by utilising readily available local carbon dioxide that is otherwise wasted, has the potential to radically increase the use of sustainable feed ingredients, while addressing problems related to cost and availability (Costa-Pierce, 2010). However, if we are to succeed in developing a more sustainable, fair, and humane aquaculture industry on a whole, then advances in technology and methods should go hand in hand with reshaping our ethics concerning human beings, the Earth, and the animals that are implicated in our food production systems, both wild and farmed (Anthony, 2012). Costa-Pierce (2010) holds a similar view and argues that if we want to expand aquaculture to meet the future demand for seafood, then we must integrate ecological science, share technological information, and promote innovation and efficiency by "incorporating social and environmental costs, not externalizing them (Culver & Castle, 2008)" (Costa-Pierce, 2010, p. 91 – his reference).

Costa-Pierce (2010) suggests three principles for "an Ecological Approach to Aquaculture": (1) that it "should be developed in the context of ecosystem functions and services (including biodiversity) with no degradation of these beyond their resilience capacity," (2) that it "should improve human well-being and equity for all relevant stakeholders," and (3) that it "should be developed in the context of other sectors, policies and goals" (p. 92–93). These principles share central ideas with environmental virtue ethics, for example, in the work of Ronald Sandler (2007), who writes that "If a particular technology is likely to cause ecosystem disruption or undermine the production of goods necessary for the cultivation of moral agency, virtue, or human flourishing, then that technology misses the target of virtues of sustainability and stewardship" (p. 126). According to Sandler (2007), we should only support a particular technology

> if there are reasons to believe that it will not disrupt the integrity of natural and agricultural ecosystems we depend upon for environmental goods or that the prospects for continued production of those goods without adoption of the technology are worse than they would be if it were adopted.
>
> (p. 126)

Sandler (2007) calls this "an external goods criterion" or a virtue-rule (v-rule) and suggests that we should evaluate particular technologies against this criterion or v-rule (p. 126). In the case of cultivating algae from flue gas, there is reason to believe that this technology would pass the external goods criterion, based on several aspects: it mitigates carbon dioxide from the ferrosilicon factory, it can lead to a reduction in carbon dioxide from fisheries, and it can reduce carbon dioxide emissions from transport of agricultural feed ingredients that would otherwise have been used. It also reduces the use of feed that is based on land-farmed soy that might be grown on cleared lands that displace Amazonian rainforest. The use of algae-based feed also seems to reduce the occurrence of salmon lice in the fish farms (Eilertsen et al., 2021), which benefits both farmed and wild fish.

Anthony (2012) argues that a change of attitude or a reorientation in values, the latter understood as action-guiding ideas that help us live well, is necessary for us to overcome what he calls the view of "food as device" (p. 134). Furthermore, he argues that to overcome "concealment" associated with the food production system and the "plight of farmed animals," we must deconstruct the barriers that might prevent us from acting on virtues of care (Anthony, 2012, p. 134). We can find support of this view in Ronald Sandler's (2007) work, who writes that:

> Given a proper framing of the historical record, a comprehensive accounting of the causes of our environmental and agricultural challenges and what is required to address them, and a proper understanding of what humility regarding technology and the environment involves, it does appear to be hubris for us to rely primarily on further manipulation and domination, in the form of technological solutions, for addressing our agricultural and environmental challenges.
>
> (p. 135)

The implementation of technological solutions should at least be accompanied by societal and character change, and, according to Anthony (2012), part of this change should come in the form of *responsiveness*, which, according to him, is one of four elements that constitutes the "Virtue of Caretaking" (p. 138). Responsive consumers must, according to Anthony (2012), "own up to how they impact the plight of farmers and animals and their complicit behavior through the market economy" (p. 139). He continues: "Successfully addressing the 'animal issues' as a function of our relationship with technology requires long term, sustainable changes in the way we choose to live" (Anthony, 2012, pp. 139–140). In addition to responsiveness, Anthony (2012) lists three other elements; *attentiveness*, *responsibility*, and *competence* (p. 138).

According to Michael Keary (2016), we should approach the solving of environmental challenges in a way that does not rely on "future technological improvements" – we should rather "carefully utilize existing technologies to reorganise production and consumption in such a way as to lower emissions to sustainable levels" (p. 24). In our case, the technology in question is algae-based carbon capture and utilisation. Microalgae cultivation on an industrial scale has previously not been viable due to the choice of algae species, lacking technological solutions, or due to cost–benefit concerns. Yet the benefits of microalgae cultivation have kept the science moving along; microalgae can be cultivated in a range of ways that does not compete with food crops, it can use carbon dioxide from flue gas, exhibiting a very high carbon dioxide uptake (Sethi et al., 2020). The use of new methods of cultivation allows for bulk production, resulting in reduced cost. This is the approach that is taken at the Finnfjord AS factory, and this approach fits well with Keary's suggestion of reorganising production. The algae project addresses pollution from factory flue gas, transportation and fishery, unsustainable feed ingredients (e.g., soy and wild fish), and the health and well-being of both farmed and wild fish.

However, a technological solution like algae-based carbon capture and utilisation should not become an excuse to keep our consumption at current levels. Rather, it should be part of an innovative programme to address systemic problems in production processes and consumption patterns. Aquaculture agents might have to be willing to pay more for a healthier and more sustainable feed ingredient, and consumers might have to be willing to pay more for higher quality food product that is more sustainable. Peter Wenz (2005) has noted that the integration of "Third World countries into the economic system that supports First World consumerism hurts the world's poor" and points to the demand of fish intended for animal feed as an example (p. 202). Costa-Pierce (2010) has argued that higher prices for fish can be a means to secure sustainable seafood for the poor. Higher prices on fish that is used as human food directly will, according to him, lead to less fish being processed into meals intended for terrestrial animal and aquaculture feed (Costa-Pierce, 2010). He points to Peru as an example, who export half of the world's fish meal from their anchovy fisheries, while a large portion of the country's population are poor and a fourth of the country's infants are malnourished (Costa-Pierce, 2010). Peru managed to turn this trend around after a 2006 campaign, where "scientists, chefs, and politicians" cooperated to show that the fish was more valuable as direct human food than as fish meal, resulting in a great increase in demand for fresh and canned anchovies in the country (Costa-Pierce, 2010). To achieve such goals, industry agents, consumers, and decision-makers have to act according to key environmental virtues. Like Anthony (2012), Louke van Wensveen (2005) also emphasises the importance of virtues of care to counter "harmful consumerist behaviors" and suggests that caring is "integrally dependent on the virtues of *benevolence* and *attentiveness*, by which one becomes well disposed and actively notices needs beyond one's own" (p. 187).

A narrow focus on "acts of consumption and their related emissions" that ignores "production and producers" can only capture one side of "the systemic aspects of human induced climate change" (Spash, 2020, p. 125). According to Boscov-Ellen (2020), environmental ethicists tend to overemphasise the role of individual consumption and their responsibility for climate change, while forgetting the systemic problems that in actuality drive climate change. Still, a one-sided focus on the producers of goods and products would also be a mistake in the opposite direction. As Anthony (2012) notes, "Partnership between policy-makers, industry agents, and consumers will be an integral part of any succeessful [sic] transformation" (p. 140).

One way for actors in the food production system to express responsibility (understood as an element of the virtue of caretaking) can be to "speed up technological change" (Anthony, 2012, p. 138). According to Anthony (2012), some estimates show that it can take 20–40 years before new innovations and technologies achieve widespread integration. Keary (2016) also points out that it is hubris, of a sort, to believe that we can invent our way out of our current problems and notes that development of new technology often takes more time and is more expensive than we initially think. In the case of Finnfjord AS, they seem to manage this challenge well. Cooperating with academia and with governmental funding institutions has made it possible for them to scale up the project of mass-cultivating microalgae. A consistent cooperation with scientific communities, feed producers, and aquaculture actors has also ensured that the algae biomass product can be tested in a methodical way within an industry context.

Our view of living organisms (even microalgae) matters

Can the way we view and use algae "as a technology" contribute to the shaping of our moral character? According to Anthony (2012), "*technology as an agent* shapes our lives and relegates food and farmed constituents into technological artifacts or commodities" (p 123). Anthony's argument is based on a view where the technologies we use in food production are non-neutral in the sense that they are "embedded with values and norms and reflect the shape of our moral character" (p. 123). John Barry (1999) holds a similar view and suggests that most people's lack of day-to-day contact with living farmed animals and the "publicness or visibility of our treatment of them" is reflected in the amount of sympathy we hold for them (p. 62). Anthony (2012) emphasises the importance of attentiveness to counter mechanical, rote, or unthinking "interactions with others who demand our moral sensitivity" (p. 138). But he is also careful to point out that there is no guarantee that his sketch of an "environmental virtue ethics of care" will actually "produce the desired ends of a more respectful and sustainable animal agriculture" (p. 141) and that there are several other possible virtue ethics approaches that may also hold different views on the relationships we have and should have with animals and technology.

In *Character and Environment* (2007), Ronald Sandler discusses the possibility of whether plants can be disrespected or not. According to Gerber and Hiernaux's (2022) argument about how we implicitly view plants today, we should at least be mindful of this possibility. While algae are not plants, they are photosynthetic organisms and are similar enough to bear comparison. And they are the key players in the attempt to turn carbon dioxide from flue gas into fish feed. Gerber and Hiernaux (2022) argue that we tend to look at plants as machines, which is a reductive and destructive way to think about and use plants. According to Gerber and Hiernaux, this view of plants can be traced back to the "explicit animal machine thesis" put forward by Descartes. They do not argue that we see animals like Descartes did, but that the way we talk about plants, using concepts like "breeding, biotechnology, and production" tend to obscure "the vitality of plants," thus revealing an "implicit plant machine thesis of today" (Gerber & Hiernaux, 2022, p. 1). In algae-based carbon capture and utilisation, the moral considerability of the algae is, in general, non-prevalent. They are "cultivated" using carbon dioxide and are, like plants, viewed as a "product" that can be fed to farmed salmon without moral qualms. Gerber and Hiernaux (2022) argue that we should at least afford this issue some moral reflection, both for the sake of the organisms in question, but also because the ways in which we view living organisms will ultimately influence the ways in which we live. They write:

> Technological industrial rationality creates its own values and its own ontology, perpetuating its own particular way of covering the world (Ellul, 1976). It denies agency and distinctness to living organisms – plants in particular. When it stands as a normative ideology, classical scientific methodology can be a threat, because what it "touches dries up and dies, dies to qualitative diversity, to singularity, to become the simple consequence of a general law" (Prigogine & Stengers, 1979, quoted by Amzallag, 2003). By questioning or rejecting mechanistic views in ethics, we can rethink the diversity, quality and intensity of our connections with plants, and build new ways of understanding and inhabiting the world (Javelle et al., 2020).
>
> (Gerber & Hiernaux, 2022, p. 20: their references)

Following Gerber and Hiernaux's (2022) argument, the grounds to claim that plants are fully devoid of sensitivity, which constitutes the "radical organism machine thesis," and the grounds to claim "that plants are devoid of any form of reason," which constitutes the "moderate thesis," do not stand up to scrutiny. The argument bears close similarity to Paul Taylor's conclusion in his book, *Respect for Nature* (1986/2011). He contends that even a plant has "a good of its own," and that this, in turn, means that the living thing in question then also possesses inherent worth (Taylor, 1986/2011, p. 81).

All this is not to say that we should not cultivate and use microalgae, or that we should not farm salmon. It is to say that – while we do so, and continue to develop new technologies and methods for doing so – we should also develop ourselves "to be virtuous consumers and industry decision-makers who aspire to promote public-regarding concerns in the food system" (Anthony, 2012, p. 126). One of the strengths of viewing these matters through the lens of a virtue-oriented approach is that environmental virtue ethics (EVE) is a moderately pluralist framework, meaning that it rejects strongly codifiable or hierarchical models of ethics, where a set of finite rules or principles gives us clear action guidance no matter the context (Sandler, 2007). As such, EVE captures well "the range of environmental experiences, relationships, and entities that are ethically significant, without reducing, homogenizing, or otherwise distorting them" (p. 104).

The environmental virtue ethics approach – two contrasting views that are both needed – neo-Aristotelian (agent-based) and target-centred virtue ethics

> Public discourse regarding the environment is framed almost exclusively in legislative and regulatory terms, so it is easy in environmental ethics to become fixated on what activities ought to be allowed or prohibited. After all, we legislate regarding behaviour, not character; policy concerns actions, not attitudes; and the courts apply the standards accordingly. But it is always people, with character traits, attitudes, and dispositions who perform actions, promote policies, and lobby for laws.
>
> (Sandler, 2007, p. 1)

According to Anthony (2012), the main reason why environmental virtue ethics (EVE) should be further examined with regards to our food production systems is that the standard approaches of deontological ethics and consequentialism "fail to deal adequately with the animals issues because they only offer band-aid solutions to symptomatic issues and side step the root concern," which is that "we need to change ourselves and the moral shape of our institutions and those who run them" (p. 135).

Arguably, the move away from deontology and consequentialism towards virtue ethics approaches started with G. E. M. Anscombe's paper "Modern Moral Philosophy" (1958) and Alasdair MacIntyre's book *After Virtue* (1981) (Snow, 2018). Virtue ethics had lost its central place in philosophy and ethics with the emergence of modern philosophers like David Hume, Immanuel Kant, and John Stuart Mill, who focused their attention on other ethical concepts than virtue and character, for example, "sentiments, duties, rules, and consequences" (Snow, 2018, p. 1). Anscombe criticised deontology and consequentialism and argued that we should return to Aristotle's virtue ethics (Snow, 2018). The basic view of virtue ethics since then has largely been neo-Aristotelianism, where "virtue is conducive to and partly constitutive of human flourishing" (Snow, 2018, p. 3). This view was initiated by Rosalind Hursthouse in her book *On Virtue Ethics* (1999), a view that to a great extent represents the contemporary understanding of virtue ethics that predominates today (Swanton, 2021).

Hursthouse made a substantive contribution in *On Virtue Ethics* (1999), not only by establishing the groundwork for a "third type of moral theory opposed to consequentialism and deontology," but by her criterion of right action, which has later been regarded as "defining of virtue ethics itself" (Swanton, 2021, p. 4). However, this was not the intention when the criterion of right action was introduced – it was rather designed to "allow virtue ethics to compete in *applied* ethics with the deontological and consequentialist views that dominated the field" (Swanton, 2021, p. 4). Hursthouse is reacting to the common description that "virtue ethics cannot be a genuine rival to utilitarianism and deontology" because it is "agent-centered rather than act-centered" and, thus, cannot "tell us about right action" (Hursthouse, 1999, p. 26). This is a misrepresentation of virtue ethics, according to Hursthouse, who argues that:

> Virtue ethics can provide a specification of "right action" – as "what a virtuous agent would, characteristically, do in the circumstances" – and such a specification can be regarded as generating a number of moral rules or principles (contrary to the usual claim that virtue ethics does not come up with rules or principles). Each virtue generates an instruction – "Do what is honest," "Do what is charitable"; and each vice a prohibition – "Do not act, do what is dishonest, uncharitable."
>
> (Hursthouse, 1999, p. 17)

A virtue-oriented approach involves the use of virtue rules (v-rules) where the substance of the virtues is embodied in the rules (Sandler, 2007). V-rules are part of the response to the objection that virtue ethics cannot be action-guiding (Hursthouse & Pettigrove, 2016). On the contrary, according to Sandler, environmental virtue ethics and the virtue-oriented approach can be an important part of the decision-making process and can indeed provide "effective and nuanced action guidance on concrete environmental issues" (Sandler, 2007, p. 7). The idea of v-rules can be traced back to Elizabeth Anscombe, who noted that we can find "a great deal of specific action guidance . . . in rules employing the virtue and vice terms" (Hursthouse & Pettigrove, 2016, p. 20). According to Hursthouse and Pettigrove (2016), the benefit of v-rules compared to deontological rules is that even if "our list of generally recognized virtue terms is comparatively short, our list of vice terms is remarkably, and usefully, long" (p. 20). And even if the list of "generally recognized virtue terms" is short, the vocabulary of ecological virtue language (including ecological virtue terms) is rich, as Louke van Wensveen has demonstrated in her book *Dirty Virtues: The Emergence of Ecological Virtue Ethics* (2000). Sandler (2007) writes that one of the main advantages of tools like virtue rules (v-rules) is to provide decision-makers, who are not necessarily virtuous, a tool or a method that makes them capable to follow a scheme that will allow them to act in accordance with virtue.

However, this is not to say that it is sufficient to act in accordance with virtue to be virtuous, or that the principle of right action or the v-rules should be taken as core principles in the virtue ethics framework. This would reduce the otherwise holistic and demanding virtue ethics framework to some kind of deontological or consequentialist approach where rules and consequences become the main guiding principles. Still, it is important to note that environmental virtue ethics and a virtue-oriented approach can offer action guidance for decision-making. Sandler (2007) writes:

> A virtue-oriented approach to decision making is one in which the virtues are the primary evaluative concepts. Actions, practices, and policies are assessed in terms of them, and what makes one more justified than another is that it better accords with, expresses, or hits the target of virtue. It is the virtues that are action guiding, and that some action does or does not accord with virtue that is reason giving, rather than, for example, its consequences or its compliance with deontological rules or contractual constraints.
>
> (p. 85)

Arguably, Aristotle would not trust that a person who did not possess the virtues would be able to act in accordance with them in a consistent way. A person might be able to do so when things are easy going, but when the going gets tough things will suddenly look different. We might expect that a politician who is not a virtuous person to be able to make prudent decisions based on a set of rules or guiding principles when nothing is on the line – but could we trust the same politician to make a tough and prudent, but unpopular decision for his community right before an election, if it could cost this politician his or her career? According to the neo-Aristotelian view at least, a person must be made from the right stuff (meaning that he or she must possess a virtuous character) in order to be able to make tough and unselfish decisions in difficult times. The same also goes for industry actors and consumers today. If we are left to our own devices, equipped only with a principle of right action or a set of guidelines like the v-rules, then we may indeed follow these when doing so takes little to no effort. But such a principle or such guidelines would hold little value if it were not seen as part of a more demanding ethical framework that takes a holistic approach to what it means to be in the world. When considering our relationship to nature, to ecosystems, to the environment, to the climate, to non-human animals, etc., a consistent ethical behaviour grows out from cultivating our dispositions towards nature, a transformation of character on a societal or global scale that rests on upbringing and education.

Virtues of position and respect for nature

According to Rosalind Hursthouse (2007), the virtue of respect for nature is perhaps the only novel virtue brought to the table by environmental virtue ethics. It was Paul Taylor (1986/2011) who suggested that we should adopt an attitude of respect for nature to improve our relationship with nature. Hursthouse (2007) suggests that, rather than viewing "respect for nature" as an "attitude" or "an ultimate moral attitude," we should think of "respect for nature" as "a virtuous character trait" (p. 162). She points out that we must not be misled by Taylor's use of words such as "taking up" or "adopting" the attitude of respect for nature into thinking that this is in any way an easy thing to do (p. 163). If we read Taylor carefully, she notes, we quickly come to realise that "taking up" or "adopting" the attitude of respect for nature involves a "complete transformation of character" (Hursthouse, 2007, p. 163). While this alludes to a transformation on the individual level, constant effort to bring environmentalism into the educational system, into scientific research, into the political forums, and into the business sphere, all contribute to what we can call an attempt to make "a complete transformation of character" – not only on an individual level but also on a societal level.

According to Louke van Wensveen's classification (2005), the virtue of respect fits into a group of virtues of position. By her classification, this group contains the largest number of virtues; and in addition to the virtue of respect, we find the following virtues in this group; *humility*, *self-acceptance*, *gratitude*, *appreciation of the good in others*, *prudence*, *practical judgement*, *sensibility*, *sensitivity*, and *practical wisdom* (Van Wensveen, 2005, pp. 176, 186–87).

When we are assessing algae-based CCU in connection with the ferrosilicon factory, the most obvious feature of both is that they are situated in a place, within an environment, in nature, alongside ecosystems, wild animals, and people. This is as true for a factory as it is for individuals. It is no surprise, then, that van Wensveen mentions Aldo Leopold in connection with virtues of position, and his suggestion that we should consider ourselves as plain citizens in an ecological community, a view that, according to her "implies a style of interaction" that is "a dynamic process of listening, cautious trying, looking for feedback, and modifying when necessary" (Van Wensveen, 2005, p. 176).

Target-centred virtue ethics

Based on what Christine Swanton (2021) sees as weaknesses with the agent-based, or eudaimonic, versions of virtue ethics, she has formulated her own view, which she calls Target-Centred Virtue Ethics. Here, most of the content of virtue ethics is brought along, but the *rightness* of an action is now judged on whether, or to what extent, it hits the target of a given virtue. Target-centred virtue ethics is relevant when discussing the case of algae-based carbon capture and utilisation technology. It can help us to determine whether, or to what extent, this technology will make the industries, factories, or farms operate in a way that accords to environmental virtues and their targets. As such, we can speak of a virtuous ferrosilicon smelter plant or a virtuous salmon farm within the terms of target-centred virtue ethics. It would be a conceptual error, however, to do the same within a neo-Aristotelian virtue ethics framework, where neither a technology nor a factory can possess a virtue – the activities of the business can accord with the virtues, but within this framework, it is people who have character, and who can be virtuous. It is of course people who make up businesses, factories, fish farms, and the consumer market, so it still makes great sense to hold on to a neo-Aristotelian ethics as well as a target-centred approach. The target-centred virtue ethics approach, as it is proposed by Swanton, would even go so far as to claim that whether or not an act hits the target of the virtues, in fact, determines whether the person acted virtuously or not. This view fits well with the concept of v-rules of course, since the rules indeed specifies certain targets based on the virtues. But the target-centred approach, or the v-rules seen in isolation from the context of a neo-Aristotelian framework, would represent a major break from the core of what has traditionally been thought of as the core of Aristotelian virtue ethics.[1]

In a target-centred virtue ethics, "What makes actions right, feelings appropriate, and traits of character virtues is understood through the notion of the targets of the virtues," where "Target centredness is the distinctive feature that makes Target Centred Virtue Ethics opposed to other forms of virtue ethics, notably neo-Aristotelianism" (Swanton, 2021, pp. 6–7). According to this view, "one acts rightly (or correctly) if one *hits* the targets of the virtues" (Swanton, 2021, p. 7). As Sandler puts it:

> The concept of 'hitting the target of virtue' enables specifying right action directly in terms of the point of the virtues, rather than mediated by or filtered through an agent, actual or idealized. Therefore, target principles of right action capture well the way the virtues are reason giving with respect to actions.
>
> (Sandler, 2007, p. 93)

Swanton (2010) also notes another reason why she thinks it is important to consider a target-centred approach to environmental virtue ethics. To avoid the anthropocentric aspects of virtue ethics, she suggests it is necessary to move away from the view that "excellence of character is what we are after when we preserve those endangered species" (Rolston, 2005, p. 70, referenced by Swanton) because this view is a misrepresentation of virtue ethics (Swanton, 2010). What a virtuous agent is really "concerned about is action and attitudes in line with the *targets* of virtues, such as environmental virtues whose targets involve for example care for the environment" (Swanton, 2010, p. 147).

Virtues of place

Louke van Wensveen suggests four virtue groups, all related to *place* in its own way. These groups are *virtues of position*, *virtues of care*, *virtues of attunement*, and *virtues of endurance* (Van Wensveen, 2005, pp. 176–177, 186–188). According to van Wensveen, *virtues of position* "are constructive habits of seeing ourselves in a particular place in a relational structure and interacting accordingly" (Van Wensveen, 2005, p. 176). *Virtues of care* "are habits of constructive involvement within the relational structure where we have found our place" (Van Wensveen, 2005, p. 176). *Virtues of attunement* "are habits of handling temptations by adjusting ('tuning') our positive, outgoing drives and emotions to match our chosen place and degree of constructive, ecosocial engagement" (Van Wensveen, 2005, p. 177); while *virtues of endurance* "are habits of facing dangers and difficulties by handling our negative, protective drives and emotions in such a way that we can sustain our chosen sense of place and degree of constructive ecosocial engagement" (Van Wensveen, 2005, p. 177).

Nancy M. Rourke (2011) paints a picture of van Wensveen's "virtue ecology" where attunement assumes the role of practical wisdom. Van Wensveen (2005) argues that without the virtue of attunement to match our engagement to our positive drives, having all the other virtues may be useless. "This is key," Van Wensveen (2005) continues, "because without such personal adjustments, all our humility and respect, our wisdom and sensitivity, our attentiveness and friendship, may still amount to nothing" (p. 177).

Let us consider what van Wensveen writes about practical wisdom as sensitivity, and an agent's sense of place:

> The exercise of practical wisdom thus takes on an intensified form, which environmentalists tend to refer to as *sensitivity*. This environmental favorite can therefore be considered a synonym of practical wisdom . . . [t]he more modest one's sense of place, the more actively one will try to monitor and modify in order to respond fittingly to what is going on. Thus, the cultivation of practical wisdom has become integrally dependent on virtues such as *humility*, *respect*, and *gratitude*, all of which contribute to an agent's modest sense of place.
>
> (Van Wensveen, 2005, p. 187)

However, it is not possible to get a sense of one's place if there is a lack of openness. Like Anthony (2012) and Barry (1999) note, the concealment that happens in our food production systems contributes to our inability to respond appropriately to the way animals are treated there. For us to be able to "monitor and modify in order to respond fittingly to what is going on" (Van Wensveen, 2005, p. 187), we must strive for food production systems that are transparent (Anthony, 2012).

Concealment and lack of openness in food production systems need not be intentional on the part of the producers. It can simply be an unintended consequence of the way our society and market is structured. To amend these structures, both producers and consumers could exercise practical wisdom, i.e., be more sensitive to the place where production and consumption take place. When the ferrosilicon smelter plant owners partner up with academic researchers to monitor their surroundings (including soil health, seawater health, the state of wild fish in the area), and partner up with other institutions and businesses to get a sense of important social factors (the local community, including other businesses and industries, like the fish farming industry), the sense of place will increase, leading to a more modest attitude towards one's environment in a broad sense.

The false tragedy of the market

Steven Vogel (2015) has criticised the view that environmental virtue ethics provides us with a good ethical framework for thinking about business decisions. He argues that a virtuous factory owner will commit economic suicide if she was to follow her dispositions and install expensive technology to make her factory more environmentally friendly, basing this on the assumption that there are other actors who are not so disposed, and who will be able to run their factories at a lower cost, thereby outcompeting the virtuous factory owner (Vogel, 2015). According to Vogel's argument, the factory owner may be virtuous to a fault.

One way for a virtue ethicist to respond to Vogel's example is to argue that the factory owner he depicts "falls short of full virtue" because she lacks phronesis, or "moral or practical wisdom" (Hursthouse & Pettigrove, 2016, p. 6). Having moral wisdom can be understood as having complete virtue, in the sense that one's moral habits, one's knowledge, and the virtues are integrated into an "intelligent, authentic, and expert manner" (Vallor, 2016, p. 154). Shannon Vallor (2016) discusses practical wisdom, or phronesis, using the term "techno-moral wisdom," and calls it a

> general condition of well-cultivated and integrated moral expertise that expresses successfully – and in an intelligent, informed, and authentic way – each of the other virtues of character that we, individually or collectively, need in order to live well with emerging technologies
>
> (p. 154)

Vogel (2015) attempts to apply the issue of practical wisdom in his descriptions of the virtuous factory owner. He writes:

> The environmentally concerned factory owner, faced with the decision about whether to install new scrubbing devices on smokestacks, may completely understand the toxic consequences of the pollution such factories emit, but at

> the same time she knows the cost of the devices and the effects on her business of incurring such costs when her competitors do not: if she's bankrupted by the additional costs, nothing is gained in terms of pollution reduction.
>
> (Vogel, 2015, pp. 206–207)

Vogel (2015) further writes:

> Knowledge in these cases in no way lessens the problem but rather in certain ways renders it more acute and even poignant.
>
> The problem of the commons, I am suggesting, is very appropriately called a tragedy, in the classical sense. The agents are faced with an implacable and unavoidable destiny of which they are themselves the authors: it is their own acts, engaged in for the best of reasons and in the fullest understanding of their consequences, that bring about the effects that they produce but that they have no way to collectively determine, as Fate. The other name for Fate here, however, is the market.
>
> (p. 207)

Vogel's view of the market as "Fate" is drastic, but it does reflect some sentiments found in the environmental virtue ethics literature, for example, in Anthony (2012) and Barry (1999), that the scale and complexity of the market contribute to the concealment of the agency of living organisms and ethical issues in our food production systems. They do not, however, share Vogel's view that this leads to an inevitable tragedy of the commons. Rather, they argue for a transformation of character of consumers, producers, and of the institutions that govern them.

This allows that business is not as black and white as Vogel depicts it. Finnfjord AS is a business with a long history. Experience helps them seek solutions that are not wholly idealistic – rather, they can be seen as expressing phronesis, partly by cooperating with scientific and academic communities across various disciplines, to make prudent decisions on sustainable business models that are both environmentally and economically sustainable in the long run.

I am also not convinced that the situation Vogel describes, of the virtuous factory owner, is a tragedy in the classical sense. Vogel affords the factory owner only two choices – she can forgo the new factory, install new scrubbing devices, and put her company at risk of bankruptcy; or she can build another factory and choose not to install the new scrubbing devices (Vogel, 2015). However, Vogel's case can also be interpreted as a case where the factory owner is lacking in virtue. Hursthouse (1999) notes that "it will be the mark of someone lacking in complete virtue that they too readily see a situation as one in which they are forced to choose between great evils, rather than as one in which there is a third way out" (p. 86). This third way out might, indeed, be to risk bankruptcy if the only other option is to conduct business in a way that causes great harms to the environment.

A virtue ethics approach does not exclude the possibility that "there may be situations in which the virtuous agent will be condemned to death or sorrow or called upon to let herself be killed" (Hursthouse, 1999, p. 84). But the case of Finnfjord

AS shows that a practice in line with environmental virtues – like farsightedness, attunement, cooperativeness, perseverance, commitment, optimism, and creativity (Sandler, 2007) – can present businesses in a cut-throat market with an opportunity to thrive and develop in a more sustainable direction. Moreover, virtuous agents can potentially emerge as more robust companies, for example, by transforming polluting by-products into non-polluting sellable products, thereby increasing efficiency and profitability (Scherer, 2003). There is, of course, a financial risk when innovating and developing new solutions to deal with polluting by-products, but there is also virtue in seeing the potential in solving these practical problems, as the Finnfjord AS factory attempts to do by utilising the large amount of carbon dioxide emitted during ferrosilicon production. There is also virtue in seeing the potential in existing technologies and natural processes, for example, that diatoms have a unique capability to capture carbon dioxide and that the biomass can be turned into valuable products like biofuels, biofertilisers, nutritional supplements for animal production, pigments, and more (Marella et al., 2020).

A point that is also worth pointing out with regards to Vogel's discussion is that we do not need to limit discussions of virtuous persons to business owners. Of course, for the example of the tragedy of the commons to work, we also need to depict the market as a sphere that is totally separated from governing institutions. Because, especially in Norway, there are both regulations and support programmes to help businesses follow sustainable practices and develop sustainable projects. Anthony (2012) argues that partnerships between industry agents and government agencies should be increased. This will, on the one hand, help with knowledge sharing (Anthony, 2012) and can, on the other hand, also help businesses pursue more costly projects that can make their practice more sustainable.

Note

1 Christine Swanton (2021) is explicit in stating that the target-centred view indeed is an attempt at formulating an alternative approach to a neo-Aristotelian Virtue Ethics.

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10 Unifying the threads

Is carbon a resource?

Øyvind Stokke and Elin M. Oftedal

Making the future by breaking the narrative of the past

The history of Norwegian industry, energy, and natural resources is intertwined with institutional learning processes that, in the end, provide the foundation for a democratic, redistributive, and knowledge-based state. The values made through these learning processes, *knowledge* and *trust*, are also the foundation of Finnfjord, and so its history is a classic example of industrial modernisation, Norwegian style. One important takeaway from this anthology is that we need to detach our thinking about sustainable innovation in the industry from the narrative of modernisation as the structural adjustment to paid work in industry – a narrative that gives increasing concessions to the petroleum interests. Even though the national strategists (public officials and visionary politicians) in the 20th century Norway may have *needed* the imaginary of a poor and obsolete country in their efforts to modernise Norway, an increasing number of researchers and historians paint an alternative, more prosperous picture of Norwegian modernisation processes in the 19th and 20th centuries. *They* break the one-dimensional narrative of modernisation as an irreversible process where the rural subsistence economy is replaced by industrial paid work in central urban areas.[1]

Whereas our recent industrial history bears the imprint of off-shore oil and gas – of carbon – our early industry could benefit from hydroelectric power, thanks to inventive engineering and Norwegian topography. A distinction developed in Malm 2016 between proto-fossil and fossil economy parallels this narrative and has important consequences for the discussion of whether carbon is a resource or a curse. We should not collapse the narrative of the family owner starting up in 1960 with a vision to achieve some private (and public) goals, to create a business and jobs for the benefit of the community, and to make a product necessary for our overall material infrastructure, into the global capitalist process of self-sustaining economic growth predicated on fossil fuels. *The social trust built through the hard work of slowly transiting the production into a circular and more sustainable economy, and taking corporate social responsibility along the way, is much more valuable than mineral oil:* that statement, if not expressed explicitly in Skirbekk's analysis of social and political modernisation in the 19th and 20th centuries, is nevertheless an important takeaway from that book. Interestingly, this statement

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also finds experimental scientific support in a recent research project at the Norwegian School of Economics on moral universalism embodied in social and political institutions.[2]

Finally, important comparative research on the early industrialisation in Norway and England allows a more precise outline of the specific form Malm's distinction between the fossil and proto-fossil economy did take in rural Norway. In the words of professor and MP Ottar Brox (1932–2024), whose ethnographic work from the 1960s and onwards documents Norwegian modernisation as a *Sonderweg*:

> To a certain extent, manufacturing became a rural industry – also because small farmers were available as labour as long as they did not have to leave their properties. Simply put: Norway was industrialised at the same time as important aspects of the pre-industrial subsistence economy was maintained. . . . We might put it this way that the industrial revolution "replaced" the traditional self-sufficiency economic system in Britain with a completely new system, which implied drastic welfare losses for working people. Norwegians were lucky enough to get the benefits of the machine age in addition to, or on top of, our old subsistence economy. In this way, we have enjoyed the best of both worlds for a long time. While the industrial revolution created greater class differences in many other countries, there is much evidence that industrial growth in Norway, together with the democratization process, laid the foundation for the level of equality we reached in the post-war period. The Norwegian "Sonderweg" . . . created a durable basis for a modern, democratic welfare society, primarily because we avoided the inequalities that have created such great class differences in British society.
>
> (Brox, 2013, my translation)

As heir of the early history of Norwegian rural industry, the UiT-Finnfjord project is *making* social and economic values, and, at the same time, has the potential for *breaking* the market for unsustainable products in Norwegian aquaculture.

This is also the takeaway point made by Erik W. Strømsheim in Chapter 9: a technological solution like algae-based carbon capture and utilisation should not become an excuse to keep our production processes and consumption patterns at current levels. Rather, it should be part of an innovative programme to address systemic problems in those processes and patterns. According to Strømsheim, aquaculture agents might have to be willing to pay more for a healthier and more sustainable feed ingredient, and consumers might have to be willing to pay more for higher quality food product that is more sustainable.

From the broader perspectives of environmental ethics and responsible innovation, the interesting question is how we can create an alternative future based on the correct understanding of the past as the Norwegian *Sonderweg* giving us "the benefits of the machine age in addition to, or on top of, our old subsistence economy." Add to this the ethical virtue of frugality inherent in the traditional subsistence economy, and we are on our way to breaking the spell of the fossil economy by detaching wealth and happiness from the idea of continual economic growth.

Like most examples of economic development, two stories unfold. One shows increased prosperity, better health, and quality of life. The other depicts a narrative exposing unintended outcomes of continual economic pursuits, chiefly, the significant escalation of carbon dioxide emissions beginning in the mid-18th century. This also happened in Finnfjord: 300,000 tonne of CO_2 were emitted into the atmosphere and a foul smell was diffused in the village. The optimistic villagers called it “the smell of money.” Nevertheless, the smelter was seen as a necessary evil, rather than something to be proud of.

The initial thread in this picture focuses on the climate crisis and the continuous increase of CO_2 emissions. Originating during the infancy of industrialisation, this trajectory has exponentially intensified, casting a shadow globally. The question of where to place the responsibility of this situation is interesting. In the Introduction, we discussed the carbon majors and whether they are ill-intended actors or if they are victims of a system that favours high consumption and, consequently, production. The answer may be: Both! If actors position themselves to benefit from a certain system, they also do not want it to change.

However, as the discussion evolves, a second story surfaces, embodying hope and innovation. This story, indicative of a resilient spirit of innovation and adaptability, based not only on the changes we are observing, but also on new laws and regulation, inspiration from leaders, and new knowledge, is exemplified by initiatives such as the interdisciplinary carbon capture and utilisation (iCCU) project. The UiT-Finnfjord project did not start with one idea, but rather many small ideas, building on each other, being supported by new knowledge from research and science, personal relations and trust, and supportive legal and funding frameworks. With an intrinsic commitment to sustainability, the UiT-Finnfjord project not only encapsulates the capture and utilisation of CO_2 but also pioneers the development and promotion of algae-based products.

The use of CO_2 to produce algae biomass may offer a potent alternative to traditional, emission-intensive procedures. As such, the project may both indicate a path out of the escalation of CO_2 emissions and further give us a new commodity that can be used in many different products as a more sustainable alternative than what we use today.

However, without the integration of a third perspective, the story remains incomplete: the doctrines of human rights, the objectives within the sustainable development goals (SDGs), environmental history, and the philosophical underpinnings offered by environmental ethics, theory of science, and critical social theory. Taken together, these pieces combine to construct a normative framework, serving as an ethical compass to navigate the complex maze of sustainable development.

This framework, fundamental to our comprehension and methodology towards sustainability, responds to a problem in the dominant take on “sustainability” since the Brundtland Report from 1987: the problem that the ecological boundaries tend to be compromised under weak sustainability.

> According to the weak sustainability perspective, any form of capital – including all forms of natural capital – is “negotiable” as far as the aggregated

> income does not decrease. Trade-offs between economic activity and the quality of the environment seem unlimited according to this view.
>
> (Janeiro & Patel, 2015, p. 440)

Taking the perspective of strong sustainability, the iCCU project sets out to *righten the balance* between the fundamental value of life-generating nature and capitalism, a unique economic form to the extent that it is "based on the one process which fails to reproduce, or assist the reproduction of, other forms of life" (Brennan, 2000, p. 2). Recycling and reusing a waste product like CO_2 emissions in the factory production line is the first condition of making the economy ecological. As we have seen, the carbon capture and utilisation (CCU) project at Finnfjord includes a second stage of reuse in terms of producing sustainable and nutritious fish feed for the regional aquaculture industry, in itself struggling with its reputation as an unsustainable business. The ethical groundwork is still necessary for safeguarding the basic needs of the individual and an equitable distribution of resources. But these two "anthropocentric" imperatives belonging to the threefold concept of sustainability no longer should be prioritised to the detriment of a life-generating nature on which we all, in the last instance, depend. As such, the project demarcates the permissible boundaries of our actions and illuminates the pathway towards a harmonious environmental coexistence, where development does not inexorably lead to irreversible ecological degradation.

Within the complexity of this story emerges the case of Finnfjord representing the possibility of transforming a detested waste product into a valuable asset. Although the project did not originate from one grand idea, the relentless pursuit of knowledge culminated in a project that harmonises with, rather than opposes, nature.

Addressing the carbon dilemma: the business perspective

Not all business owners are created equal. On the contrary, they exhibit considerable diversity in terms of market presence, financial might, and political leverage. While certain conglomerates wield substantial power in these domains – dubbed "carbon majors" – numerous smaller enterprises, like Finnfjord, navigate intricate systems, predominantly responding to demands from both customers and markets. Situated within an isolated Arctic community, Finnfjord competes internationally, its operations integral to the local livelihood. The owning family, deeply rooted and committed to the community, plays a pivotal role in its sustenance. Such smaller enterprises necessitate robust support systems for survival and flourishing. The case of Finnfjord illuminates the instrumental roles in which both state and academia can play in such contexts. Support from these entities not only facilitated Finnfjord's transition towards carbon neutrality (potentially even carbon negativity) but also possibly spearheaded the emergence of a new industry.

Achieving harmony between industrial operations and environmental imperatives demands significant shifts in scientific, industrial, and consumer attitudes. The environmental virtue ethics approach offers an insightful framework to navigate this transformation and is foundational to developing sustainable and eco-conscious food production systems. This approach is exemplified by collaborative initiatives undertaken at the ferrosilicon smelter Finnfjord AS. Such practice – in line with environmental virtues including farsightedness, attunement, cooperativeness, perseverance, commitment, optimism, and creativity (Sandler, 2007) – goes beyond presenting businesses in a cut-throat market with an opportunity to thrive and develop in a more sustainable direction. Erik W. Strømsheim argues that they can emerge as more robust companies, for example, transforming polluting by-products into a sellable product, thereby increasing efficiency and profitability. While this alludes to a paradigm shift on the individual level, constant effort to bring environmentalism into the educational system, into scientific research, into the political forums, and into the business sphere all contributes to what we can call an attempt at "a complete transformation of character" – not only on an individual level but also on a societal level. If green technologies can only be tools for ecological renewal if they are linked to a cultural revolution which redefines prosperity and abandons growth-driven consumerism (see Introduction, p. 13), then this complete transformation of character by means of environmental virtues might be the only way forward.

The discourse presented by Oftedal and Stokke explores the synergies between universities and industries, shedding light on the enabling institutional frameworks that uphold the principles of basic research and researcher autonomy. Such frameworks are crucial for older factories embroiled in the challenges of survival while grappling with significant CO_2 production. Each actor in this scenario, while pursuing individual interests (echoing Adam Smith's (1776) concept of the "invisible hand"), contributes not only to market vitality but also to environmental and perhaps social well-being. On the other hand, Oftedal and Stokke lean on Mazzucato's (2013) analysis which diverges from the classical economic theories. While Smith (1776) advocates for minimal government intervention, Mazzucato underscores the government's proactive and invaluable role in fostering innovation. Oftedal and Stokke contribute to this discussion by showcasing the university as another important agent in helping firms become more sustainable. As Mazzucato argues, institutions such as the state or the university need not merely set the stage for innovation, but may actively participate in and propel the innovative process forward. Further, good regulations may shape the avenues by which businesses create revenues. When the carbon tax was presented by the government, the management of Finnfjord had to develop an organisational response. They found the solution within other branches of the state: funding for eco-oriented projects and a university cooperative.

Theresa Scavenius takes this one step further and argues that democratic institutions have the responsibility of designing a legitimate, effective climate policy (Scavenius, 2019). She criticises the global justice discourse for a dichotomising focus on global versus national justice, which has resulted in neglecting the democratic state's potential to deal with environmental and climate problems. It is time to ask what the state's political institutions can and should be held responsible for (Scavenius, 2019, p. 3). The answer is: to help change people's behavioural space! People may intend to act climate friendly, while their behavioural spaces might not allow them to do so – due to different types of constraints (both hard and soft) which can ultimately make it difficult to avoid harming the climate. When different market agents can purchase ferrosilicon with a reduced CO_2 footprint, the university-business innovation project at Finnfjord, in fact, contributes to changing the behaviour space, and helping individuals fulfil their moral duty to avoid harming the climate. The discussion of climate change within political theory and climate ethics has been particularly led astray by the dominant spotlight on economics and cost distribution. Here, Scavenius points to the dominance of theories of rational choice that do not take account of social, institutional, and political explanatory factors (2019, p. 6). This critique fits well with Mazzucato's institutional theory of the entrepreneurial state.

Interestingly, Mazzucato's views the entrepreneurial state as vision driven, identifying and investing in promising opportunities. From the business perspective, the Finnfjord project can be argued to be vision driven: Inspired by a political leader, they envisioned becoming the first carbon-neutral smelter. From the university side, there was no grand vision other than The Researcher's Weberian adherence to science as a vocation – the slow but steady process to untangle the mystery of the diatom algae.[3]

Interdisciplinaria and innovation: the case of iCCU

The iCCU project is a part of the larger algae project. The iCCU research group, consisting of biologists, philosophers, innovation scholars, social scientists, and computer scientists, casts an interdisciplinary light on the project. The roles of researchers from the natural versus the social sciences vary significantly in approach and in scope, and this has also been a challenge and a learning opportunity in this project. Scientists such as the project's biologists often direct their attention towards external systems, delving deep into the intricacies of the physical and natural world. Their research is more likely to lead to ground-breaking discoveries which could establish them as pioneers in their fields (Kuhn, 1962). This is exemplified in the valuable insights concerning microalgae cultivation derived through the course of this project, which has paved the way for fresh avenues in both research and practical application.

Conversely, social scientists, philosophers, and professionals in the realm of information technology (IT) each adopt distinctive lenses to understand the world. Social scientists, embedded within the societal frameworks they study, are driven to decipher and interpret the patterns, systems, and phenomena governing human interactions and societal formation (Berger & Luckmann, 1966; Bryman, 2012; Chalmers, 1999). Within this project, Agwu, Jaber, and Oftedal link the CCU versus CCS discussion to the diffusion of the innovation. The diatom algae may be diffused into a plethora of products, some of which are more sustainable than others.

Philosophy, not a social science in itself, frequently intersects with its methodologies and concerns, especially in realms like the philosophy of social science. It provides a critical lens, scrutinising the techniques and premises of social scientific research (Hollis, 1994). Furthermore, profound philosophical musings on topics like justice or freedom often parallel themes explored in social science research (Rawls, 1971). Strømsheim emphasises the innovative efforts at Finnfjord Ltd., showcasing how modern factories can create circular economies at various levels. The chapter argues for the mass cultivation and use of marine microalgae as part of a broader sustainability programme, drawing from environmental virtue ethics (EVE) and engaging in debates between EVE and ecological ethics to elaborate on the concept of sustainability in this context.

Computer science operates at the confluence of the formal, natural, and applied sciences. As a discipline steeped in abstract concepts and theory, it is rooted in formal sciences like mathematics, focusing on the theoretical underpinnings of computation and information (Knuth, 1997). It extends into the natural sciences through computational models that help explain complex phenomena (Mitchell, 2009), and its practical applications in software engineering and AI demonstrate its role as an applied science in solving real-world problems (Sommerville, 2015; Brooks, 1995). Additionally, computer science's overlap with engineering is seen in the shared emphasis on the design and optimisation of technology, a trait it shares with fields like electrical and computer engineering (Walden & Roedler, 2010).

IoT technologies and a distributed architecture with edge computing, together, enhance the efficiency and robustness of bioreactors used for algae cultivation and experimentation. This technological advancement facilitates data processing, fosters redundancy, and promotes independent research. It's a live testament to how technology can advance SDGs while promoting academic and industrial collaboration. Roopam Bamal, Daniel Bamal, and Singara Singh Kasana provide an overview of Internet of Things (IoT) technologies used in environments such as large bioreactors for algae cultivation. They discuss the potential of using multiple bioreactors for independent research experiments and to optimise production. The authors propose a distributed architecture supported by edge computing, which allows each bioreactor to operate independently, thereby enhancing robustness. The chapter also touches on the IoT ecosystem's energy demands and introduces new technologies like smart underwater sensor networks to monitor aquatic environments.

With the SDG ways into the future

Escalating CO_2 emissions represents a pressing global challenge that necessitates a concerted effort among policymakers, scientists, and various stakeholders, as highlighted by international agreements like the Paris Agreement (Daneshvar et al., 2022). The sustainable development goals (SDGs) are a universal call to action to end poverty, protect the planet, and ensure that all people enjoy peace and prosperity by 2030. Notably, the Paris Agreement is a legally binding international treaty on climate change, integral to the pursuit of these goals.[4] The SDGs provide pathways toward a more sustainable, equitable future. A comprehensive exploration of how these goals can be and are being implemented across different sectors and scales, from local to global, has the potential to steer the world towards a more sustainable trajectory.

Yet, despite progress towards sustainable development, significant challenges and knowledge gaps persist. For instance, the Finnfjord project aligns with several of the SDGs. However, SDG 13, which is dedicated to climate action, may be further challenged. The environmental impacts of large-scale algae cultivation and the complexities of producing sustainable aquaculture feed require additional research. Moreover, aligning innovations with SDGs while minimising negative impacts requires continuous effort and vigilance. SDG 8, dedicated to promote inclusive and sustainable economic growth, could be questioned in light of the following statement from the European Environmental Agency:

> Accelerating technological innovation is fuelled by the widespread digitalisation of economies and societies worldwide. While this can increase productivity and energy efficiency, it is not yet clear whether the energy and materials savings are enough to outweigh the negative sustainability impacts of information and communications technology (ICT) (UN Environment, 2019), such as its huge demand for critical raw materials.
>
> (Benini & Asquith, 2019, p. 46)

A scientific article published by the same agency speaks even more clearly and critically:

> Economic growth is closely linked to increases in production, consumption and resource use and has detrimental effects on the natural environment and human health. It is unlikely that a long-lasting, absolute decoupling of economic growth from environmental pressures and impacts can be achieved at the global scale; therefore, societies need to rethink what is meant by growth and progress and their meaning for global sustainability.
>
> (Kovacic et al., 2021, p. 1)

This can be aligned with the ethical virtue of frugality, and our book's vision of breaking the spell of the fossil economy by detaching wealth and happiness from the idea of continual economic growth.

In addressing these concerns, it is crucial that research and innovation efforts remain closely aligned with the broader objectives outlined by the SDGs. It entails not only recognising the potential environmental impacts but also developing strategies that pre-emptively mitigate these challenges. As we navigate the intricacies of sustainable development, projects like Finnfjord must continuously adapt and evolve to contribute positively to climate action and beyond. One critical aspect that has not been adequately explored is the balance between atmospheric oxygen and carbon dioxide. Historically, Earth's oxygen levels were in equilibrium with CO_2 generation, but human activities – especially the combustion of CO_2 since the Industrial Revolution – have disturbed this balance, affecting the planet's capacity to convert CO_2 back to O_2 through photosynthesis (Ighalo et al., 2022).

Current emission models often overlook the consumption of oxygen during the combustion of fossil fuels, which is a significant oversight (Sampaio et al., 2022).

To approach climate anomalies in a more integrated manner, Sampaio et al. (2022) introduced the concept of "Atmospheric Profit & Loss (AP&L)." This framework aims to enhance underground CO_2 storage and increase atmospheric oxygen levels while simultaneously addressing the issues of oxygen depletion and CO_2 emissions. It underscores the necessity of considering both CO_2 and O_2 dynamics in combustion reactions and their environmental ramifications. Consequently, strategies like CCU, especially those involving microalgae, are vital for CO_2 sequestration and the restoration of atmospheric oxygen (Daneshvar et al., 2022).

Langhelle, Sareen, and Silvester similarly gravitate towards this view, aligning with Morrow et al. (2020) in questioning the dynamics of CO_2 sequestration, specifically asking, "Where does the carbon come from and where does it go?" They conclude that although the products derived from algae might be relatively short-lived, these products possess other beneficial properties that contribute to mitigation efforts. This underscores the complexity of CO_2 sequestration and the importance of considering a wider range of factors, including the life cycle of carbon products and their overall impact on both CO_2 reduction and oxygen generation.

A deeper dive into the SDGs reveals their strong anchoring in human rights, serving as benchmarks and moral grounding. Furthermore, navigating through the complex interplay of human rights and SDGs necessitates a capability approach, guiding us in managing inevitable trade-offs in specific contexts. This approach, when applied to initiatives like algae-based product development, illuminates pathways to alleviate conflicts and promote sustainability and human rights simultaneously. Anna-Karin M. Andersson contributes to this endeavour in Chapter 4 – particularly in addressing the need to handle trade-offs between the SDGs. This account can be utilised to develop adaptation initiatives such as the development of algae-based fish feed at the Finnfjord facility. A good starting point for any discussion of political responsibility for climate change is the theoretically sound assumption that abstract principles about what *should* be done with regard to climate are not enough to judge the concrete question of who *should* do what, and, at what institutional level, they *should* do it (Scavenius, 2019, pp. 48–58). It is, therefore, necessary to distinguish abstract from concrete attributions of *should*, i.e., of responsibility. Concrete attributions of *should* concern the design of normative criteria to identify conditions that must be met in order for an agent to be ascribed as morally responsible for climate change. Such fact-sensitive considerations are necessary for any viable climate mitigation and adaptation effort, and, in the UiT-Finnfjord project, the interplay between SDG's, science, innovation, and industry illustrates a multi-level structure of agents to address the questions of what *should* be done and by whom. In the collaborative innovation effort, not only do different scientific perspectives complement each other but different ethical perspectives do as well.

Despite strides towards sustainable development, various challenges and knowledge gaps remain. For instance, the environmental impacts of large-scale algae cultivation and the intricacies of producing sustainable aquaculture feed warrant further investigation. According to Sten Siikavuopio and Edel Elvevoll, there is a growing interest in the nutritional value of underutilised marine sources and by-products (Chapter 3, p. 7). It has, they continue, been suggested that harvesting, fermenting, or cultivating organisms from the base (or lower end of the marine food web) might present the largest potential to increase sustainability across the industry. These developments appear to be all the more important, given that all intensive production or harvest of resources for feed has an impact on climate (by emission of GHG) and the environment (by use of land, water, energy, and other resources). The high integration of soy as feed ingredients in the Norwegian salmon industry has significant indirect land-use effects, and the prospected growth can be expected to contribute to overall deforestation (Rainforest Foundation Norway, 2018) (ibid., p. 5).

Moreover, aligning innovations with SDGs while minimising negative impacts requires continuous effort and vigilance. A deeper dive into the SDGs reveals their strong anchoring in human rights, serving as benchmarks and moral grounding. Furthermore, navigating through the complex interplay of human rights and SDGs necessitates a capability approach, guiding us in managing inevitable trade-offs in specific contexts. This approach, when applied to initiatives like algae-based product development, illuminates pathways to alleviate conflicts and promote sustainability and human rights simultaneously. Andersson contributes to this endeavour, particularly, to address the need to manage trade-offs between the SDGs. This account can be utilised to develop adaptation initiatives such as the development of algae-based fish feed at the Finnfjord facility.

If nature-respecting sufficiency is the starting point of Strømsheims request to attune our consumption and our food production systems to the environmental reality and develop ourselves "to be virtuous consumers and industry decision-makers who aspire to promote public-regarding concerns in the food system" (Chapter 9), then philosopher of innovation Raphael Ziegler seems to connect our two chapters on ethics, namely on the philosophical underpinnings of the human rights-based SDGs and on environmental virtue ethics, respectively. Ziegler develops a position named "nature-respecting sufficiency" starting out with a reflection on "enough," leading to "a double exploration within justice of a minimum threshold and of respect for upper limits to resource use" (op. cit., p. 18): "The sufficientarian position taken here adopts for the threshold specification capabilities as the category of evaluation: the real opportunities of people to do and to be what they have reason to value" (op. cit., 19). Besides adopting Nussbaum's well-known theory of justice spelling out dignity via a list of central capabilities, Ziegler outlines his sufficientarian capability position by adopting environmental philosopher Paul Taylor's

> normative position that recognises and respects the flourishing of all life . . . once we note that our knowledge of the evolution of life places us as living beings among other living beings, who have their own good and who cannot be demonstrated to be inferior to us . . . it is prima facie not irrelevant what happens above the threshold, that us, when basic interests have been met . . . Turning to enough as a limit, the discourse of limits to growth and its revival in eco-space boundaries and the planetary boundaries discussions, suggests a use of sufficiency that calls for a reduction in production and consumption.

The key question becomes the justification of consumption and production beyond the resource threshold in living in dignity (op. cit., 24–25).

Interestingly, the capability approach as the philosophical underpinning of the SDGs and the position of environmental virtue ethics both seem to meet and combine in what Ziegler designates *sufficiency as limit* (op. cit., p. 24). The many disciplines collaborating in the iCCU project seek to promote a progressive conversation about a case of responsible innovation where both technical and social innovation contribute to turn a waste product into a resource – one of many pathways to respect sufficiency as a limit.

We have seen that a third-order innovation society emerges if the rules of second-order reproduction in innovation societies become problematic, when they become the object of reflection, have lost their certainty – when society has to ask whether innovation is needed or not, whether progress is needed, or what kind of innovation is needed, or if innovation should be resisted, accelerated, or slowed down (for the last question, see Odum & Odum, 2006). Society is compelled to ask such questions when the unintended consequences of innovations "undermine its own social and ecological preconditions" (Ziegler, 2020, p. 4). Langhelle, Sareen, and Silvester shed light on an interesting example of problematic innovation promoted by the US Department of Energy. In 2012, the Department stated that it was "strategically focusing the program's R&D toward the economic 'utilisation' of captured carbon dioxide (CO_2) for commercial purposes, evolving from CCS to Carbon Capture, Utilization and Storage, or CCUS." By putting the captured CO_2 to use, it was argued that "CCUS provides an additional business and market case for companies or organisations to pursue the environmental benefits of CCS" (US Department of Energy, 2012, cited in Bajura & Clemente, 2012, p. 13). However, the major near-time opportunity described was in CO_2 enhanced oil recovery (EOR), where CO_2 is injected into depleted oil wells to recover untapped oil. But accelerating innovation to enhance the fossil economy, while the UNFCCC has urged since 1990 to limit the increase in CO_2 emissions to 2°C to avoid dangerous global warming, is far from responsible innovation. In contrast, nature-respecting sufficiency and its reflection on "enough" represent a line of thinking compatible with the social thresholds and the ecological limits defined by the UNFCCC. Eilertsen, Ingebrigtsen, and Striberny remind us in Chapter 2 that if we are to reach the Paris Agreement and practise global carbon neutrality by 2045, captured carbon should be utilised rather than buried (Li et al., 2023).

Circular economy?

The industrial economy in Europe is not circular, but entropic. Entropy means disorder: the energy is "thinned out," scattered to the wind and impossible to recover in quality; thus, "fresh" energy must be provided. It produces polluting waste and requires new supplies of energy and materials taken from old and new frontiers for resource extraction.[5] Estimates for the economy in the EU-27 are that only around 12% of the material input was recycled in 2019. The figure testifies to a "circularity gap," rather than a circular economy. One has to ask whether the material basis for producing more and more goods is actually present. A true circular economy would, in any case, require technology adapted to ecological efficiency (not just economic efficiency), as well as the reuse, sharing, and use of secondary materials. In this sense, the dominant economy is also undemocratic because it overrides the absent voices: the animals, the future generations, and indigenous peoples. A circular economy is a first step towards strong sustainability, but it is not a sufficient step in itself. We should be

> critical of sustainability strategies such as decoupling (in which economic growth is unlinked from resource use and environmental damage) and the circular economy (which aims to use resources more efficiently and reduce waste). Both of these concepts are at the core of the European Green Deal, the EU's 2019 to 2024 growth strategy. We are not critical of these ideas because they are bad, but because their applicability is limited. They are not enough to bring about changes on the scale needed to move toward true environmental sustainability while ensuring growth in quality of life.
>
> (Kovacic et al., 2021, p. 17)

In the iron grip of neoliberalism, it is instead argued that the market is the best tool for distributing goods such as natural land or emission quotas. The key word is compensatory measures: the planning authorities may well decide to build a four-lane motorway through this protected bird reserve, as long as they compensate for the natural damage by protecting a wetland area elsewhere in Norway. The idea for compensatory measures originates from President George W. Bush who experienced that the protective measures from the environmental authorities in Washington stopped too many infrastructure developments. Because, as was said, by compensating for natural damage, the final sum becomes "Net Zero." However, the "net zero emissions" policy has received a lot of criticism because in some cases, it has been a sleeping pillow for authorities and companies to pollute or damage more nature, but without the compensations being real.

The big opportunity: slowing consumption growth

According to a recent article in *The Lancet*, the real opportunity to slow entropy lies in changing demand patterns in high-income countries. This is also in line with the recommendations from the International Panel for Climate Change (IPCC), which finds that a controlled reduction in consumption and production will be able to lower emissions by as much as 40–70% by 2050 (Vogel & Hickel, 2023). The task before us is to revive the legacy of sustainability that was so strong in the past, to save a culture of frugality with its associated vocabulary and set of practices from oblivion, an attitude of caution in resource management that we find in various phenomena from our recent history. This includes the guidelines for petroleum extraction formulated by Norwegian politicians in the first years of extraction on the continental shelf – the Ten Oil Commandments – as well as the traditional culture in Norwegian seascapes, which values practices that have stood the test of time, and which prescribes life within the framework of the local landscape, practises conservation, and respects the knowledge of the ancestors (see Introduction). There is a powerful temporal element of social trust inherent in this attitude, which expresses a principle of intergenerational resource justice, that is, an attitude of frugality. It is necessary that the administration, politicians, business, and industry take this legacy seriously – of sustainability and prudence in the management of natural resources, social responsibility, and personal commitment. It reveals an important relationship between trust and sustainability, as intergenerational justice is a core principle of any robust conception of sustainability.

The main argument of this book is that the CCU project in Finnfjord mimes nature's photosynthesis, capturing CO_2 for the purpose of producing valuable fish feed, as well as releasing O_2 as a side product. We argue further that this kind of industrial ecosystem should play an important role in the making of an ecological and circular economy that, at the same time, releases Norway from its dependence on the global fossil economy that started with Konkraft's "work to maintain the competitiveness of the Norwegian continental shelf, so that Norway remains an attractive investment area for the Norwegian and international oil and gas industry" (cf. Introduction, p. 11). In an oil-free future scenario, this kind of industrial ecology binding CO_2, releasing O_2, and producing marine food through the utilisation of a waste product, in fact represents a "prosperous way down," the result of a reflection on "enough" – in a way that affects the aquaculture industry at the end of the value chain as well, where a prosperous way down equates better human and animal welfare. The point is that, in the future, we must drive innovation within the framework of a prosperous way down. After all our most precious values lie in the quality of life, not in quantitative growth.

Notes

1 Skirbekk (2011), Brox (2013), and Myhre (2012).

2 See Centre for Experimental Research on Fairness, Inequality and Rationality (FAIR) at the NHH Norwegian School of Economics, and especially Cappelen et al. (2022). See also discussion on resource management regimes and Keynesian welfare state in Norway in Introduction (this book).

3 Cf. Max Weber's speech "Science as a vocation," published in 1919, where he argues for the distinction between value-free science, on the one hand, and value-relatedness as constitutive condition of the social sciences broadly understood, on the other. "The Researcher" here refers to the Professor in Oceanography presented in Chapter 5.

4 Nevertheless, critics point out that the Treaty does not impose penalties, such as fees or embargos, for parties that violate its terms, and that there is no international court or governing body ready to enforce compliance (see "Is the Paris Climate Agreement legally binding? Experts explain," World Economic Forum 2021). According to Maljean-Dubois et al., a Conference of Parties (COP) decision can have political force. But, as a legal tool, it is not automatically legally binding . . . The international Court of Justice ruled on the legal effects of resolutions of the General Assembly of the UN, noting that "even if they are not binding, [they] may sometimes have normative value" (Maljean-Dubois et al., 2015, pp. 72–73).

5 Martinez-Alier, J. (2021). Circularity, Entropy, Ecological Conflicts and LFFU. *Local Environment*, *27*, 1182–1207, https://doi.org/10.1080/13549839.2021.1983795

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