Skyclean: Stiesdal Pyrolysis Project

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Is the project a case of…:

☐ State-initiated co-creation
☒ Entrepreneur-driven co-creation
☐ Grassroots-based co-creation*

**For an elaboration of the typology, please consult the GOGREEN theoretical framework p. 25.*

Integrated case analysis

Before proceeding to the scoring of the GFs, please provide a *3–5 page case analysis* in which you describe the background, history, and national, regional, and local contexts of the case, the problems and goals addressed by the local collaboration, the participating actors and their relationships, the unfolding of the co-creation process, the most important governance factors (this may include factors other than those in focus in this project), and the generated outputs and outcomes. The conclusion may specify a few lessons learned from the case study.

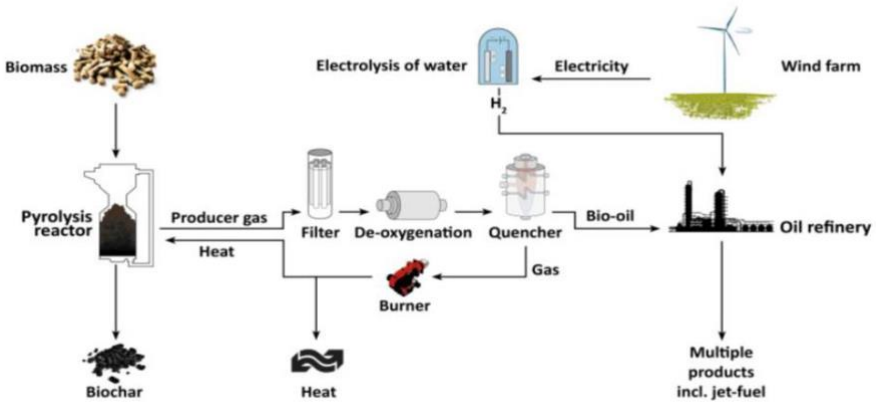
1) Background, history, and national, regional, and local contexts of the case

It was the **Danish Technical University** (DTU) at Risø in Denmark that developed the new break-through pyrolysis technology in a laboratory bench model that is now being scaled in the Stiesdal-owned SkyClean project that will create the first fully-automated commercial pyrolysis plant, which is planned to be in full operation by April 2024.

Pyrolysis involves heating an organic material, such as biomass, in the absence of oxygen in order to split it into green pyrolysis gas that can replace fossil natural gas and biochar that is so clean and stable that it can be tilled down in agricultural soil and sequester large amounts of CO_2. In principle, the green pyrolysis gas can be sold to pay for the spread of biochar leading to the sequestration of carbon in agricultural soil.

The prototype of the new pyrolysis technology was available around 2018-2019. It heats biomass such as straw, manure, wood chip, biogas fiber residue, etc. to about 600 degrees Celsius in a reactor with no oxygen (the system is flushed with nitrogen). The pyrolysis process leads to the production of **pyrolysis gas** (57%) that may be used for heating or condensed into biooil to be used as a fuel for ships and trucks, or through upgrading and addition of hydrogen, into fuel for jets. The pyrolysis process also produces **biochar** (42%) that can be safely stored in agricultural soil for hundreds of years.

Here is a **schematic illustration** of the pyrolysis process:



The **research in pyrolysis** took pace in the 1960s, but at that time the focus was mainly on the production of green pyrolysis gas. Triggered by the climate crisis, a new focus on the production of biochar emerged in 2008. The climate crisis led to a rebirth of pyrolysis research as the biochar could be sequestered in the soil and thus transport CO_2 from the atmosphere to soil depots.

There was a **biomass group at DTU** that worked theoretically and practically with pyrolysis. In 2012, they had broken the code and found a way of doing pyrolysis that resulted in the production of clean and stable biochar that can safely be spread on agricultural land. Researchers at DTU regularly invite private business firms to work with them with the purpose of creating spin off companies based on new technologies. SkyClean is a result of collaboration between DTU biomass researchers and business engineers from Stiesdal SkyClean.

Henrik Stiesdal, the founder and owner **of Stiesdal SkyClean**, comes from the wind turbine sector where he played a leading role. He built his first wind turbine when he was a teenager and developed it into the first Vestas wind turbine. Later, he was the chief entrepreneurial developer in big wind turbine companies such as Bonus and Siemens. Despite his huge contribution to the development of sustainable energy in Denmark, he ended up concluding that it is not enough to reduce the production of CO_2 emissions; we need to **reduce the CO2 concentration in the atmosphere** to fend off the climate crisis.

He wrote a newspaper article mentioning the promise of pyrolysis for becoming carbon negative but without mentioning the perennial problem with the toxic tar compounds of biochar. In response to the newspaper article the big Danish beer-brewer Carlsberg invited him to a meeting to discuss some business ideas. Here he accidentally met a guy from DTU who connected him with some biomass researchers at DTU. They told him that they had solved the tar problem. This information started the **SkyClean project based on collaboration between DTU and Stiesdal Fuel Technologies and with the farmers' interest organization Agriculture and Foods on the sideline.** There was a formal collaboration agreement with DTU and one of the DTU researchers moved over to the new SkyClean subsidiary company (one of four Stiesdal subsidiaries), thus stressing the close relation between the DTU researchers and the engineers at Stiesdal.

Researchers from other universities soon joined. The goal of SkyClean was to rapidly scale the pyrolysis technology into a national catch and capture solution.

To provide 'proof of concept' by showing that the technology would work outside DTU, SkyClean first built a fully automated test plant with the same size as the original DTU model. The test plant was built in 2021 in the small town of **Brædstrup** with the help from a local blacksmith who had time on his hands because he had just crashed with a big company. In 2022, a ten times bigger pyrolysis plant (2MW) was built in **Skive** as a part of a local energy cluster called Greenlab that aimed to produce synergistic relations between different sustainable energy producers. This plant was designed to use straw pellets as feedstock.

In 2023, a ten times bigger commercial plant was built in **Vrå** (20MV). This plant was designed to use biogas fiber residue from an existing local biogas plant. Since the biogas fiber residue is wet, it needs to be dried to make pellets that can be used in the pyrolysis reactor. There is a synergistic relationship between the biogas plant and the pyrolysis plant. The former delivers feedstock to the pyrolysis plant, and the latter delivers biogas that is used to produce heat in the biogas plant. The gradual scaling of the pyrolysis technology into a fully-automated commercial plant serves to gradually eliminate the problems that always arise when technological solutions are scaled.

The 20MW pyrolysis plant in Vrå is built as a part of the **'Scale-up project'** that received 124 million Danish Kroner (about 18 million Euros) from a central government program. It is the Scale-up project that is the key focus of this case study. The Scale-up project originally applied for money for an additional work package on the governance of the national implementation of pyrolysis technology, but that was cut away by the funding program. This part was funded later as a part of the SIMPLY INNO-CCUS project.

The **prospects for pyrolysis** in Denmark are promising. With about 50 double-size pyrolysis plants spread around the country, it is estimated that there will be an annual CO_2 reduction of more than 1.8 million tons CO2e. Added to that, the green biogas will help to reduce the consumption of natural gas leading to an annual reduction of 1.6 million tons CO2 from fossil fuels. That being said, it is important to note that while burners of fossil natural gas can be used to burn biogas, they cannot burn gas from pyrolysis. Hence, there is not a one-to-one substitution for all purposes.

Denmark is an **agricultural country** and Danish farmers will be able to deliver a lot of manure and straw for pyrolysis, although they may want to keep some for themselves and till it down to improve soil quality. Interestingly, tilling 1 ton of biochar produced through pyrolysis has a much bigger sequestration effect than tilling 1 ton of straw and manure.

2) The aims of the project and the sustainability problems that it seeks to address

The SkyClean project aims to **scale the use of pyrolysis to solve the climate crisis**. Pyrolysis literally means "splitting by fire". SkyClean aims to split biomass into green biogas and clean and stable biochar. While green biogas may crowd out fossil natural gas, the tilling down of biochar will sequester carbon, improve soil structure and enhance plant growth due to the phosphor compound of the biochar, which is significant when the feedstock is manure.

A PowerPoint **presentation of the SkyClean project** presents the aims in the following way:
"The purpose of the project is to scale up the SkyClean concept that offers climate change mitigation through carbon capture and sequestration combined with the production of green fuels. At the most aggregate level, the project aim is to facilitate abatement of climate gas emissions from the agricultural sector in the megaton range. At a more specific level, the project aim is to deliver a pre-commercial SkyClean plant scaled to commercial-level 20 MW rating. In addition to the physical plant, the deliverables will also comprise significant improvements in the scientific basis for pyrolysis processes and product to end-uses. So, the indirect goal is also to develop a business model that makes it possible for all the involved parties—from farmers to investors—to build and operate new pyrolysis plants.

3) The participants and their interaction and communication in and between meetings
Participants in the **early R&D phase**:

a) **Denmark's Technical University (DTU):** The biomass group at DTU Risø led by Ulrik Henriksen and Jesper Arenfeldt invented the new pyrolysis technology that could produce safe and stable biochar.
b) **Stiesdal A/S:** Parent company that has four subsidiary companies. Led by Henrik Stiesdal who connected with the researchers at DTU and created SkyClean to scale and commercialize the new pyrolysis technology.

Jesper Arenfeldt at DTU soon joined SkyClean and became a cornerstone in promoting a very close collaboration between DTU and Stiesdal. The close collaboration is evidenced by the fact that Jesper Arenfeldt still has an office at DTU Risø. Currently, 8 SkyClean people are based at Risø where SkyClean has its R&D department.

Additional participants in **the later scaling phase**:

a) Industrial partners:

1. Stiesdal SkyClean: Technology developer formed by Stiesdal Fuel Technology in collaboration with DTU researchers and other partners
2. BB Bioenergy, Vrå: Biogas plant that hosts of pyrolysis plant in Vrå
3. KK Wind: Technology developer with responsibility for automation and traceability
4. AEA: Energy systems development
5. Topsø: Syngas and methanol synthesis

b) Logistics partner:

1. West-Jutland Cooperative: Handling and logistics of biochar

c) Research & Development partners:

1. DTU Chemical technology: Pyrolysis technology, biochar characterization and toxicity
2. DTU Mechanics: Thermodynamic modelling
3. RUC: Feasibility studies
4. SEGES Innovation (affiliated with Agriculture and Foods): National field trials with biochar and research about how farmers can play a role in pyrolysis
5. KU – Plen: Field trials and lab trials with biochar
6. AU – ENVS: Ecotoxicity, effects of biochar on soil biome in lab and field trials
7. AU – AGRO: Lysimeter trials and greenhouse gas emissions

d) Project management partners:

1. Energy Cluster Denmark: National cluster organization for energy—partly state funded through participation in state-funded projects and partly membership funded—supporting collaborative energy development projects and has responsibility for writing project proposals, project administration, project development, process leadership, and responsibility for dissemination and running energy follow group
2. Food & Bio Cluster: National cluster organization for food and bio resources helping companies accelerate innovation and sustainable development through inspiration, network collaboration and business development in partnership. Responsible for dissemination and the energy and agricultural follow group

e) Other partners:

1. Hjørring Municipality: Permissions and local business development
2. Local farmers: Provision of straw and manure and tilling down biochar

An informant contends that there are **participants from all parts of the value chain**. That is important to identify bottlenecks in the process and remove them.

4) How often do they meet, and do they communicate between meetings?

In the publicly funded SkyClean Scale-up project, the **plan was to have a lot of joint meetings** for all the participants, but the **actual need for meetings has been limited**. Collaboration mostly takes place within the work packages between which there is a sharp division of labor. The leaders of the work packages are supposed to meet with the leaders of the Scale-up project every month, but not all meetings are held.

Outside the formal meetings, there seems to be **a lot of informal interaction** where participants meet at DTU, at the Stiesdal headquarters in Give and at the test and building sites in Bræstrup, Skive and Vrå.

On the whole, there is a tendency for the researchers to interact a lot with each other and for the industrial development, building and construction partners to interact with each other, although the bilateral contacts of the later to Stiesdal rather than to each other are predominant. Some of them tend to be more subcontractors than partners. Both groups have close contact with Stiesdal. In sum, **collaboration takes place within two distinct clusters with Stiesdal as the central contact point that ties it all together.**

The relatively **few farmers** are both in contact with construction partners and researchers (especially SEGES), while the **municipalities** only collaborate with the managers and constructors at the different test and construction sites. The different **agricultural organizations** work mostly with the researchers.

5) The role and forms of knowledge sharing, coordination and collaborative problemsolving

In SkyClean there is a joint ambition to solve the climate crisis by developing and upscaling pyrolysis plants. This is achieved by **sharing knowledge and coordinating activities**, but also through **collaboration** and dialogue about emerging problems and challenges in the scaling process.

There is a **considerable focus on external collaboration**. In a press release it says: 'We are working together with knowledge institutions, agricultural organizations and public authorities to create a framework supporting the use of biochar in Danish agriculture'.

The need for **crosscutting collaboration** was particularly big during the writing of the Scale-up application. There is less collaboration during the implementation that takes place in and through small, dedicated expert groups. However, there are still some crosscutting collaborations, e.g., engineers in Skive and Vrå working together to develop and optimize the plants.

6) The relation between consensus and conflict and the handling of the latter

In general, there is **very little conflict**, perhaps due to the **strongly articulated common goal and the high degree of alignment**. There are some minor conflicts between the research and business parts of the project and there have been some conflicts with subcontractors at the building site. Still, everybody tends to agree that the goal is to scale up the Skyclean pyrolysis technology.

7) The role and form of leadership: lead actor, steering group and/or collective leadership

Henrik Stiesdal is the undisputed owner-leader of Stiesdal and SkyClean, although the CEO and COO are the formal leaders. Being the parent company of SkyClean, Stiesdal Fuel Technologies has the power to recruit and dismiss partners and sub-contractors. Hence, Stiesdal is the backbone organization for the entire SkyClean operation that includes lots of formal and informal collaborations. This position is bolstered by all the funding provided by Stiesdal, and the reputation and charismatic personality of Henrik Stiesdal.

The **Scale-up project** is a central part of SkyClean and is a publicly financed collaborative project with money from the Danish Government Pyrolysis Fund. While the **project-owner is Henrik Stiesdal, Jesper Noes is the formally appointed leader**. He is in charge of the budget, project management and contact to the researchers. **Christian Munk Jensen is the vice-leader**. Christian and Jesper have weekly meetings. **Jesper Arenfeldt is leader of research and Uffe Eriksen is the leader of the building site** in Vrå. Jesper Arenfeldt and Uffe Eriksen are leaders of 2-3 work packages each. The distributed leadership means that Jesper Noes floats above the waters. The distributed leadership also counterbalances the lead actor model that is the predominant leadership model.

In the relatively autonomous **work packages of the Scale-up project** there is a **flat team-based project leadership** where everybody chips in.

Work package leaders are supposed to meet regularly in a kind of **steering group**, but meetings are few and far between. There is a clear division of labor between the work packages that minimizes the need for meetings.

There are some **plenary meetings** with updates and status reports from the different parts of the Scale-up project, but they are also few and far between. The construction part does not need to hear about the progress in the research part and vice versa.

In sum, in the company SkyClean Henrik Stiesdal is the **lead actor in the development of new pyrolysis plants**, but in the Scale-up project this **lead actor model** is complemented by a **distributed leadership** and a **collective leadership** within the work packages and the crosscutting steering group. The people from the R&D work packages rarely communicate with people from the construction work packages and there are very few plenary meetings bringing together all the project participants.

8) The temporal unfolding of the co-creation process: major shifts and ups and downs

The **research and development phase** was in 2018-2021; then came the upscaling phase from 2021-2023; and the **commercial expansion phase** began in 2023. There has been an enormous pace in the scaling process.

There are **two important turning points**. The first is when Henrik Stiesdal hooked up with the DTU researchers. The second is when the Up-scale project received money and thus public recognition from the Pyrolysis Fund.

Interestingly, most actors talk about the **time pressure and the need to deliver** massive reductions before 2030. There must be quick and big results for the political interest in pyrolysis to persist.

9) The most important governance factors

Contributing to solving the climate crisis is the goal that every must commit to in order to be part of the collaborative SkyClean scale-up project. The project is supported by a public sector that is open to collaboration and citizen participation. This makes it easy for the project to leverage support for its project to pecuniary support and remove legislative barriers. Collaboration between researchers and business actors is at the heart of the project, but many other actors joined the public-private partnership, even some lay actors. Collaboration is supported by a broad recognition of interdependency between the actors, the use of physical and digital platforms and a facilitative leadership. Collaborative experiences from the wind turbine and biogas sector also played a supportive role. The core of the project is experimentation based on iterative cycles of testing, evaluation, scaling and revision that in the daily work was supported by critical evaluation of chosen solutions. Blended financing that has mainly combines money from Stiesdal and the public Pyrolysis Fund was decisive to facilitate rapid scaling.

10) The generated outputs and outcomes

A key informant summarizes the output of SkyClean in this way: “The scaled SkyClean pyrolysis technology can take biomass residues from agriculture and forestry and turn them into energy that can substitute fossil fuel while simultaneously turning them into a clean and stable biochar that can be stored in agricultural soil, cement or asphalt. The primary goal is to till down biochar in agricultural soil where it will add phosphor but remove all the hormones etc. that is found in manure due to the pyrolysis process”.

One informant claims that a combined biogas and pyrolysis plant for each ton CO_2 it emits will remove 5.6 tons CO_2. The general conclusion is that pyrolysis is the most cost-efficient net-zero CO2 solution to date.

11) Lessons learned about the conditions for co-creating green solutions

Several informants talk about how strategic entrepreneurship also depends on accident and luck. It was accidental that Henrik Stiesdal learned about the DTU technological breakthrough, that his cousin worked with scientific investigations of biochar; that the blacksmith in Brædstrup was available and ready to work in a new innovation context, etc. Nothing suggests that those connections would not have been made if not by accidence. That being said, accidents like these tends to happen more often to people with many connections and a readiness to use them.

The green climate-energy sector is heterogeneous and difficult to work in. There is a lot of uncertainty and high risks and everybody is waiting for anybody else. At the same time, we need swift action. So, collaboration and alliance formation is needed to absorb risk, but at the same time competition is necessary to drive innovation.

Scoring and analysis of governance factors

1. Perceived importance of biosphere conditions

QCA score:	Scoring confidence:	Data sources:
☐ 0	☐ Low confidence	☒ Interviews
☐ 0.33	☐ Medium confidence	☒ Documents
☐ 0.66	☒ High confidence	☒ Observations
☒ 1		

Please elaborate on the reasoning behind your scoring for this governance factor:

All informants agree that the **SkyClean pyrolysis project from its inception has been driven by the concern for severe biosphere problems** epitomized by the climate crisis. Here are examples of the answers to the question about the role of biosphere conditions:

a) "SkyClean was solely initiated to solve the climate crisis. Had it not been for the climate crisis, we would never have done this. That is the brutal reality of it".
b) "That can be said very clearly: the climate crisis is all-decisive for the project. 100% (…) The development of pyrolysis is triggered by the Paris Agreement and has in turn been a driver for the formation of partnerships. The Paris Agreement clearly says that net-zero requires removal of CO2 from the atmosphere".
c) "It is the climate crisis that informs and drives the project. We need to solve that".
d) "The main driver for the project participants has been to solve the climate crisis and doing it in a way that is economically viable".
e) "Bread on the table is important, but for me it is more important to contribute to the green transition and solve the climate crisis".

Conference observations confirm that **severe biosphere problems are the main and overarching reason for initiating the project** that will help the agricultural sector significantly in reducing CO2 emissions.

An informant claims that there is also **another driver for the development of pyrolysis** than the climate crisis and that is the growing interest in clean smart energy technologies amongst people who do not necessarily have the climate crisis at the top of their agenda.

Besides, there is also an emphasis on **how pyrolysis may generate future incomes stream** for farmers. That came out clearly at the SkyClean conference in November 2023.

Nevertheless, the perceived importance severe biosphere problems is the main driver of the project.

2. Legislation, programs, and formal goals

QCA score:	Scoring confidence:	Data sources:
☐ 0	☐ Low confidence	☒ Interviews
☐ 0.33	☐ Medium confidence	☒ Documents
☐ 0.66	☒ High confidence	☐ Observations
☒ 1		

Please elaborate on the reasoning behind your scoring for this governance factor:

In central SkyClean documents there are frequent references to **international policy goals and programs** such as the Paris Agreement and to EU's climate goals and to the new EU directive about fertilizers from 2022 that makes biochar available in the EU internal market for soil improvement products.

Moreover, several **national policy agreements and reports** provide direct or indirect support for the SkyClean Scale-up project:
In the report **Known ways and new paths to 70 percent reduction** from 2020 the Danish Climate Council states that new technologies are necessary to achieve the 70% reduction goal in 2030. New technologies for Carbon Catch and Storage amounts to half of the aggregate reduction potential in the development track.

The **Agricultural Agreement** from 2021 between a broad selection of political parties in the Danish parliament supports new CCS initiatives supports the development of new technologies that can deliver future solutions reducing the emissions from Danish agriculture. It sets aside 575 million DKR for the development and demonstration of new technologies. The goal is to reduce emissions of 7.4 million tons CO_2e from agricultural production before 2030 hereof **2 million tons CO2e before 2030** through Carbon Catch and Storage technologies such as pyrolysis. Most of the informants refer to the 2 million reduction goal and see it as a key objective of the project to contribute to achieving it within the given timeframe. The time pressure for fulfilling the goal urges them forward and means that the scaling must be done fast. In addition to the 575 million in the development track, there will be new money for bio refinery. 200 million DKR is reserved for pyrolysis in 2021-22 and 196 million DKR i in 2023-24

In the Danish **Energy Analysis Report** from 2022 it says that: 'EU and a number of member states have agreed on ambitious climate goals for 2030 and 2050 in order to live up to the Paris Agreement. In

Denmark the goal is a 70% reduction of climate gasses in 2030 compared to 1990, and to reach climate neutrality in 2050. The EU Commission has recommended intensive electrification combined with energy efficiency and carbon sequestration as key tools for reaching the 2050 goal.'

At the **local** level, the City Council of Hjørring Municipality has drafted **The Big Climate Journey Plan** addressing citizens and private companies and the need for them to transition into low-carbon behavior. The local climate plan refers to the government's 70% CO2 reduction goal in 2030 and specifies what citizens and private firms can do to help achieving them. The climate plan indirectly mentions pyrolysis as it talks about the new innovative development projects of the local biogas plants.

3. Relative openness of public governance paradigms

QCA score:	Scoring confidence:	Data sources:
☐ 0	☐ Low confidence	☒ Interviews
☐ 0.33	☐ Medium confidence	☒ Documents
☐ 0.66	☒ High confidence	☒ Observations
☒ 1		

Please elaborate on the reasoning behind your scoring for this governance factor:

Traditionally, Danish municipalities were well-lubricated local **public bureaucracies** delivering social, health and educational services to the citizens and regulating social and economic life. Due to pressure from the Ministry of Finance and shifting governments, the municipalities were transformed by a series of **New Public Management** reforms from the mid-1980s onwards. Gradually more and more services were contracted out to private service providers, citizens were given a free service choice in newly created quasi-markets, and professional leadership based on performance management was used to trim the remaining public organization. More recently, New Public Management has been criticized, first by Danish PA researchers and employee organizations, and later by the government and leading political parties for being based on mistrust and for straitjacketing public employees through an accelerated production of performance targets and documentation demands that ended up reducing the efficiency and quality of public services. A new focus on wicked problems has opened the door for **New Public Governance** ideas about the role of collaborative networks and partnerships in spurring effective problemsolving and innovation (see Torfing and Køhler, 2016)

Ideas about collaboration, effectiveness and innovation pervade the **Municipal Plan** of Hjørring Municipality where the section on 'Horizon and resolve' says: "The City Council wants to meet the future with proactive measures. We will shape the future through close collaboration with external actors. We will build on our strength and potential and we must all be ready to change. We are stronger when we work together and are open to new future solutions".

More specifically, the climate plan of Hjørring Municipality, **The Big Climate Journey,** talks about the need for a "climate partnership between municipality, citizens and private firms".

The **Mayor** is quoted saying: "Together with the City Council, I want to enter into a dialogue with citizens and business firms so that we find the good climate solutions together. I will experience that we invite you to participate in a dialogue and that we will invite ourselves to come visit you".

The **Municipal CEO** is quoted saying: "We must reduce our carbon footprint by 70% in 2030 and we can do it if we all contribute and collaboration with each other. Neither citizens and private firms nor the municipality can do it alone. We must all embark on in the big climate journey".

A municipal climate leader says that his **role is to be outward-going and think in terms of collaboration and partnerships**. Other informants reports that Hjørring Municipality was very keen to support the construction of the pyrolysis plant and actively engaged in the collaborative planning process to make things as smooth as possible. This is different from Skive Municipality where the process was slower and more bureaucratic.

A public official claims that there are many progressive, green and entrepreneurial farmers in the municipality and that the municipality has been **very open to their ideas**. This has led to the establishment of a whole series of biogas plants and one of them now works closely with Skyclean. However, there are some dilemmas since the municipality is both a proactive promoter of the green transition and a regulatory authority that must give permissions and approvals. As for the latter, there were some problems with the biogas plant that both had some discharge of manure and biogas and contributed to enhanced traffic in the local area with big lorries coming and going. Attending to these problems slowed down the construction of the biogas plant that now provides feedstock to the pyrolysis plant.

A concrete example of the openness of the municipalities to citizens and local actors is that the municipality has a **mobile climate outdoor office** that moves around in the municipalities and makes it possible for people to come and discuss green environmental and climate issues with municipal workers.

There is also a question of **the relative openness of national-level ministries**. A key informant says: "We are constantly contacting the ministerial agencies to get them to regulate our area in a supportive way. It is fine that they are raising demand, it just needs to go fast and support the transition to circular rather than linear economy." Apparently, there is no problems discussing these matters with the ministries. There are many meetings, and an informant reports that the government is underway with a new pyrolysis strategy. Hence, national-level government seems to be open and responsive.

4. Formalized institutional channels for citizen participation and community mobilization

QCA score:	Scoring confidence:	Data sources:
☐ 0	☐ Low confidence	☒ Interviews
☐ 0.33	☐ Medium confidence	☒ Documents
☐ 0.66	☒ High confidence	☐ Observations
☒ 1		

Please elaborate on the reasoning behind your scoring for this governance factor:

Like all other Danish municipalities, Hjørring Muncipality has **the whole package of channels for citizen participation**. Consultation of local citizens is mandatory in urban planning. Most public service institutions have elected user boards. There is a tradition for citizen involvement in local policy development. Right now, a new business development policy focusing on green innovation is subject to intense debate with local stakeholders. Finally, Hjørring Municipality has a special Citizen Councillor that helps citizens and private business to find ways of contacting and collaborating with the municipality.

Danish municipalities are strong decentralized units with huge service delivery responsibilities, a democratically elected City Council and taxing power. There is a lot for the local citizens to influence. This results in a high voter turn-out in local elections (typically around 86%). The **local civil society is well-organized** and local stakeholders are eager to participate to influence political and administrative decisions. The strong local governments and strong civil societies have traditionally been connected through formal and informal networks.

There is **a long and strong corporatist tradition for public and private cooperation**. A SkyClean informant claims that this type of corporatist cooperation is a precondition for being successful with the new pyrolysis technology, not only locally, but also at the national level. As a matter of fact, public-private cooperation between a university and a business is the sine qua none for SkyClean.

In addition, **Danish Agriculture** with its cooperative movement and many local farmers organizations has a **strong tradition for collaboration, participation and public enlightenment**. There are many local meetings where the future of farming and the use of new technologies are discussed, often with presentations from invited speakers.

5. Mechanism for ensuring top-down government and bottom-up social accountability

QCA score:	Scoring confidence:	Data sources:
☐ 0	☐ Low confidence	☒ Interviews
☐ 0.33	☐ Medium confidence	☒ Documents
☒ 0.66	☒ High confidence	☒ Observations
☐ 1		

Please elaborate on the reasoning behind your scoring for this governance factor:

SkyClean is committed to total transparency for use of financial means and reports back to the government Pyrolysis Fund every time there is a new grant payment. There is also a big annual report about spending and achieved results that must be submitted. While the EUDP secretariat is praised for being supporting an unbureaucratic in its grant administration, the accountability and reporting demands from the Pyrolysis Fund are so heavy that SkyClean may not apply for money again. A positive aspect of the **top-down accountability** is that it has forced SkyClean to put more emphasis on the organization and the formulation and achievement of strategic goals. Otherwise, there is little feedback from the accountability holder and it is limited what SkyClean has learned from the upward accountability to public authorities.

The Scale-up project has a **whole work package dedicated to stakeholder engagement and stakeholder dialogue**. It also has a **Follow Group** consisting of public and private stakeholders that it reports to on a regular basis and gets feedback from. The purpose is to build support though down-ward accountability.

SkyClean has also written and published a **White Paper about biochar** that is meant as a form of community-focused accountability as it aims to document and account for the impact of pyrolysis on local farming communities.

One of the SkyClean managers says: "It may sound a little holy, but we believe that we cannot move forward before **all the different stakeholders have an understanding** of what we are doing". Hence, dialogue with downstream actors such as farmers is crucial. One of the Scale-up project leaders confirms this: "The main objective of our dissemination activities is to ensure that relevant stakeholders such as the farmers can keep up with the development of the project so that they are ready to receive and spread the biochar".

From SkyClean informants we learned that they **proactively approach different audiences** to inform them about the present state and results of the use of pyrolysis. They contacted the Climate Council to set up an information meeting about pyrolysis where the council members could ask critical questions. They have organized similar meetings with different groups of farmers. They have also had visits from school classes at the VRÅ plant. They also hosted a conference in November 2023 on pyrolysis where key stakeholders could come and ask questions.

At the **November conference** a multitude of researchers gave presentations on the newest evidence on various aspects of pyrolysis, including its environmental consequences (see conference program for details). It seems like an **important purpose of this event was to demonstrate accountability and legitimacy towards key stakeholders**, including the Danish Environmental Agency, who make important decisions that will influence the prospects for upscaling the project further. In particular, they are the one to reduce the regulatory barriers in paragraph 19 to tilling down biochar. However, the Government Environmental Agency had cancelled their participation in the last minute.

The day after the conference, a **workshop** was arranged for key stakeholders of the project and pyrolysis experts (researchers), where the purpose was to discuss different stakeholders' questions about pyrolysis. Participants were invited to pitch questions for the workshop.

There seems to be different ways of ensuring downward social accountability, but there are hardly any reports about **how critical feedback creates learning and transformative response**. There are only stories about farmers worrying about what the biochar does to the soil, and also some complaints about the biochar creating too much dust when spread out and tilled down. The reason for that was apparently that the pelleting process had not been optimal due to some technical problems and thus produced biochar that was a little brittle. The learning from this was to always ensure a high pressure in the pelleting process.

Overall, there are various attempts to inform local audiences, but it is more about preempting criticism than actually engaging with bottom up questions and judgements from accountability holders and learning from their response.

6. Strategic agenda-setting by means of translation

QCA score:	Scoring confidence:	Data sources:
☒ 0	☐ Low confidence	☒ Interviews
☐ 0.33	☐ Medium confidence	☒ Documents
☐ 0.66	☒ High confidence	☒ Observations
☐ 1		

Please elaborate on the reasoning behind your scoring for this governance factor:

One of the leading figures in SkyClean says that **the SDGs are fine, but SkyClean only focusses on finding climate solutions**. In Stiesdal Fuel Technologies, we are told, the mission statement is: "Climate, jobs, good things, having fun and no quarrels in the corporate board in that order".

Another key partner in SkyClean says that the partners may **talk indirectly about the SDGs and goal 13, but never mention them explicitly**. Instead, the key reference is to the Paris Agreement and the Danish CO2 reduction goals of delivering 2 million tons CO2 reduction before 2030.

A third informant confirms this: 'To be perfectly honest, **we have not focused on the UN SDGs at all'** and another states: "To be perfectly honest: we have not been driven by the UN SDGs". A leading SkyClean partner puts it this way: "The climate crisis is the most important problem. **Water, education, gender equality etc. is also important, but we cannot be the driver in solving these problems**. We do not have the bandwidth".

When we observed discussions at the November 2023 conference there was **no mentioning of the UN SDGs** by any of the participants.

Hjørring Muncipality works actively with the UN SDGs although they are said to have **moved a little more in the background**. There is still reference to the SDGs when environmental permissions are granted, but there has come a new focus on climate and green innovation. While the SDGs are a little general, abstract and fluffy, CO2 reduction and sequestration is more concrete.

The municipality seems eager to find a way to **translate the climate agenda to the local farmers** and mentions "model farms" as a good way to do it. Farmers are persuaded by what they can see, touch and smell. Good and innovative examples of green and sustainable farms have been made visible together with the local farmers' association.

There has been a clear focus on translation of the climate agenda and the role of pyrolysis in SkyClean. Hence, the actors in SkyClean are well aware that it is important to **sell pyrolysis to the farmers** since they

have to deliver the biomass and til down biochar pellets. One informant says that the project members do all they can to recognize the pressure on agriculture, appreciate the need for agricultural food production and then show the farmers that the agricultural carbon footprint can be lowered through pyrolysis. An informant claims that pyrolysis may appeal to the farmers who can go from being climate sinners to becoming climate heroes. They can even save money on it if sequestering carbon by tilling down biochar can reduce their CO_2 tax, which is about to be introduced in Denmark. Unused straw can deliver the first million tons CO_2e reduction through pyrolysis. The next million tons may be harder to get but may come from biogas fiber residue. A third informant says that farmers will also be interested in the soil improvement resulting from use of biochar.

The **translation work in relation to pyrolysis is hard** as people must understand photo synthesis, the climate problem, the pyrolysis technology and the difference between sequestering carbon and crowding out fossil fuels. The challenge is that the problems as well as the solutions the project work with rely on complex science and technologies that lay people struggle to understand so there is a huge communication challenge. On the other hand, the farmers are really looking for solutions that can improve the reputation of the sector and produce new income streams. The experience with introducing wind turbines has made them susceptible to implementing new green solutions. So, they are **willing to listen to new ideas.**

7. Construction of narratives about successful multi-actor collaboration

QCA score:	Scoring confidence:	Data sources:
☐ 0	☐ Low confidence	☒ Interviews
☐ 0.33	☐ Medium confidence	☐ Documents
☐ 0.66	☒ High confidence	☒ Observations
☒ 1		

Please elaborate on the reasoning behind your scoring for this governance factor:

There are **no previous examples of successful collaboration in the pyrolysis sector**. SkyClean started from scratch with developing pyrolysis technology in Denmark. However, there are positive stories about multi-actor collaboration in other sectors.

The **Danish wind turbine adventure** was driven by collaboration between private companies, public authorities and researchers. Success would never have been achieved without this collaborative partnership. Many of the SkyClean people came from the wind energy sector and are now copying the collaborative partnership approach from the wind energy sector to the new and emerging pyrolysis sector. As an informant puts it: “there is a total parallel (…) and we refer to it in our slide shows”. Another informant confirms: “The collaboration between politicians, universities and private companies about wind turbines has been a source of inspiration”. A third informant adds that the wind turbine adventure was driven by four factors: 1) The government was committed politically; 2) It created long-term framework conditions including 30% subsidy, power companies were obliged to buy power from wind turbines, there was a fixed tariff for purchase of wind turbine power, etc.; 3) There was a clear approval procedure; and 4) researchers and private companies worked well together.

In the **biogas sector** that has aimed to crowd out fossil natural gas by making biogas out of straw and manure, there is a strong tradition for forming partnerships. The farmers' interest organization Agriculture and Foods has helped organizing an industrial network for the biogas sector and has done the same for pyrolysis, thus creating a collaborative environment where everybody knows each other and there is a lot of trust and belief in partnerships as the way forward.

8. Building or harnessing institutional platforms and arenas

QCA score:	Scoring confidence:	Data sources:
☐ 0	☐ Low confidence	☒ Interviews
☐ 0.33	☐ Medium confidence	☐ Documents
☐ 0.66	☒ High confidence	☒ Observations
☒ 1		

Please elaborate on the reasoning behind your scoring for this governance factor:

In the early development phase, DTU Risø provided a **joint innovation platform** with testing facilities, tools, technologies and offices. Several private companies such as Aquagreen, Mash Makes and Stiesdal were present and worked with DTU researchers. They borrowed ideas and tools from each other and provided mutual inspiration. There was more collaboration than competition in this early development phase.

The small test plant in Brædstrup is still in use as a place for testing new ideas. When we visited, engineers from SkyClean and an international PhD-student were experimenting with condensing biogas into biooil. The location of the second pyrolysis plant in Skive was motivated by the presence of an innovative **energy platform Greenlab**. The Skive plant itself functions as an **innovation platform** for the researchers and construction partners of the Scale-up project since new solutions can be tested before they are scaled at Vrå. However, there are also regular meetings in Give where the SkyClean engineering department lies and in Risø where the R&D department is located.

The distributed workplaces in SkyClean means that collaboration is often enabled by use of **online meeting platforms** such as Teams. In one of our observations, we saw how people at DTU, Give and Brædstrup solved problem in a Teams meeting. Several informants reports that digital meeting work well for them. The Scale-up participants also share files via the SharePoint site that makes available work files wherever they are physically located.

9. Provision of access to blended financing

QCA score:	Scoring confidence:	Data sources:
☐ 0	☐ Low confidence	☒ Interviews
☐ 0.33	☐ Medium confidence	☒ Documents
☐ 0.66	☒ High confidence	☐ Observations
☒ 1		

Please elaborate on the reasoning behind your scoring for this governance factor:

The original technological breakthrough at DTU Risø was **paid for by the state** and thus the Danish taxpayers. DTU is a public university that receives state money per student and for basic research.

The construction of the plants in **Brædstrup** and **Skive** were **financed by Stiesdal** that owns SkyClean. However, in 2021, the project received a large **public grant from the EU's Energy Technology Development and Demonstration Program** (EUDP) to advance the SkyClean technology to TRL 7 (technology Readiness Level) and de-risk the technology sufficiently to make the final investment decision for the first full-scale plant.

Moreover, in August 2022 the **scale-up project** aiming to build the **big new pyrolysis plant in Vrå** received a large **public grant from the government Pyrolysis Fund** that was established as a part of the Agricultural climate agreement. An informant claims: "Without this grant Skyclean would not have come to the market". However, the building and construction costs in Vrå were larger than the grant money could finance, so Stiesdal has also made a considerable **private investment** in Vrå.

The building of the plant in Skive was financed by Stiesdal, and running it is partly financed by **carbon credits** from a big Swizz helicopter company and from sale of biochar pellets.

In addition to the money from the Pyrolysis Fund and Stiesdal, the Scale-up project that built the plant in Vrå also received some **co-financing from the industrial partners and the research institutions** that are only partly reimbursed for the time they spent on the project (their costs are reimbursed with different percentages: 40%, 60% or 90%). Even the **local municipality** claims that at least two employees use a considerable amount of their salaried work time to support SkyClean in different ways. Finally, BB Bioenergy that owns and operates the biogas plant provides the land and some physical facilities,

The Vrå plant may also end up **producing heating** for private houses if there is surplus biogas, but this will be provided **free of charge** to earn local goodwill for the pyrolysis plant.

A recent memo from Stiesdal on **Price and Potential of Pyrolysis** presents calculations about the economic viability of future pyrolysis plants based on current and projected prizes. **Wet pyrolysis plants** based on biogas fiber residue that needs drying will produce and sell gas for heating and biochar whereas **dry pyrolysis plants** based on straw that needs no drying will produce heating, biooil. In addition, both types of plants will bear operation costs and costs of distributing biochar, while also receiving income from carbon removal certificates. The calculations for 2025 shows a negative EBIT (result before interest and tax), but when the current subsidy from the Pyrolysis Fund is added the EBIT becomes positive. The calculation for 2030 shows a positive EBIT without subsidy because the prize of biooil is expected to go up. The conclusion is that building of 50, 80 or 200 pyrolysis plants in Denmark is **economically viable**.

Since the amount of biogas fiber residue is limited, there will be a need to **combine biogas fiber residue with straw as feedstock** if 50-80 are going to be built. However, with rising prizes on biooil, pyrolysis plants will later on be able to pay for the purchase of straw.

The **future scaling plan** is for Stiesdal to build another 5-6 pyrolysis pants in joint venture and then open up for licensing. The attitude seems to be that if the Chinese copy the plants without paying for license, then it is still good for the climate. However, while the original break-through technology is open source, the new pyrolysis plant will not be available in open source: the partners have argued that it would mean that if they contributed to the project, they would help their competitors.

The **alternative** to private investment in pyrolysis plants is the formation of **joint farmer ownership** through cooperatives that have a long tradition in Denmark. That solution will zero the costs of buying straw and transporting and tilling down biochar. At the Vrå biogas plant, they have already started selling shares to farmers depending on the straw and manure supply. The idea is to expand farmer ownership to the pyrolysis plant in three years' time.

According to the owner of the biogas plant, the plan is to **build pyrolysis plants in connection with the 50 existing biogas plants** using their fiber residue as feedstock for pyrolysis and using biogas to power the biogas plants. Together with Stiesdal and a German investor, the plan is to form a new company investing in pyrolysis with money coming from farmers so that their money stays there. Hence, biogas and pyrolysis will potentially create value in poor peripheries of Denmark.

A farmer that we interviewed who was in the process of transitioning into sustainable farming listed a number of reasons **why farmers have an incentive to make such a green transition**: 1) Farmers have their back against the wall as they are constantly portrayed as climate sinners; 2) The interest on bank loans to farmers is lower if they can document they are transitioning to sustainable agriculture; 3) The big dairy company ARLA has created a system where green farmers get more for their milk than other farmers: the big retailer Salling Group pays the cost of this by adding a little to the price of their other commodities; 4) Investing in pyrolysis will give farmers access to carbon credits; 5) Farmers can increasingly sell the story of their product as consumers are willing to pay for animal welfare, CO2 reduction, biodiversity, etc.

10. The capacity to leverage support from authorities to enable local collaboration

QCA score:	Scoring confidence:	Data sources:
☐ 0	☐ Low confidence	☒ Interviews
☐ 0.33	☐ Medium confidence	☐ Documents
☐ 0.66	☒ High confidence	☒ Observations
☒ 1		

Please elaborate on the reasoning behind your scoring for this governance factor:

There are several **barriers to the expansion of pyrolysis**. SkyClean has several people who are **cultivating upwards contacts** to national-level politicians and public authorities as well as to the EU Parliament and Commission in the hope that these contacts will help to remove the existing barriers. Sometimes they invite representatives from Agriculture and Food along to the meetings, but not always as they are careful not to be "guilty by association" with the farmers that have a bad environmental reputation.

As an indicator of the **effort to influence public agendas and national and European policy makers**, the SkyClean Chief Communication Advisor claims that he spends 5% of his time on media and 95% of his work time on interaction with public decisionmakers.

Founder **Henrik Stiesdal is the heavy weigher** in the dialogue with central government and in EU lobbying efforts. He is well respected and well connected.

SkyClean gets help from **Agriculture and Foods** to lobby for regulatory changes, but there is no support from **Local Government Denmark**.

In addition to the work of the Chief Communication Advisor and Henrik Stiesdal, Skyclean has hired a **professional public affairs bureau** called Grace Public Affairs to help influence decisionmakers and improve the framework conditions for pyrolysis.

SkyClean is also member of the sector organization **European Biochar Industries** that lobby for the pyrolysis sector at the EU level.

In November 2023, SkyClean/Stiesdal **contacted the powerful Danish Ministry of Finance** with recommendations about removing 8 barriers for the expansion of biomass pyrolysis based on the experiences from the Scale-up project:

a) The government should make the EU categorize pyrolysis as industrial permanent carbon sequestration (CCS) rather than as carbon farming to enhance the income from carbon certification (certification options are described in the SkyClean White Paper.
b) The regulatory responsibility for pyrolysis that is divided between three different ministries (transport, environment and agriculture) should be given to one ministry to simplify communication and regulation.
c) The access to tilling down biochar on agricultural fields without first having to apply for exemption from the Environmental Law's §19 should be secured by implementing relevant EU directives in Danish law.
d) A safety certification of biochar should be introduced to enhance public trust in pyrolysis as a safe climate tool.
e) The government should issue instruction for municipal approval of pyrolysis plants to ease and shorten case processing.
f) The government should issue a tender for Carbon Catchment and Storage to enhance economic viability of the sector.
g) The government should integrate pyrolysis with the plans for supply of biofuels for transport and energy production.
h) The Government should make pyrolysis and biochar a strategic research area.

A proof of the success of SkyClean to lever support from higher-level government is **that it was contacts to government officials that led to the establishment of the Pyrolysis Fund that ended up giving SkyClean money to build the pyrolysis plant in Vrå.**

11. Inclusion and empowerment of relevant and affected actors

QCA score:	Scoring confidence:	Data sources:
☐ 0	☐ Low confidence	☒ Interviews
☒ 0.33	☐ Medium confidence	☐ Documents
☐ 0.66	☒ High confidence	☒ Observations
☐ 1		

Please elaborate on the reasoning behind your scoring for this governance factor:

There is a **diversity of public and private actors involved in the scale-up project**. At the November 2023 conference here were more than 90 project partners and associated stakeholders. However, at the conference there was **no direct participation of affected actors, namely farmers**. They were represented by their interest organizations Agriculture and Foods and SEGES Innovations.

The **farmers also play a limited role** in the day-to-day work as they are mostly and infrequently involved in discussions about supplying feedstock, tilling down biochar and future investment in and joint ownership of pyrolysis plants. However, SEGES is involves in national agricultural field trials where they work directly with farmers who use biochar in different ways to measure the results.

Many of the **sub-contractors are not involved in the general project collaboration**, and according to one of the leaders in SkyClean, they are intentionally kept at arms-length and prevented from communicating with each other. After all, they are for the most part commercial building contractors and not partners.

In the construction part of the Scale-up project there are constantly new people recruited and they are **given some readings and participate in learning workshop** to bring them us to speed. There have also been organized trips to Brædstrup and other sites and event to integrate newcomers.

To make everybody **feel appreciated and empowered**, there is also a catalogue where project participants at construction sites can **write up their ideas for improvement and further development** that are then later discussed and evaluated.

12. Clarification of interdependence vis-à-vis common problem and joint vision

QCA score:	Scoring confidence:	Data sources:
☐ 0	☐ Low confidence	☒ Interviews
☐ 0.33	☐ Medium confidence	☒ Documents
☐ 0.66	☒ High confidence	☒ Observations
☒ 1		

Please elaborate on the reasoning behind your scoring for this governance factor:

A key informant says: “When we have to move fast, we cannot do everything ourselves and therefore, **we need other actors’ knowledge and competence**”.

Another informant claims that: "**Professional interdependence between the researchers** has brought them close together."

A third informant says that when building prototypes, there is a **need for collaboration and knowledge sharing between researchers and constructors**.

Similarly, a municipal climate leader argues that the **actors in the green transition need each other**: "they are each other's preconditions". If they stay within each their silo, it becomes difficult to produce the new solutions.

From the interviews we learn that the **pattern of interdependency** is that universities can develop break-through technology, private business can build pyrolysis plants, public money is needed to scale and to do it quickly, the municipality can be supportive and provide permissions, and agricultural researchers must demonstrate that biochar is clean, safe and stable for farmers to til down in their soil.

An informant notes that the **interdependency-induced collaboration helps to give SkyClean greater external credibility**: "Public authorities believe us because we have all these different organizations and actors on board".

13. Trust-building and conflict mediation

QCA score:	Scoring confidence:	Data sources:
☐ 0	☐ Low confidence	☒ Interviews
☒ 0.33	☐ Medium confidence	☐ Documents
☐ 0.66	☒ High confidence	☒ Observations
☐ 1		

Please elaborate on the reasoning behind your scoring for this governance factor:

One of the key informants finds that SkyClean is pervaded by **the idea of generosity and trust**. There is a profound openness about everything even the break-through technology generated at DTU. Everybody shares everything: experiences, results, worries etc. The partners both meet each other and external actors with trust and showing trust breeds reciprocal trust. An informant claims that this "reflects the Danish trust culture". Surveys show that 74% of Danish people trust other people.

The presence of a high level of trust is confirmed by other informants. The **explanation of the high trust level** is partly that many of the participants in the Scale-up project has known each other for a long time and partly that power is concentrated in the top of the project, and everybody expects violation of rules, norms and joint plans to be sanctioned. A third explanation offered by some of our informants is that all the participants work knowledge based and respect each other's commitment to knowledge.

Hjørring Municipality has worked closely with SkyClean scale-up project from the early construction phase and the **continuous interaction has built a lot of trust between the partners**. The municipality tends to

consider itself as a partner and has taken upon itself to talk with other municipalities about how local government can support the establishment of pyrolysis plants in the future.

There are traces of **minor conflicts** between the **research partners** that search for evidence and work on long-term solutions and the **commercial business partners** of the project that want to accelerate everything and produce fast results. Research informants say that it sometimes goes too fast, and decisions are too quick. Still, the conflicts have been small, perhaps due to the existence of several boundary spanners. Among them are scientists who work for SkyClean and thus understand both worlds and can translate and mediate between them, and others are Stiesdal engineers who are deeply involved in building the testing-, demonstration and production facilities together with local craftsmen. One of the "boundary spanning" researchers found it difficult to come from the small scale experimental world of research and then to a big company that aims for fast mass production of pyrolysis plants even when all the evidence was not there. Discussions related to when data is strong enough to scale up production are ongoing and tend to produce some conflict.

There are also sometimes **conflicts in the construction part of the Scale-up project**, but one of the leaders is generally very good at getting people to work well together. We are told that conflicts are **ironed out in the lunch break** and most often in ways where nobody is complete right or completely wrong. Moreover, there is no discussion regarding who has the last say.

There have been **some conflicts with industrial sub-contracts** about what they are supposed to deliver and how much it must cost. Some budget transgressions have occurred and Stiesdal pays the extra costs.

There were **no observable conflicts between the participants during the November conference**, despite a lot of critical questions from the participating stakeholders. There was allocated good time for questions multiple times during the workshops, and all questions were answered. Extended dialogue seemed to be the way to deal with potential conflicts.

14. Use of experimental tools for innovation

QCA score:	Scoring confidence:	Data sources:
☐ 0	☐ Low confidence	☒ Interviews
☐ 0.33	☐ Medium confidence	☒ Documents
☐ 0.66	☒ High confidence	☒ Observations
☒ 1		

Please elaborate on the reasoning behind your scoring for this governance factor:

The fact that biochar goes from being a useless biproduct of biogas production to a key climate product enabling carbon sequestration required the development of new research and new theories. From the initial breakthrough discovery of a pyrolysis technology that can produce clean and stable biochar, it is **all about developing and testing scaled versions of the initial prototype through continuous theory-driven experimentation based on trial-and-error**. Experimentation is the reason d'etre of the SkyClean project.

Experimentation is not limited to the scaling of the pyrolysis technology from FTU and Brædstrup via Skive to Vrå. There are also **living labs** focusing on how farmers can be motivated to use biochar and what happens to the soil and the plants?

Many of the **sub-contractors needed to invent new thi**ngs to be able to deliver new factory parts, which required a great deal of experimentation. This does not least count for the blacksmith, SmedTek from Brædstrup who now plans to turn his firm into an innovation hub that assists other businesses to develop their products.

15. Ongoing critical self-reflection and learning (i.e., process and/or developmental evaluation):

QCA score:	Scoring confidence:	Data sources:
☐ 0	☐ Low confidence	☒ Interviews
☐ 0.33	☐ Medium confidence	☐ Documents
☐ 0.66	☒ High confidence	☒ Observations
☒ 1		

Please elaborate on the reasoning behind your scoring for this governance factor:

An informant contends that every time the pyrolysis plant was scaled **something had to be changed based on learning through critical reflection and trial and erro**r. For instance, when the first test plant was built in Brædstrup the small blacksmith company Smedtek had to develop lots of innovative solutions in dialogue with researchers and engineers. There was a lot of ping-pong back and forth between builders and researchers. However, Smedtek was too small to build the big new plants in Skive and Vrå where Runarson is brought in, but it is still used for certain development tasks. The Skive plant was much bigger and required new solutions and the same with the Vrå plant. In the building process, new solutions are designed, tried, evaluated and revised based on ongoing dialogue. Our observation saw evidence of this in the lunchroom where small and big puzzles were discussed based on critical evaluation.

An informant reports that from the very beginning, SkyClean was focused on the concerns raised by farmers. There were discussions with the farmers about their worries and experiments were launched to see whether some of the problems could be addressed and alleviated. The **dialogical interaction of the farmers** has aimed to solve problems such as dust from biochar and also served to remove other barriers.

The **November conference provided a space for critical self-reflection and learning**. The conference highlighted the possibilities and obstacles for pyrolysis and biochar now and in the future from different scientific and industrial perspectives. For instance, there were presentations from researchers on how the use of biochar in farming affects environment and biodiversity, the prospective stability of biochar when stored in the ground, and alternative uses of biochar than carbon capturing. The industrial perspectives focused primarily on the legal framework for carbon storage with biochar as well as the prospective business cases for biochar and pyrolysis.

16. Exercise of facilitative leadership:

QCA score:	Scoring confidence:	Data sources:
☐ 0	☐ Low confidence	☒ Interviews
☐ 0.33	☐ Medium confidence	☐ Documents
☒ 0.66	☒ High confidence	☒ Observations
☐ 1		

Please elaborate on the reasoning behind your scoring for this governance factor:

In Stiesdal Fuel Technologies and its SkyClean subsidiary company, there is a **traditional directional top-down leadership** and in the construction part of the Scale-up project subcontractors are dealt with one by one and fired if they are not delivering.

In the SkyClean Scale-up project as a whole and particularly in the research part, there is **a facilitative leadership** that aims to distribute leadership tasks and support relatively self-governing groups working on each their different part of the common project. The formal leaders report that it is easy to lead and they only step in to lead when there are problems. The leaders also organize crosscutting dialogue meetings where everybody gets to report what they are doing and ask questions. Micro-management is demotivating, so there is none of that, explains one of the informants. The best leader is said to the one who is not noticed.

One of the informants **characterize the exercise of facilitative leadership as being mild**, also when you send out reminders or someone misses a deadline, it is about asking questions that helps to address difficult issues and remove barriers, and it is about creating conditions for people to discuss and seek agreement with each other.

The high degree of **self-government supported by facilitative leadership** is made possible by the fact that everybody in the project work knowledge-based, founded on either practical expertise or science. Everybody respects each other's knowledge.

Still, the **facilitative leadership of the self-governing groups** in the scale-up project operates in the shadow of the **traditional directional leadership** exercised by the owner of the SkyClean company that 'owns' the scale up project. Hence, although facilitative leadership is significantly present, it has a limited impact.

Outcome variable: Successfully co-created green transitions

The outcome variable 'co-created green transitions' will be scored in two parts. First, 'co-creation' will be scored based on an assessment of whether the participants in the initiative, project or process engaged in collaborative problem-solving that fostered creative ideas and innovative solutions (data will consist of survey data combined with interviews and documents). Next, 'green transitions' will be scored based on an assessment of whether the initiative, project or process has fulfilled or is expected to fulfill its green goals, ambitions and aspirations (data will consist of survey data combined with interviews and internal and/or external evaluation reports, including scientific publications).

The scoring of this variable is done in two parts:

1. *Is the developed solution based on collaborative problem-solving spurring creativity and innovative solutions?*
2. *Does the developed solution engender a green transition?*

This scoring should be conducted based on both the survey and complementary green outcome evaluations. Please consult Sections 4.4 and 6.10 in the Research Protocol for more details.

1. Is the developed solution co-created?

QCA score:	Scoring confidence:	Data sources:
☐ 0	☐ Low confidence	☒ Survey
☐ 0.33	☐ Medium confidence	☒ Interviews
☐ 0.66	☒ High confidence	☒ Documents
☒ 1		☒ Observations

Please elaborate on the reasoning behind your scoring for this part of the governance factor, including the data sources used for the scoring.

The SkyClean pyrolysis project aims to develop and implement a new breakthrough technology and to provide proof of concept by scaling it into a commercial and fully automated plant that can produce biogas and biochar. So, **innovation is the key purpose of the project**.

This innovation is produced through **collaboration between distributed actors from the public and private for-profit and non-profit sector**. The partnership involves all parts of the value chain, **even farmers and their various organizations** in collaborative innovation aiming to solve the climate crisis. The development and testing of prototypes is an integral part of the co-creation process.

The Up-scale project is initiated and owned by a private company Stiesdal Fuel Technologies, but the **co-creation project seems to have considerable autonomy** as it has its own funding and leadership. However, the co-creation is clearly operating in the **shadow of hierarchy provided by the corporate governance of Stiesdal Fuel Technologies**.

The results in terms of co-creation from our qualitative analysis based on interviews and documents are **confirmed by the results from our mini-survey**. The survey questions focus on the presence of collaborative problemsolving (1), the fostering of creative and innovative solutions (2-6), the support for process, outcomes and the level of engagement (7-12), and the attainment of goals that are robust and serve to enhance sustainability (13-15).

With 100% of the respondents either agreeing or strongly agreeing to the first 6 items (except for 5 where some who only slightly agree), we can safely conclude that SkyClean scale-up project has been a co-creation process where different actors have collaborated and the collaboration has resulted in the development of innovative solutions. The more evaluative items 7-13 show a slightly more critical assessment, especially of the collaborative process (see item 8). However, although the answers are a little

more evenly distributed and with a few respondents disagreeing with three items, the majority of the answers fall in the agree or strongly agree category. **In sum, the results from the mini-survey support that there was developed a co-crated solution and our 1 score.**

If possible, please insert your survey responses in the table below (in % for each response), including the mean/average % for each survey item.

N = 13	Strong. dis.	Dis.	Slight. dis.	Neither agr/dis	Slight. agree	Agree	Strong. agree	Mean
1. Problem-solving mobilized different experiences, and/or ideas and/or forms of knowledge to develop new perspectives						20%	80%	2,8
2. Through the collaborative problem-solving process, different experiences and/or ideas and/or forms of knowledge have been mobilized to search for unconventional solutions						50%	50%	2,5
3. The collaborative problem-solving process mobilized different experiences, and/or ideas and/or forms of knowledge to search for solutions that go beyond standard/text-book solutions						40%	60%	2,6
4. The co-created solution breaks with established practices						70%	30%	2,3
5. The co-created solution disrupts conventional wisdom					22,2%	44,4%	33,3%	2,11
6. The co-created solution offers new ideas to address the green transition problem						30%	70%	2,7
7. I'm supportive of the co-created solution				14,3%	14,3%	57,1%	14,3%	1,71
8. I'm content with the overall collaborative process of the project			10%			50%	40%	2,1
9. I feel the multi-actor collaboration process was a prerequisite for the success of the project					10%	30%	60%	2,5
10. I'm satisfied by the results of the co-creation effort in terms of expected impact on the welfare of the community					12,5%	50%	37,5%	2,25
11. The collaborative interaction in the project has led to an innovative solution			10%			40%	50%	2,2

12. The actors involved in the project are engaged in collaborative interaction that stimulated creative problem-solving						50%	50%	2,5
13. The co-created solution meets the proposed goals of the project			10%			20%	70%	2,4

2. Does the developed solution engender a green transition?

QCA score:	Scoring confidence:	Data sources:
☐ 0	☐ Low confidence	☒ Survey
☐ 0.33	☐ Medium confidence	☒ Interviews
☐ 0.66	☒ High confidence	☒ Documents
☒ 1		☐ Observations

Please elaborate on the reasoning behind your scoring for this part of the governance factor, including the data sources used for the scoring:

Based on a commissioned **expert report** from Associate Professor Tobias Pape Thomes, Roskilde University, the SkyClean project culminating in the construction of the scaled-up plant in Vrå seems to have a significant green impact and is destined to trigger further Scale-up efforts if it manages to invent a viable business model.

The new SkyClean pyrolysis plant at the Agri Energy[1] biogas plant in Vrå with integrated biogas production, dewatering and drying of fiber residue and subsequent pyrolysis is expected to treat around 70-80.000 tons of dewatered digestate fibers annually, containing around 20-25.000 ton fiber dry matter.

Isolated climate impact effects:

According to a recent assessment of isolated climate effects of digestate fiber pyrolysis, the treatment of these fibers can be expected to reduce greenhouse gas emissions with 15-35.000 tons CO_2e annually. Estimation based on parameters in Table 1 below and the before mentioned capacity.

Table 1: Climate impact of three isolated effects of drying and pyrolyzing biogas digestate fibers compared to alternative management with storage and application to soil.

[ton CO_2e/ton TS]	Carbon sequestration	Avoided emissions of CH_4 and N_2O	Substitution value of energy production	SUM of 3 isolated effects
Elsgaard et al 2022[2]	293	197	373	863
Thomsen et al 2023[3]	620	260	680	1550

[1] https://agrienergy.dk/anlaegget/

[2] https://dcapub.au.dk/djfpublikation/djfpdf/DCArapport208.pdf

[3] https://cipfonden.dk/wp-content/uploads/2023/06/RUC-IMT-2023-Opgave-om-understoettelse-af-effektvurderinger-ifm-DK-pyrolyse_til-udgivelse.pdf

System impact effects of integrating pyrolysis in digestate management:
The before mentioned assessment of 3 isolated climate impact effects does not account for the full system impact of having a 20 MW digestate fiber pyrolysis plant compared to the previous situation without having such a plant. In particular this effect evaluation does not consider that currently, there are very few biogas plants that dewater digestate and produce a fiber fraction with high dry matter content. Estimating full system climate impact effects require a comparative assessment in a life cycle perspective. Such work has not yet been completed but is currently undertaken in the INNO-CCUS project SIMPLY[4]. Preliminary assessments of integrating digestate fiber pyrolysis at large biogas plants indicate full-system climate impact around 800 kg CO_2e/ton total solids. For the Vrå plant, this amounts to 16-20.000 t CO_2e/year if operated continuously at near-full capacity. This effect is valid for both a short term 20 years perspective and a longer term 100 years perspective. Recent advances in this work indicates that the beneficial impact may be 10-20% higher, especially on the longer term. However, these are also still preliminary models and estimations.

Climate impact of the integrated system:
The previous estimations are based on the difference between a scenario with a pyrolysis plant at a biogas facilitate and a reference situation with the same biogas facility without pyrolysis (and supporting unit processes). However, it may be relevant to account for the benefit of the integrated system – biogas + pyrolysis – compared to a situation without neither. In a report from AU from 2021, it was estimated that – a biogas plant alone may provide a climate effect of 65-106 kg CO_2e per ton of (wet) biomass input in the baseline scenarios[5]. The effect of adding a system with digestate pyrolysis could be expected to increase this effect to around 100-160 CO_2e per ton of (wet) biomass input. The total climate impact of the integrated system at Vrå compared to a reference with neither biogas plant nor pyrolysis unit is expected to be in the range 40-50.000 tons CO_2e/year. However, the inconsistency of the applied methods in the two studies makes this estimate uncertain.

Nature impact of biochar spread on agricultural land:
Biochar from pyrolysis is a strong cost-efficient climate mitigation tool, but it also has a positive impact on nature when tilled down in agricultural soil:

a) Remains of antibiotics, pesticides, hormone-like substances and micro plastics occur in slurry and manure and tend to be concentrated in soil. Pyrolysis decomposes these elements.
b) The pyrolysis process leaves the nutrients in mineralized form, adsorbed to the biochar leaching into the soil.
c) Return of biochar to farmland increases the carbon content improving soil health.
d) Biochar may improve the water retention in sandy soils.
e) Biochar is reported to increase crop yield in acid soils

Our mini-survey **confirms our qualitative assessment** that the co-created solutions supports a green transition as 86% of the respondents believe that the scaled pyrolysis technology has or will produce a green transition solution that improves the status quo.

[4] https://inno-ccus.dk/project/supporting-implementation-of-pyrolysis-via-constructive-alignment-of-climate-impact-assessment-methods-goals-frameworks-and-incentives/
[5] https://dcapub.au.dk/djfpdf/DCArapport181.pdf

If possible, please insert your survey responses in the table below (in % for each response).

1. The project:	Distribution
…did not produce any green transition solution	0%
…is expected to produce/has produced a green transition solution aiming to avoid a worsening in the status quo	0%
…is expected to produce/has produced a green transition solution aiming to maintain the status quo	14.29%
…is expected to produce/has produced a green transition solution aiming to improve the status quo	85,71%

Please list all the informants you have interviewed for the case study:

Interview persons:
Lecturer, IMT Roskilde University
Leader, SkyClean
Chief Communication Advisor, SkyClean
Machine engineer, SkyClean
Chief Research Officer, SkyClean
Climate Chief, Hjørring Municipality
Energy Cluster
SEGES Innovation (former part of Danish Agriculture and Food)
SmedTek
Construction site Manager, Stiesdal
BB Bioenergy
Local farmer from Vrå
Stiesdal
Stiesdal

All interviews were carried out by Eva Sørensen and Jacob Torfing between the 2nd of October 2023 and the 16th of November 2023. About half of the informants were interviewed online and the rest were interviewed on location in different parts of Denmark.

Please list all the observations you have made:

Observations:

a) Guided tour at the SkyClean plant in Brædstrup with explanation of the different processes and ongoing experiments with condensation of biogas to biooil.
b) Guided tour at the SkyClean plant in Skive with explanation of the different processes and information of ongoing experiments with new filters.
c) Guided tour at the SkyClean plant in Vrå with explanation of the different processes through which biogas fiber residue is dried, turned into pellets and used in pyrolysis.
d) SkyClean conference 22. November 2023.

Please list all the documents you have analyzed (document name + source + year):

The following documents have been retrieved either online or from informants:

Danish Government (2021), Aftale om grøn omstilling af dansk landbrug. (The Agricultural Agreement)

Elsgaard, L. et al. (2022), *Knowledge synthesis on biochar in Danish agriculture*, DCA report.

Hjørring Kommune (2023), *Den store klimarejse, Hjørring Kommunes Klimahandlingsplan 2030.*

Lindholst, P. (2023), *SkyClean introduktion*, PowerPoint slides.

SkyClean (2023), *SkyClean Scale-up projectkonference invitation*.

SkyClean (2023), *Deltagerliste SkyClean Scale-up conference*

SkyClean (2022), *Projektoversigt Scale-Up kick-off WP1 Project Management*, PowerPoint slides

Stiesdal (2023), *SkyClean biokul* (White Paper)

Stiesdal (2023), *Eksternt notat: Barrierer for udrulning af pyrolyse*.

Stiesdal (2023), *Detaljeret priskatalog.*

Stiesdal (2023), *Priskatalog og potentialet i pyrolyse.*

Stiesdal Press Releases from: 10.02.21; 18.08.21, 14.03.22, 28.06.22, 26.10.22 available at the SkyClean website.

Thomsen, T. P. (2023), *Kick-off møde for INNO-CCUS SIMPLY*.

Thomsen, T. P. (2023), Estimated climate impact of 20 MW SkyClean pyrolysis plant in Vrå, commissioned research assessment.

Thomsen, T. P. (2022), *Introduction to production and use of biochar 2022,* Roskilde University.

Thomsen, T. P. (2021), *Climate Footprint Analysis of Straw Pyrolysis & Straw Biogas*, Roskilde Universitet.

Please note the response rate for the survey/measurement of outcome variable:

The mini-survey was answered by 13 out of 14 participants leading to an exceptionally high response rate of 93%.