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SIMPLY Project
Assessment of pyrolysis product market sizes, location and context

Report

SIMPLY WP1.3-03
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Revision History

Rev.	Date	Description of revisions
01	01-11-2024	• Original version - PLI
02	16-04-2025	• Document updated to include insights from Carla Soleta on the value of BCR in regulatory frameworks • IMO agreement included.
03	28-05-2025	• Document revised based on input from SIMPLY-project members.

Contents

1 Introduction

This report documents activities conducted as part of the SIMPLY-project, work package 1.3: *Assessment of pyrolysis product market sizes, location and context.*

On 24 of June 2024 the Danish Government presented “Aftale om et grønt Danmark” [1]. This agreement mentions pyrolysis of biomass as an important technology to deliver on the GHG-reduction emission targets. The agreement includes a tax on GHG emissions from biological processes in the agriculture sector.

October 2024 the announced strategy on pyrolysis of biomass was released as “Strategi og arbejdsprogram for pyrolyse”. This working program forms part of the plan to enable carbon sequestration by means of biochar stored on farmland as a tool to meet the 2030 climate targets and beyond in the agriculture sector.

1.1 Reference

This report forms part of the delivery of information as part of the SIMPLY-project.

1.2 Scope of Report

The report focuses on assessing the pyrolysis product market sizes, location and context in Denmark.

2 Market assessment of pyrolysis value streams

The underlying business assumption for Stiesdal SkyClean is that carbon capture and storage by means of biochar i.e. Biochar Carbon Removal (BCR) becomes sufficiently valuable to attract private investors. Thus, BCR must be bankable seen from an investor perspective to scale the technology. Compared to wind energy, pyrolysis is more complex as the number of value streams are larger and interdependent. The overall process has been shown in Figure 1.

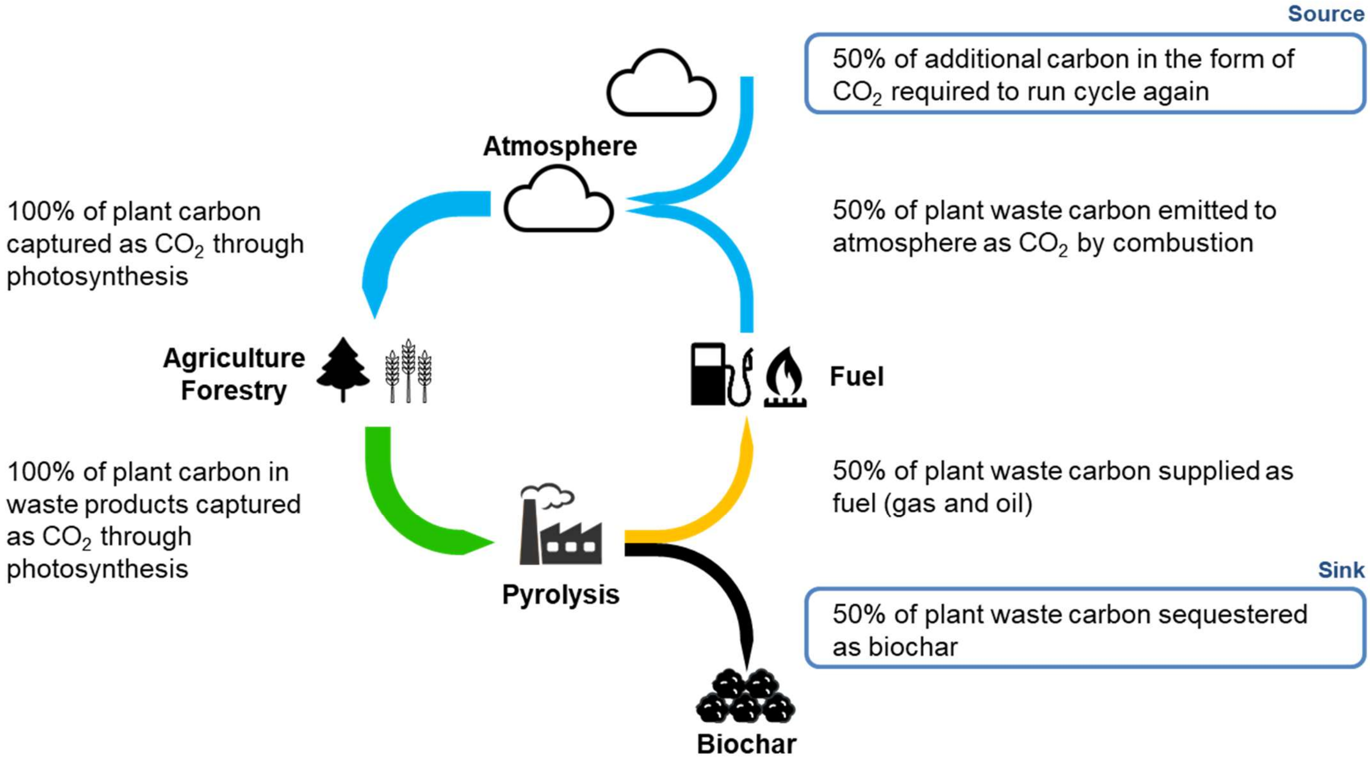

Figure 1: CO_2 is removed from the atmosphere and carbon is stored in the form of biochar through pyrolysis.

Risks are typically handled through long-term offtake agreements on feedstock, BCR, and energy streams arising from the pyrolysis process.

Depending on the type of feedstock and configuration of the posttreatment of the pyrolysis gas several, siting constraints arise which need to comply with the local legislation. Making all these constraints fit is the art of project development. Since pyrolysis of biomass to achieve BCR is a young industry, identifying stakeholders to fill all required roles in the ecosystem is far from trivial.

3 key activities have been identified in the official working program for pyrolysis:

- Investigating the environmental effects of large-scale deployment of biochar on farmland
- Designing an incentive scheme supporting BCR in Denmark
- Developing a methodology for the inclusion of BCR in the Danish GHG accounting system

All 3 activities are prerequisites for rolling out pyrolysis in a Danish context, but they will not guarantee capacity build-up as additional requirements are imposed by financial investors.

Referencing WP1.2 [6], potential pyrolysis products include:

- Biochar as physical product
- Biochar as BCR

- High temperature heat
- Bio-methane
- Bio-oil
- Bio-methanol

In the following sections each of these value streams will be described.

2.1 Biochar as physical product

While biochar as physical product has been reported to have several positive effects as a soil amendment, the monetary value in a Danish context is expected to be relatively limited and thus less important in the viability assessment.

2.2 Biochar as BCR

BCR is currently being or about to be included in regulation:

- National scheme in Denmark
- EU regulation e.g. CRCF, ETS
- Shipping via IMO
- Aviation via ICAO
- SBTi for companies

During the SIMPLY-project BCR regulation has been analyzed in detail by master student Carla Soleta [2] leveraging SIMPLY-members to contribute to the work.

The demand and scale of BCR largely depend on buyers motivated by self-imposed (voluntary) or national compliance climate targets, typically guided by frameworks (set of rules).

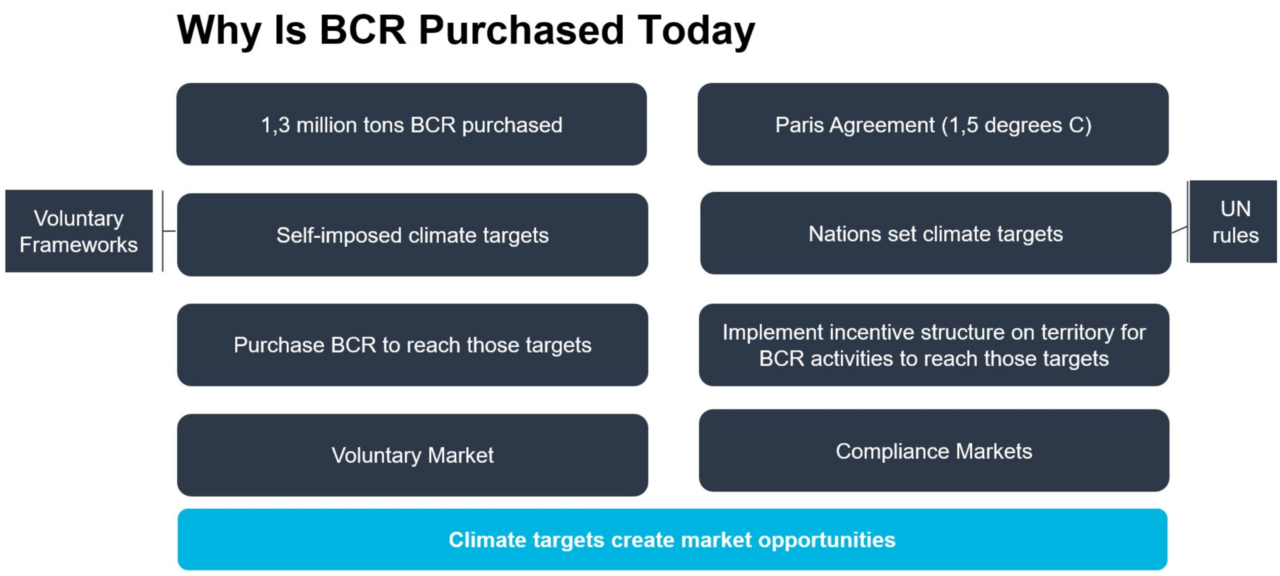

Figure 2: The current BCR market consists of a voluntary and a compliance part.

However, the recognition of BCR as a viable tool for achieving these targets in relevant frameworks remains limited, restricting market opportunities. An overview of different regulations and voluntarily frameworks that either already include or are considering including biochar as BCR has been provided in Figure 3:

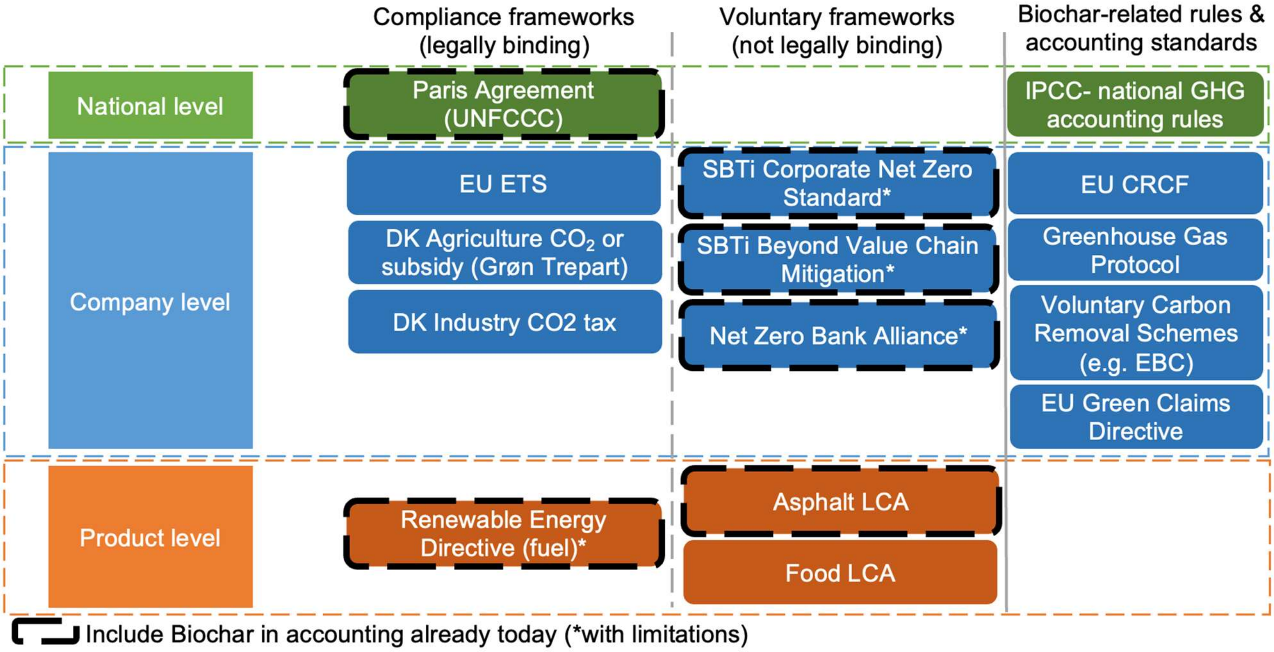

Figure 3: CO2-emission compensation by means of biochar appears to enter both voluntary and compliance frameworks in several sectors on national and international level.

The overview is not exhaustive and not considering the activities in shipping and aviation. Biochar as BCR-carrier can be sold through carbon credits to different markets. A BCR credit verifies the removal of 1 ton CO2 from the atmosphere through biochar. The so-called ”voluntary market” has bought 1,3 million tons of BCR credits in the last three years[1]. As of 2024, the voluntary market values BCR at approximately €155 per ton of CO_2 through BCR. While literature and industry surveys anticipate cost reductions over time due to technological advancements and economies of scale, expert interviews highlight persistent cost drivers—such as feedstock availability, regulatory uncertainties, and logistical constraints—that create uncertainty around long-term price trends. The market is evolving, potentially leading to expanded opportunities in the future. A key bottleneck for scaling BCR, identified by both industry and policymakers, is the lack of reliable and predictable demand. The integration of BCR into compliance mechanisms, particularly the EU ETS, is considered the most promising approach to establishing strong incentives and addressing this barrier. Until 2026, the EU Commission has been tasked to assess the integration of Carbon Dioxide Removal (CDR) technologies, BCR being an example of such CDR, into the EU ETS system. Recently, the EU Commission developed a standard for CDR technologies, including BCR, and verification of removal units, called CRCF. Thus, BCR is on the radar of the EU Commission and could potentially be considered an eligible candidate for integration into the ETS system. A deeper analysis of each regulation is provided in Carla Soleta’s thesis [2].

The following subsections outline a market assessment of pyrolysis gas energy products.

2.3 Direct use of pyrolysis gas as high temperature heat source

In Denmark, natural gas is used in most sectors. Within the heating and industry sector natural gas is often used as an energy source to produce heat. While district heating demand can be supplied by heats pumps, industry applications typically require high temperatures where heat pumps are less efficient. Major parts of this demand could be covered by pyrolysis gas.

High temperature heat as a product must be produced close to the consumer as transport is not an option. This introduces further constraints on the siting of the plants. However, if these constraints

[1] Data Analysis based on CDR.fyi database by Carla Soleta, Master thesis, Link

can be met, the product is typically capable of replacing fossil fuels from a technical perspective. The decision to deploy is then dependent on the cost of the energy sources including both potential ETS quotas, CO2-taxation, and the value of being green seen from a customer perspective.

2.4 Bio-methane

Bio-methane is a commodity with almost infinite demand. The huge advantage of this commodity includes a well-established infrastructure including energy storage facilities. The value of bio-methane is strongly dependent on political regulation. The past few years only very limited investments have been in bio-methane production due to perceived unattractive business cases. In particular, the biogas certificate market has been less attractive.

Recently, increased interest from shipping using LNG/LBG as fuel in combination with the recent IMO agreement on a proposal for a CO2-tax ramping in from 2028 might generate interest in buying biogas certificates.

The penalty amounts to 380 USD/t CO2 (app. 423 EUR/t CO2) measured on a well-to-wake basis. LNG-fueled ships are likely to emit at least 500 kg CO2/MWh resulting in a cost of 211 EUR/MWh in addition to the price of fossil natural gas. Natural gas is traded at levels around 45 EUR/MWh. Thus, bio-methane ought to get a value of 255 EUR/MWh.

The levels of fuel prices are significantly different than what the industry experiences today and it remains to be seen how the implementation of the tax progresses. As for now, commitments to meet self-imposed climate goals have not proven efficient in establishing the required investments into capacity.

2.5 Bio-oil

Development and development on biooil produced on the basis of pyrolysis of biomass is still a low-volume market. The target of Stiesdal SkyClean is to offer a sufficient stable product that can be blended into fossil fuels as this will allow the existing, huge fleet of heavy fuel oil (HFO) vessels to avoid the CO2-tax. Thus, provided the IMO proposal get implemented, bio-oil ought to get a value of minimum the same level as bio-methane as the specific emissions from HFO are at least 20% higher than LNG-vessels [4]. The specific value of the biooil depends on several factors e.g. logistics, quality variation between biooil of difference feedstock origin.

2.6 Bio-methanol

Like methane, methanol is a well-established commodity offering similar qualities in terms of composition, storage ability and numbers of offtake applications. Bio-methanol was announced e.g. by Maersk amongst the most relevant green fuel future fuel within shipping. However, lack of investment in capacity due to lack of bankable off-take agreements and increasing plant and power costs have caused many projects to fail. Political instruments, e.g. the IMO agreement might improve the situation. From a pyrolysis point of view, the specific costs of producing bio-methanol are expected to be significantly higher than e.g. bio-oil og bio-methane due to both process losses and required CAPEX.

2.7 Alternative use of biochar

Depending on the source of biomass used, biochar has a potential value as a fuel similar to fossil fuels. Neglecting technical challenges involved in combustion of biochar a correlation between the energy price and the minimum value of carbon sequestration can be established as shown in Figure 4. Above the blue line, biochar is expected to be used as carbon sink and below the line, the most attractive option is to burn the biochar as fuel.

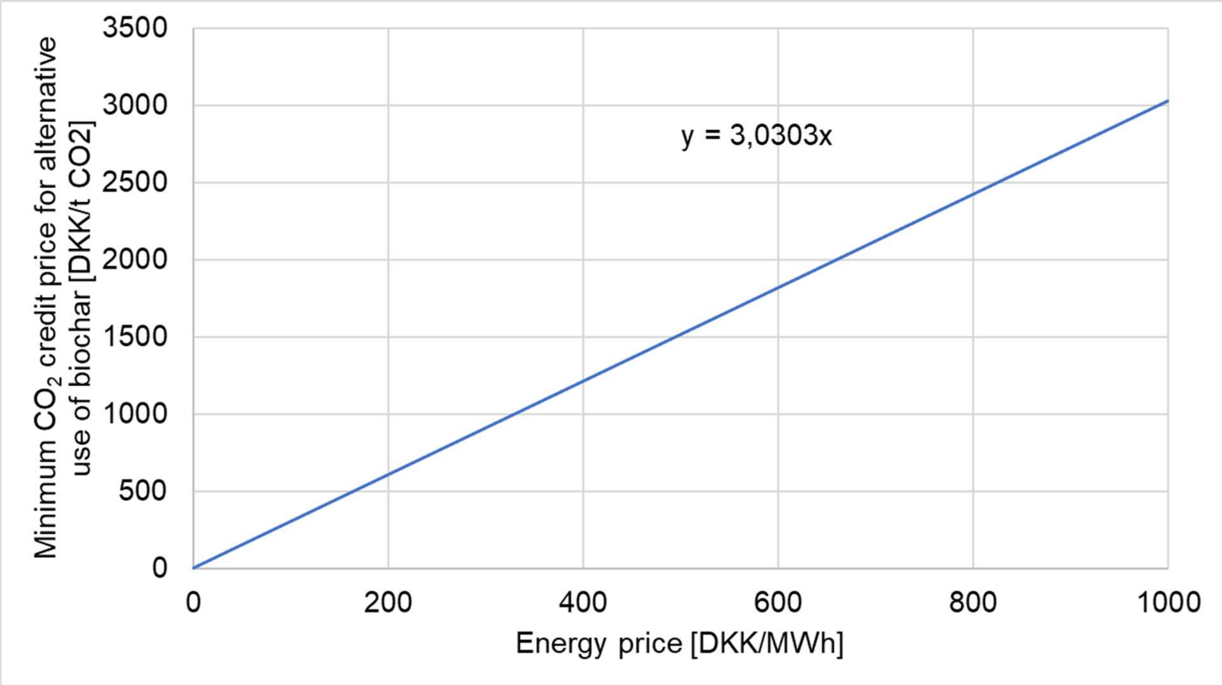

Figure 4: Biochar represents both a carbon sink and a fuel depending on the usage.

2.8 Correlation between value of carbon capture, energy price and feedstock cost

Referencing the Vrå-type configuration of a pyrolysis plant as described in [6], technoeconomic analysis can be made to evaluate the viability of such plants.

Initially, plant CAPEX is expected to be approximately 200 MDKK including preprocessing of biogas residue fibers and postprocessing of pyrolysis gas. Assuming an internal rate of return (IRR) of 10% as minimum requirement for financial investors, it is possible to estimate the correlation between feedstock costs, energy price, and the value of carbon capture.

Using 1.500 DKK/tCO_2e as example and an energy price of 350 DKK/MWh, the maximum allowable feedstock cost is around 70 DKK/ton of wet fibers assuming 70% moisture content or 233 DKK/ton dry matter. The correlation has been shown in Figure 5 for 3 different values of carbon sequestration. The analysis assumes a lower heating value of 17 MJ/kg of the fibers and a pyrolysis process like the Stiesdal SkyClean technology.

In a scenario where the value of carbon sequestration is only 750 DKK/tCO_2e, the maximum allowable feedstock cost is reduced to -60 DKK/ton of wet fiber assuming 70% moisture content or -200 DKK/ton dry matter.

The effect of a CO2-tax like the one currently being applied to non-ETS industries can be included using natural gas as an example of a fossil fuel. The net CO_2-emissions related only to the combustion of natural gas itself is 200 kg/MWh. Thus, a CO2-tax of 750 DKK/tCO_2e corresponds to 149 DKK/MWh. In this scenario, since biomass is not subject to CO2-tax the ability to complete with fossil fuels is improved to -20 DKK/t wet fiber.

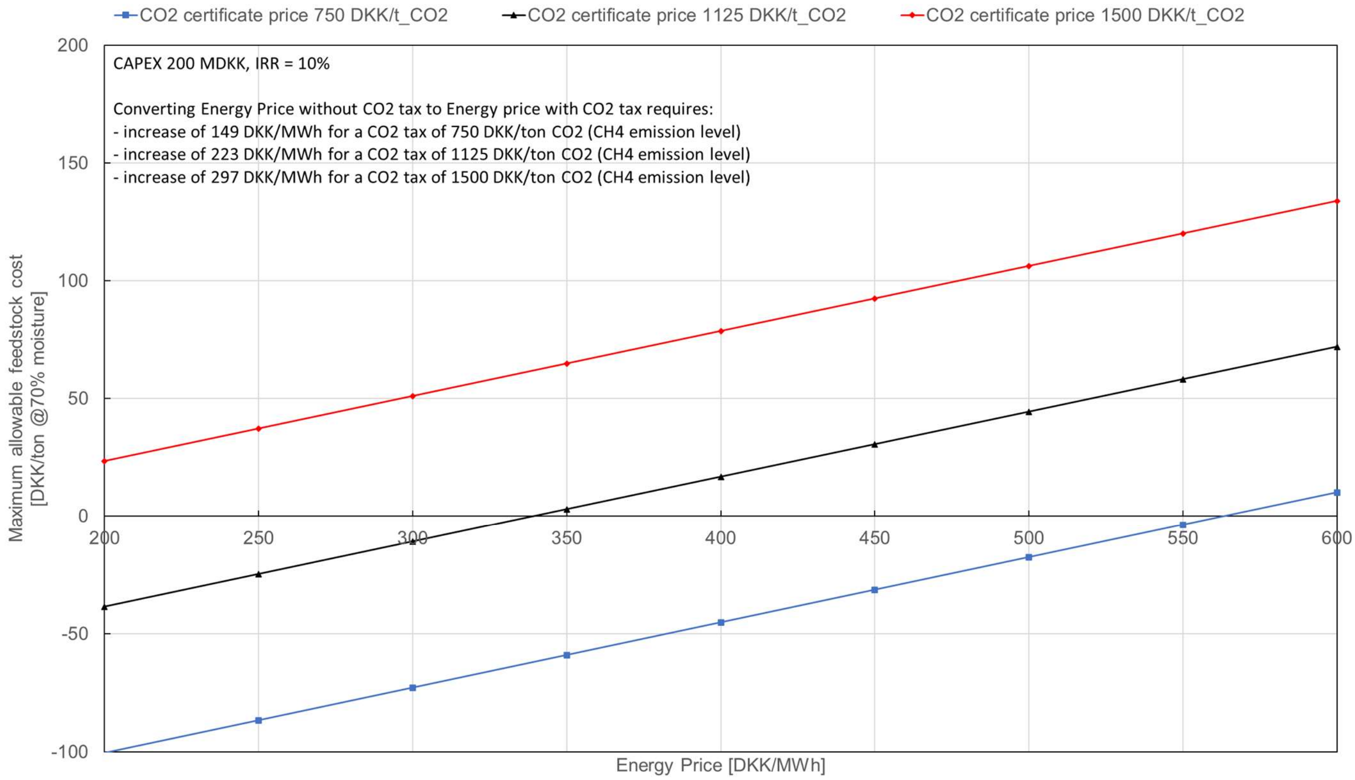

Figure 5: Correlation between energy price and maximum allowable feedstock cost depending on the value of CO_2 capture assuming an IRR-requirement of 10% and a CAPEX of 200 MDKK.

As the industry matures, plant CAPEX is expected to decrease. The effect of being able to learn in a competitive environment has been illustrated in Figure 6 where CAPEX is halved. Using the same data point (1.500 DKK/tCO_2e), the ability to pay for feedstock is improved to 170 DKK/t wet fiber or 567 DKK/t dry matter.

Similarly, for a value of carbon sequestration of 750 DKK/tCO2e, the maximum allowable feed-stock cost is equal to 40 DKK/ton of wet fiber assuming 70% moisture content or 133 DKK/ton dry matter.

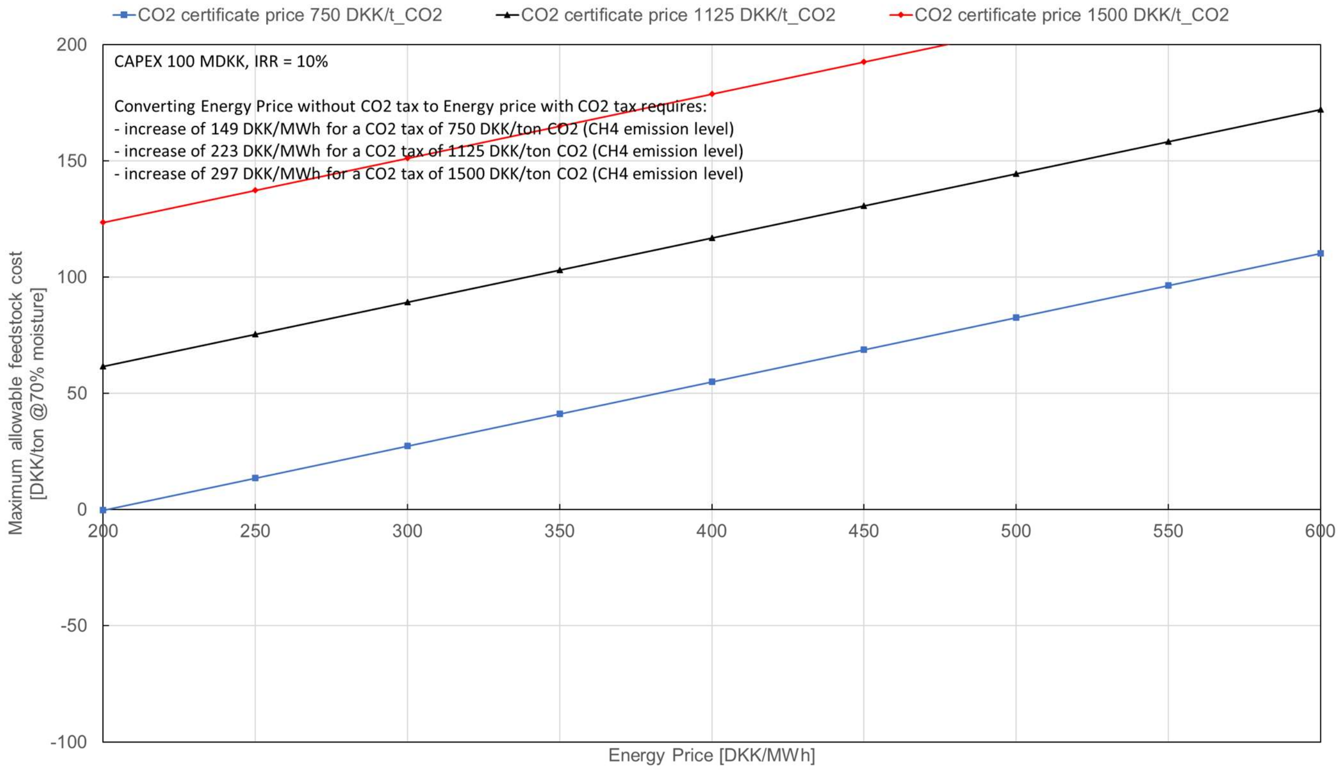

Figure 6: Correlation between energy price and maximum allowable feedstock cost depending on the value of CO2 capture assuming an IRR-requirement of 10% and a CAPEX of 100 MDKK.

3 Data driven siting of pyrolysis plants

This section uses pyrolysis technology integrated with biogas plants as configuration to illustrate the power of data driven siting as a starting point for project development. As the supply of feedstock containing high amounts of sugar and fat has been consumed by the existing fleet of biogas plant, project developers and existing biogas plants are forced to look for alternative sources of biomass to increase biogas production. Straw and other feedstocks containing lignin are required to reach the political ambitions of being self-sufficient with bio methane. Another reason for using straw as feedstock in biogas plants is flexibility in sourcing and a desire to reduce dependency of foreign supply and thus the risk of increasing feedstock costs.

In Denmark, an obvious source of biomass is straw either coming from the fields directly or in the form of deep bedding. While some biogas plants can process feedstock with high amounts of straw, issues have been reported in the subsequent distribution of degassed slurry. Typical problems include clogging pipes and hoses, and methane and dinitrogen monoxide emissions arising as fiber rich matter is left above ground when distributed. Therefore, biogas plants are increasingly separating fiber material out of the degassed slurry. Wet fiber material is a potential feedstock for pyrolysis plants.

For biogas plants based on technology within ability to process increasing amounts of straw directly in the process, straw can be processed by pyrolysis and in this way reduce the demand of fossil energy.

Thus, the availability of straw becomes an important parameter to future biogas plants and to plants that want to increase biogas production. An example of handling mapping multiparameter models has been made in cooperation with Mikolaj Januchta, a former master student from Aalborg University. Leveraging the vast amount of data available on agriculture fields in Denmark, the straw resource distribution can be estimated and mapped using GIS-analysis tools as shown in Figure 7.

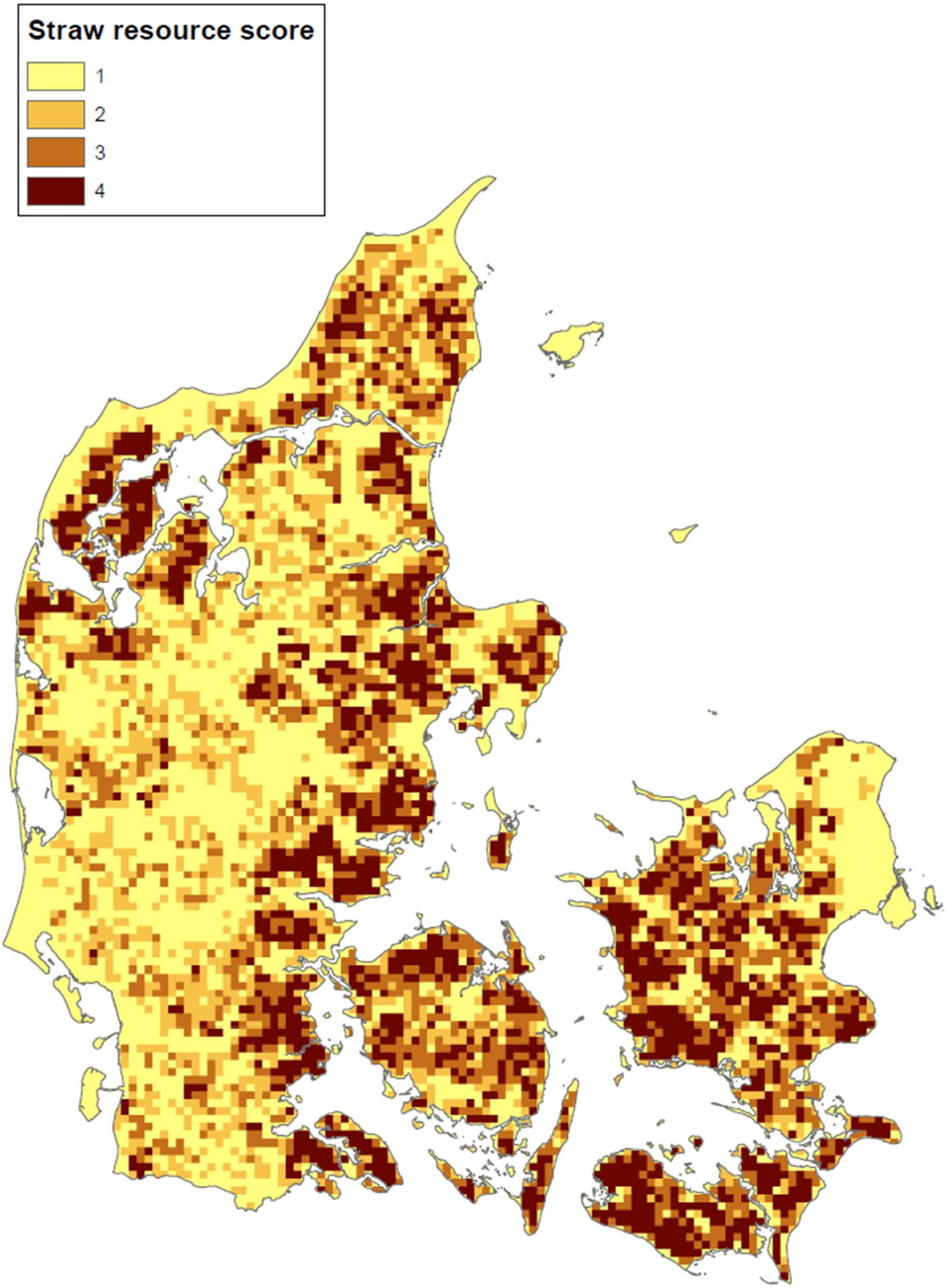

Figure 7: Straw resources in Denmark. Darker colors indicate high intensity straw production.

Similarly, the location of existing biogas plants can be mapped as shown in Figure 8.

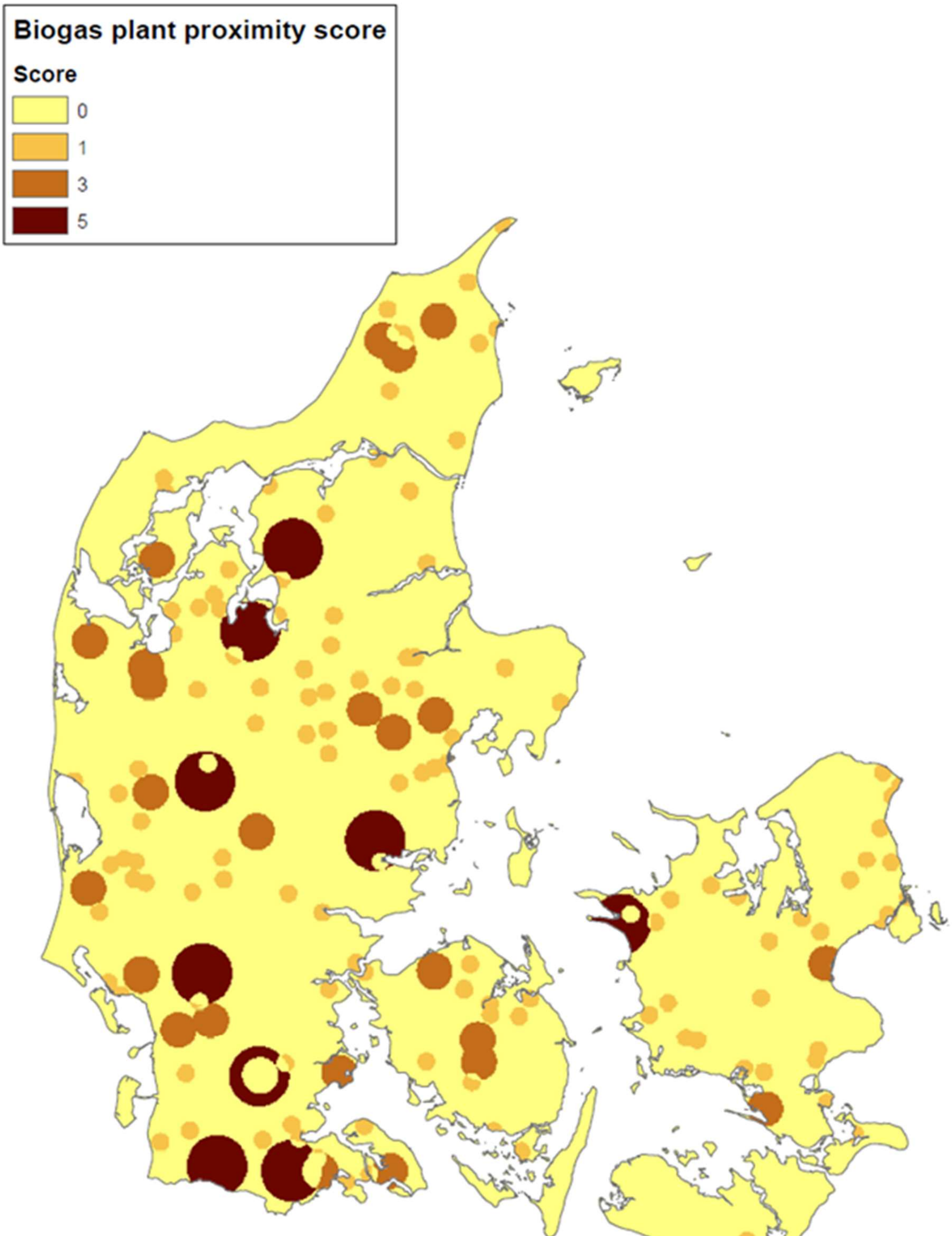

Figure 8: Location and capacity of existing biogas plants, data from 2024.The size and color of the circles indicate biomethane production capacity.

Connection to the natural gas grid in another key parameter in identifying suitable future pyrolysis plants. In Figure 9 the gas infrastructure in Denmark has been mapped using a heat map approach. Locations close to the gas grid are rated higher than areas without grid connection. Djursland is such an area. Energy parks involving biogas and pyrolysis plants might still be relevant, but a cost penalty to establish grid connection must be included.

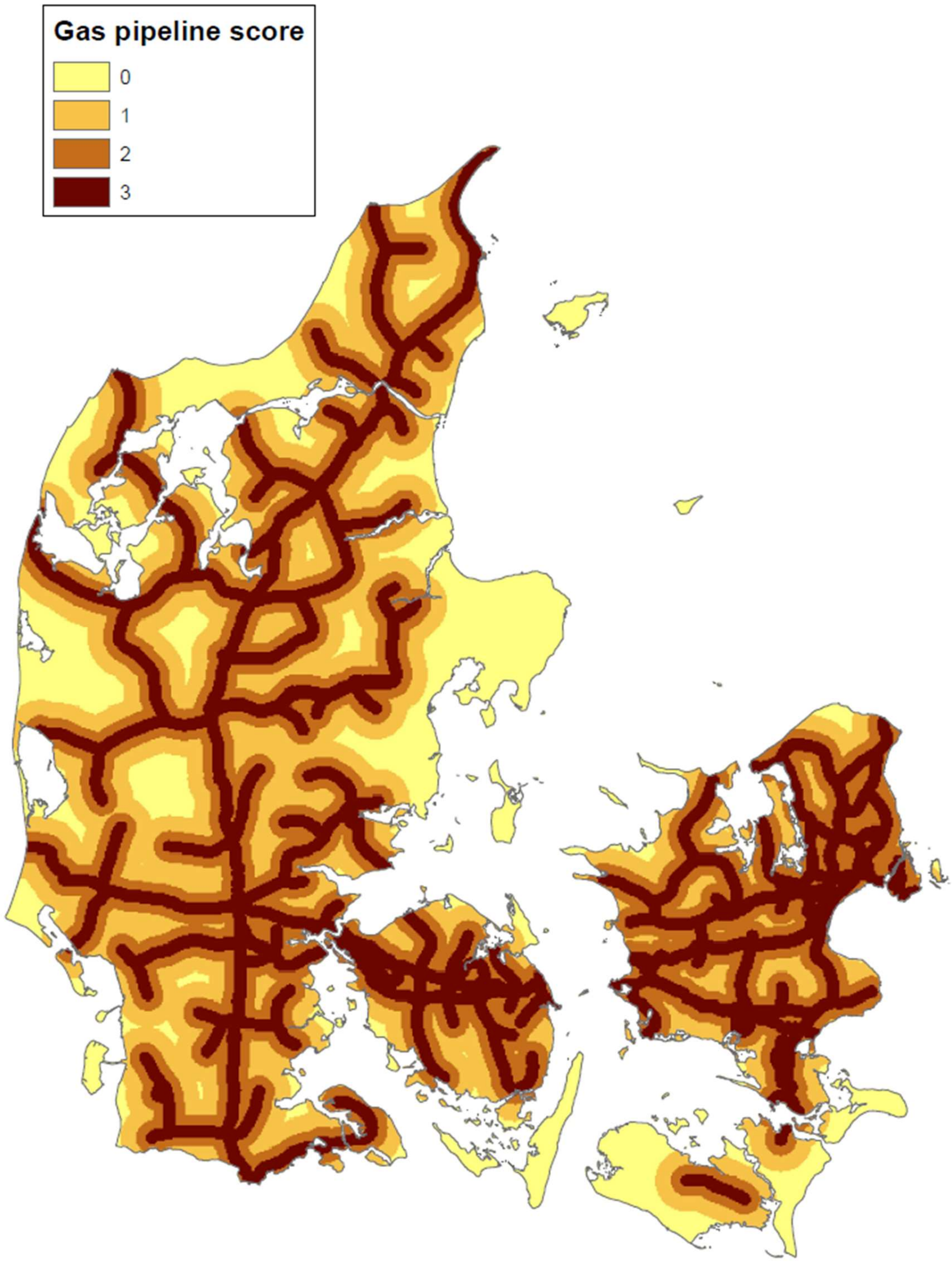

Figure 9: Map of gas grid infrastructure.

Combining the 3 layers of data a resulting heat map of potential attractive plant locations can be distilled as shown in Figure 10.

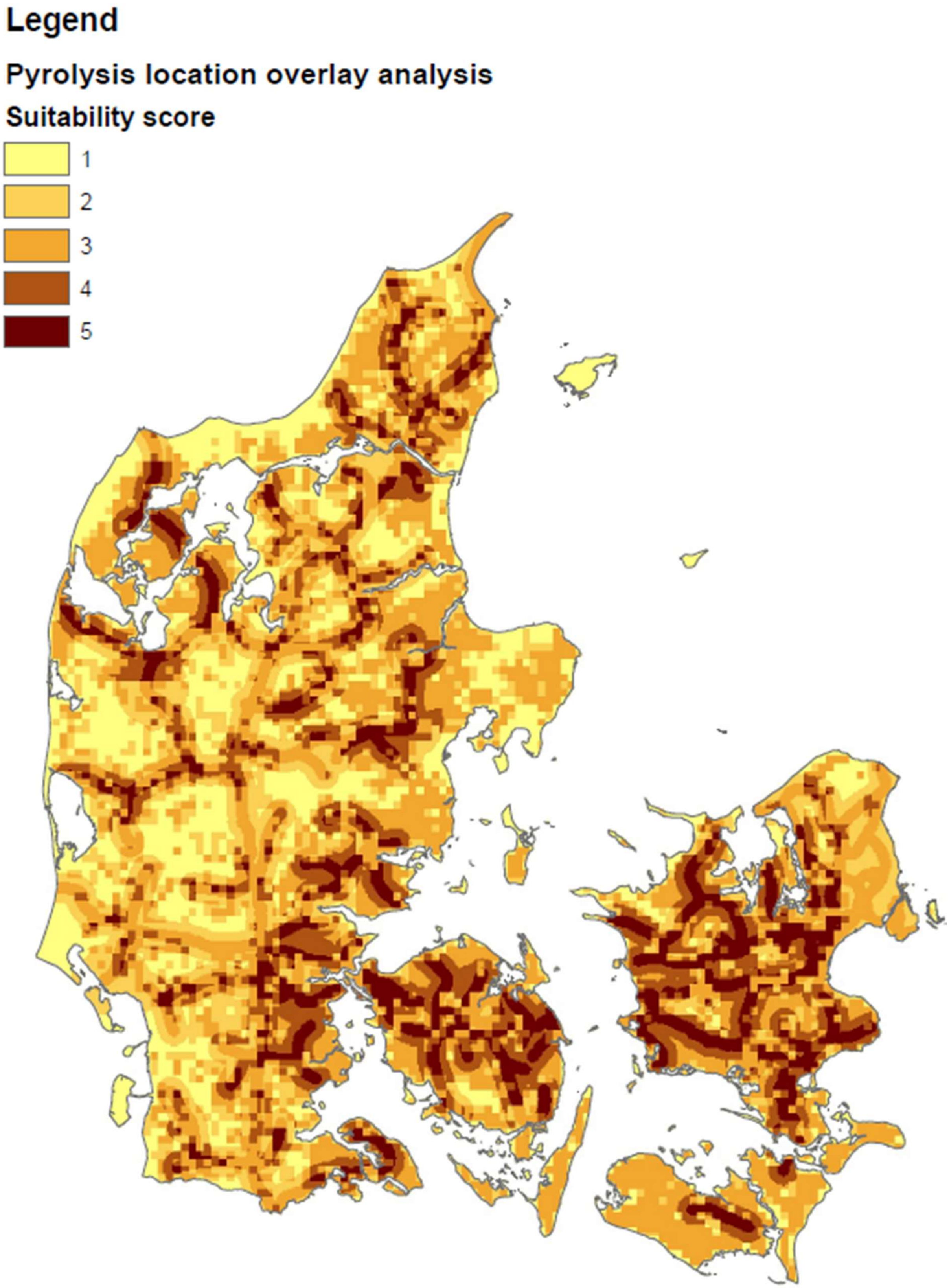

Figure 10: Heatmap of potential location of pyrolysis plants configured to fit biogas plants connected to the gas grid. Darker colors indicate potentially attractive sites for pyrolysis plants integrated into biogas plants.

The result of the analysis depends on how each parameter is factored into the heatmaps. The analysis neglects several important parameters like access roads, public acceptance – a parameter which has caused severe congestion in deployment of energy infrastructure. However, the analysis method is still considered relevant to identify potential new locations for pyrolysis technology. Similar maps can be made for other plant configurations e.g. high temperature heat customers, energy park relevant infrastructure, potential biooil consumers, or storage facilities.

4 Conclusion

Referencing previous analysis, biomass resources exist to deliver on the climate targets [5] within the agriculture sector in Denmark. Stiesdal SkyClean has provided 7 configurations of pyrolysis plants [6] converting low value agriculture residues into carbon removal and energy production.

Biochar as Carbon Dioxide Removal technology has been described. Currently, biochar appears to enter relevant frameworks e.g. in the EU and in large sectors e.g. shipping which is expected to lower the perceived risk of investments.

The demand for fuel types enabled by Stiesdal SkyClean type pyrolysis plants has briefly been described. Rather than looking into specific locations, the current study has tried to outline the prerequisites from commercially viable plants and explain the correlation between the value of carbon capture, energy, and feedstock costs under different assumptions.

Financial investment decisions (FID) demand acceptable levels of overall risk. In the current process of regulatory clarification, the perceived risk level of pyrolysis plants investments appears unattractive to private investors. In fact, the announced subsidy scheme on CDR by means of biochar has caused investors to await clarification of the regulatory framework due to the risk of opting out of the scheme in case FID is made early.

The 20 MW SkyClean plant is an important brick in the verification of regulatory frameworks and value chains besides demonstrating pyrolysis of wet biogas residue fibers.

The method og data driven site identification leveraging detailed data on crop production, gas infrastructure, and biogas plant locations has been used to establish heat maps indicating potentially attractive locations of pyrolysis plants integrated with existing biogas plants.

List of References

Ref	Standard/Author	Details
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[2]	Soleta, Carla	Carbon Removal Credits: Current and Future Value Development on Voluntary and Compliance Markets with a Focus on Scaling Biochar Carbon Removals in the EU, Master Thesis
[3]	IMO, Draft revised MARPOL Annex V	https://wwwcdn.imo.org/localresources/en/MediaCentre/HotTopics/Documents/Circular%20Letter%20No.5005%20-%20Draft%20Revised%20Marpol%20Annex%20Vi%20%28Secretariat%29.pdf
[4]	Sea-LNG news media	https://sea-lng.org/2021/04/independent-study-confirms-lng-reduces-shipping-ghg-emissions-by-up-to-23/#_ftn1
[5]	Stiesdal SkyClean, SIMPLY WP 1.1	https://innoccus-simply.dk/siteassets/resultater/01-08-2024---biomass-feedstock-potential-wp1.1.pdf
[6]	Stiesdal SkyClean, SIMPLY WP 1.2	https://innoccus-simply.dk/siteassets/resultater/01-08-2024---pyrolysis-plant-cases-wp1.2.pdf

Appendix A Carbon Removal Credits: Current and Future Value Development on Voluntary and Compliance Markets with a Focus on Scaling Biochar Carbon Removals in the EU, Master Thesis by Carla Soleta