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Pathways of Residual Straw for New Bio-Products Entailing Carbon Capture, Utilization & Storage Opportunities: Exploratory Case Study of Three Future Danish Pathways

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Abstract
Residual straw, a byproduct of cereal production, represents an underutilized biomass resource with significant potential to contribute to sustainable development and climate goals. This paper addresses the challenge of optimizing straw utilization in Denmark, focusing on its applications in renewable energy, materials production, and carbon storage. Guided by the principles of the circular bioeconomy (CBE), cascading upcycling, and carbon capture, utilization and storage (CCUS), the study investigates three case studies emphasizing: bio-refinery applications, biogas plant integration and prefabricated building materials. The theoretical framework emphasizes resource cascading to maximize the utility of straw across multiple applications. The methodology combines an exploratory case study approach with literature review and comparative analysis to evaluate the resource usage and environmental benefits of each pathway. The Bio-Refinery case demonstrates the potential to produce high-value products, such as prebiotics, ethanol and lignin, but highlights challenges related to scalability and high investment costs. The Biogas Plants case shows the highest cascading value today, efficiently integrating straw into renewable energy production, recycling nutrients through digestate and utilizing captured CO_2 for bio-product manufacturing. The Prefabricated Wall's case offers long-term carbon storage but entails only one cascading step, while production is located outside Denmark, which limits its current contribution to the CBE. The findings indicate that biogas plants provide the most immediately feasible pathway due to their broad cascading profile and existing infrastructure, while the long-term potential of straw-based building materials requires the establishment of local production. A balanced strategy that integrates CCUS with cascading upcycling and CBE principles is essential for maximizing the environmental and economic benefits of straw utilization.

Keywords: Biogas, Bio-Refinery, Carbon Capture, Utilization & Storage, Denmark, Exploratory Case Study, Pre-Fabricated Walls, Residual Straw

1. Introduction

The effective utilization of biomass resources, such as cereal straw, is vital for advancing sustainable development and addressing global climate challenges. In line with the European Union's ambitious goals for achieving climate neutrality by 2050 (European Commission, 2018) [17], EU highlights the role of sustainable biomass in renewable energy production and circular bioeconomy, while also recognising its potential contribution to carbon sequestration (European Commission, 2018; CEPS, 2020; IEEP, 2021) [17, 7, 24]. These political directives highlight the need to optimize biomass utilization to reduce waste, replace fossil-based resources and contribute to carbon capture, utilization, and storage (CCUS) initiatives. As a byproduct of cereal production, straw represents a significant yet underutilized resource. In Denmark, large volumes of straw are generated annually and optimizing its use thus offers a unique opportunity to balance economic growth with environmental responsibility. Statistic on the amount of residual straw in Denmark indicate that 5,9 M tn of straw residues are generated on an annual basis (SEGES, 2024; Danmarks Statistik, 2024) [40, 11], with approximately 2,6 M tn not being valorized (Energistyrelsen, 2020; Danmarks Statistik, 2024 [11]).

Around 1,6 M tn of straw is currently utilized for energy production on decentralized and centralized combined heat and power applications, as well as for biogas production mixed with animal manure. Besides this an estimate of 1,7 M tn residual straw are used as bedding materials in the dairy sector and for deep letter mostly within organic farm stables, and lastly as animal fodder (Energistyrelsen, 2022; Danmarks Statistik, 2024) [15, 11]. Straw however has the potential to serve multiple purposes beyond energy production. It can be refined into high-value materials, such as construction materials, food and medical ingredients, while also acting as a medium for short term carbon storage. The ability to capture and utilize CO_2 during these processes further enhances the importance of illuminating the potentials of straw for climate change mitigating. By integrating these applications, straw can address diverse environmental and economic objectives simultaneously.

This study explores three pathways for utilizing residual straw in Denmark: bio-refinery applications, biogas plant integration and the production of prefabricated building materials. Each case presents unique advantages and challenges. Bio-refineries, such as the facility in Kalundborg, convert straw into valuable products like prebiotics, ethanol and lignin but require significant investment. Biogas plants, exemplified by the Abed Biogas Plant on Lolland, provide an efficient way to integrate straw into renewable energy systems while utilizing captured CO_2 for bio-product manufacturing. Straw-based building materials, as produced by the company EcoCocon, offer longer carbon storage in construction but face logistical hurdles due to the lack of local Danish production facilities.

We will examine the three pathways thoroughly to identify strategies that maximize environmental and economic benefits while addressing scalability, environmental benefits and carbon storage potentials. The findings provide practical insights for optimizing straw utilization as part of Denmark's renewable energy transition and efforts to mitigate carbon emissions. Moreover, the paper contributes to insights into the existing knowledge gap regarding how to practically adopt and apply CBE concept in local contexts, stressed by e.g. Stegmann *et al.* (2020) [45]. Here, exemplified with emphasis on the use of biomass residues from the Danish agricultural sector for accelerating the green transition. These contributions hence address a gap in the current literature on *how* to deploy real world CBE systems within local communities for enhanced sustainability (Ibid.), and *what* the actual potentials are for utilizing and storing carbon, which align with European targets and policies presented above.

2. Materials and Methods

This chapter presents the methodological framework applied in the study. An exploratory multiple case study approach has been chosen to generate in-depth understanding of how residual straw can be upcycled through different technological pathways, entailing CCUS. The section outlines data collection, case selection and literature sources, providing the basis for comparative analysis.

2.1 Empirical Data Collection

The empirical platform consists of three case studies representing distinct straw utilization pathways: bio-refinery applications, biogas plant integration and prefabricated building materials. Data were collected from company documents, public reports, through industry communications, as well as peer-reviewed literature describing the technical processes, feedstock use, products and potential environmental performance of each pathway. In addition, relevant statistical data on Danish straw production and utilization is incorporated to contextualize the cases.

2.2 Exploratory Case Study Approach

An exploratory case study approach has been selected as the aim was not to test predefined hypotheses, but to generate an in-depth understanding of how different technological configurations and sectoral contexts influence the upcycling of residual straw. Exploratory case studies are particularly well suited for examining complex, real-world systems where multiple variables interact, and where the boundaries between the phenomenon under study and its context are not clear (Andersen, 1990; Yin, 1994; Yin, 2014) [1, 49, 50]. This approach allows for flexibility in the research process, enabling new themes and patterns to emerge during data collection and analysis. It is especially useful when addressing "how" and "why" questions (Yin, 2014) [50] related to technology adoption, resource cascading and CCUS integration in the biomass sector. The exploratory nature of the study also permits the integration of both qualitative and quantitative data sources (Andersen, 1990) [1], combining technical descriptions with contextual factors such as policy frameworks, market conditions and infrastructure availability.

2.3 Multiple Case Study

A multiple case study design is applied to capture variation across technological maturity, sectoral application, and carbon storage characteristics (Yin, 2017) [51]. By studying three distinct pathways, the research enables comparative analysis of how straw can be integrated into different sectors - pharma, energy and construction - and at different points in the biomass cascading chain. This breadth strengthens the ability to identify synergies and complementarities between pathways.

2.4 Choice of Case Companies

The three cases were selected to reflect different technological pathways and sectoral contexts for upcycling residual straw in Denmark. Each case represents a distinct form of climate change mitigation and carbon storage, offering variation in process design, sectoral application and position within the biomass cascading hierarchy. The Bio-Refinery case in Kalundborg processes straw into high-value products such as prebiotics, ethanol and lignin, demonstrating advanced biochemical conversion. The Biogas Plant case at Abed incorporates straw into renewable energy production, with integration of CO_2 utilization in the manufacture of bio-products such as furfural and wax. The Prefabricated Building Materials case employs straw as the primary material for Prefabricated Wall elements, enabling extended carbon storage in construction. Together, these cases span different levels of sectors, technological maturity, geographic settings and operational scales, providing a basis for comparative analysis of environmental performance and resource use.

2.5 Literature

Besides case-specific sources, the study draws on scientific literature on circular bioeconomy concepts, biomass cascading, CCUS technologies and Danish agricultural resource management. Policy and regulatory frameworks from the EU and Denmark were also reviewed to frame the cases within current climate and bio-economy strategies.

3. Theoretical Outline

The theoretical framework combines concepts of cascading, circular bioeconomy (CBE) and carbon capture, utilization (CCU) and storage (CCUS). Together, these perspectives guide the assessment of how straw residues can be valorized across multiple applications. The outline establishes the analytical lens for comparing the three case pathways.

3.1 Cascading and upcycling as a core concept in the CBE

Repurposing agricultural biomass residues, such as cereal straw, illustrates how to prevent wasting valuable resources from Danish agriculture. Resource cascading is a central technique for optimizing the use of resources within the CBE (Sirkin, 1990; Sirkin and ten Houten, 1994) [43, 44]. It can be defined as "the process of taking the outputs from one phase and employing them as inputs in a subsequent stage within a cascade chain" (Sirkin, 1990) [43]. The objective is to prolong the overall utilization period while maintaining resource quality. At each stage, three options must be considered:

- Upcycling the resource to a higher level within the same cascade chain or in a new cycle.
- Preserving the resource quality at the same level of utility.
- Cascading the resource to a subsequent (lower) level within the cascade chain (Sirkin and ten Houten, 1994) [44].

This paper focuses mainly on examples of elevating agricultural residues to higher cascading levels or initiating new cycles (upcycling), thus cascading upcycling's'. With this framework, the aim is to investigate future pathways for upcycling residual straw and reveal potential routes for converting straw residues into valuable resources.

3.2 Circular Economy, Bio-Economy and Circular Bio-Economy

The European Union emphasizes the bio-economy concept, widely adopted in biomass policies across member states and globally (Fund *et al*., 2018) [19]. Bio-Economy (BE), as defined by the European Commission (2012) [16], focuses on "production of renewable biological resources and the conversion of these resources and waste streams into value-added products, such as food, feed, bio-based products and bio-energy". Critics have argued that the Bio-Economy is not sufficiently circular or sustainable, often resembling business-as-usual models (Hetemäki *et al*., 2017; Pfau *et al*., 2014) [21, 39]. In contrast, the Circular Economy (CE) is defined as "minimizing the generation of waste and preserving the value of products, materials, and resources for as long as possible." To address these concerns, the EU has merged the two concepts into the Circular Bio-Economy (CBE), stressing the need for a more circular focus in the Bio-Economy for it to be effective (European Commission, 2018) [17]. The CBE concept is hence relatively new, and its role in facilitating a green transition at local and regional levels remains, according to Stegmann *et al*. (2020) [45], somewhat ambiguous.

3.3 Carbon Capture, Utilization (CCU) and Storage (CCUS)

As part of the theoretical framework, we emphasize the options for applying carbon capture, utilization and storage (CCUS) within the case companies addressed. According to literature, carbon can be stored permanently (+100,000 y), for example as mineralized carbon, bio-oil stores underground, or carbon stored in concrete as biochar or via carbon injection. Permanent storage may also be inorganic carbon dissolved in the ocean (ocean alkalinity), which entails no risk of CO_2 release (Höglund, 2022; IPCC, 2023) [22, 25]. Carbon stored for a very long time (+1,000 y) includes biochar or seaweed separated from the atmosphere as it sinks to the deep ocean. Carbon stored for a short time (+100 y) can for example includes forestation and construction materials. Very short time storage (+1 y) refers to carbon taken up by crops and utilized in products, with release occurring much sooner (Höglund, 2022; IPCC, 2023) [22, 25]. The consequent release can or cannot be reused. Carbon Capture and Utilization (CCU) imply near-immediate release, as for example with biofuels, which are consumed shortly after production. Combining examples of cascading upcycling's of residual straw, with an assessment of their simultaneous contribution to CCUS, it provides a broader basis for discussing the benefits of each case.

A comprehensive evaluation of risks such as leakage, re-release, and re-use across the carbon cascade is outside the scope of this paper; however, these aspects are emphasised in the wider CCUS literature as being important for assessing the durability of carbon storage and should be borne in mind when applying the categorisations to the case companies (IPCC, 2024; Brunner *et al*., 2024) [26, 6].

4. Results

This chapter presents the results from the three case studies on residual straw. The cases represent different technological pathways for upcycling straw and reflect variation in sectoral application, technological maturity and carbon storage characteristics. Each case is described with respect to feedstock use, processes and products, as well as the related cascading upcycling opportunities and CCU/CCUS profile. Together, the results provide the foundation for comparing how straw residues can contribute to environmental benefits, resource efficiency and climate change mitigation in Denmark.

4.1 Case studies

The following section presents the three selected case studies of residual straw utilization. Each case highlights a distinct pathway with specific processes, products, cascading value and CCUS potentials.

4.1.1 Straw for prebiotic, ethanol and lignin (The Bio-Refinery Case)

Situated in the North-western part of the island of Zealand in the city of Kalundborg within Denmark - well known for its Industrial Symbiosis which has evolutionized between major companies in the area since the late 1960s (Chertow, 2007 [8]; Lybæk *et al*., 2021) - we find the case company Meliora established in 2023. The company residents in the former Ørsted's (energy company) Inbicon Plant facility, which was a 2nd generation ethanol production facility based on residual straw, eventually closed in 2014. Meliora has retrofitted the plant and now produce various bio-products based on straw from farmers in the local community, hereunder annually 4 M kilos of pre-biotics (dietary fibres) and the capacity to produce 4,5 M tn of ethanol for transport purposes annually (Landbrug og Fødevarer, 2022) [30]. The production of lignin is a substitute for polymers in various applications (Meliora, 2025), as for example within the construction, automotive and packaging industries.

The process is based on Valmet's force feed Bio Trac pretreatment technology, which is a state-of-the-art bio-refinery that transforms the straw residues into 2nd generation bioethanol. As a byproduct, the process also produces C5-sugar utilized for the manufacturing of prebiotic products (Valmet, 2023) [47]. The straw is separated in a rough and fine fraction where the latter is utilized for prebiotic and the first for ethanol production. The residues from these processes are utilized as feedstock for biogas production at the Kalundborg Bioenergy Biogas Plant, as well as in a biomass combustion plant producing district heating to the local community (Landbrug og Fødevarer, 2022) [30]. The prebiotic, named Arrabina - added as a food ingredient by the neighbor company COMET with the purpose of promoting healthy gut microbiota products - derive from hemicellulose extracted from straw that constitutes one of the primary sugar molecules in all plant material (C5-sugars). Subsequently, this hemicellulose, which account for 20 % of the straw content (Møller and Nielsen, 2016) [37], is purified into the prebiotic fiber known as arabino-xylan (Sørensen, 2025) [46].

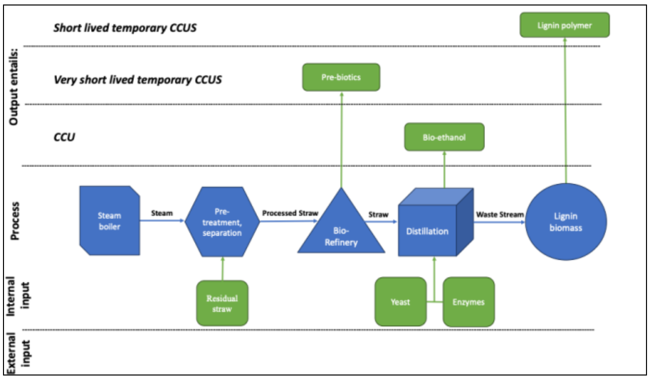
The extraction process is facilitated through specialized membrane filtration technologies, including nano- and ultrafiltration, which segregate particles based on size and charge, depending on pressure conditions and membrane pore size (Bamigbade *et al*, 2022) [2]. By combining these membrane filtration processes in series, a high level of concentration is achieved. The fibers are transformed into a white powder with various applications within the food industry, hereunder the prebiotic product Arrabina. Arrabina exhibits optimal solubility in clear liquids with high stability and no color or flavor impartation. Arabino-xylan fiber accounts for 70 % of naturally occurring fibers in grains (Landbrug og Fødevarer, 2022 [30]; Meliora, 2025) and has been documented by various scientists for its value as a prebiotic cereal-based dietary fiber component, e.g., by Kolida and Gibson (2007) [29] and Carlson *et al*. (2017). The manufactures prebiotic ingredients are primarily sold on the US market, where prebiotics as dietary supplements currently are approved. However, the company aspires to expand its presence into the European market (Meliora, 2025). The pre-biotics production implies a very short lived temporarily CCUS strategy, as shown in Figure 2, as it will be consumed within medicine or food ingredient.

Source: Valmet (2023) [47]

Fig 1: The force feed steam explosion re-finery plant at Maliora, Kalundborg

Besides prebiotic the case company also produce advanced bioethanol derived from straw, enzymes, and yeast (the latter two from local industry), and hence achieve low CO_2 footprint in the fuel production. This bioethanol, sourced from agricultural residues, serves a diverse range of applications, with its primary use involving blending with gasoline to power vehicles. Thus, this implies an immediate CCU strategy (see Figure 2), as being blended with gasoline in a Danish context. The feedstocks are typically corn and sugarcane (1st generation ethanol) being imported e.g., from Brazil, which offer comparatively lower CO_2 displacement (Landbrug og Fødevarer, 2022) [30]. By adopting the company's' (2nd generation) bioethanol the food-versus-energy challenge is also being addressed (Meliora, 2025; Sørensen, 2025 [46]).

The 25 % inherent lignin content in straw (Møller and Nielsen, 2016) [37] is currently subject to extraction within the case company's bio-refinery, where it previously was used for renewable energy generation in the form of steam that runs the steam explosion unit (Valmet, 2023) [47]. The production of lignin now holds substantials as a substitute for polymers in various applications and for substituting bitumen in asphalt production (Valmet, 2025) [48]. Adopting this business provides a short lived temporarily CCUS strategy for lignin products.



Source: Author

Fig 2: Bio-Refinery Case with upcycling of straw incl. CCU/CCUS profile

4.1.2 Straw for furfural and wax (The Biogas Plant Case)

The case revolves around the deployment of the Abed Biogas Plant in Lolland Municipality located in the South Easter part of Zealand, Denmark, established in 2023. The production of wax and furfurals on the Abed Biogas Plant is in its initial stage. The biogas plant is currently based on the use of 600.000 tn of animal manure and green substrates, including 100,000 tn of residual straw, from the local mainly agricultural community. The biogas plant will generate 198,500 MWh annually and supply energy services to 14.000 households. An upgrading facility will catch CO_2 from the raw biogas and inject pure methane into the natural gas network that is expected to be ready for operation in 2024 (Business Lolland Falster, 2025) [33]. Besides this, valuable digestate is produced substituting artificial fertilizer and a very short lived CCUS strategy (possible shot lived) are obtained for the heavy carbon in digestate (see Figure 3), which store and building up in the farm soil when distributed (Karimi *et al*., 2022; Chojnacka & Moustakas, 2024) [27, 10]. The biogas is hence primarily produced from light carbon in the substrate (easy digestible) leaving heavy carbon to be recycled to the farm soil (EBA, 2024) [18]. The production of methane, on the other hand, provides a CCU strategy as the fuel is immediately utilized in the gas grid.

Danish biogas plants in general emits 675.000 tn (Lillevang, 2022) [32] of biogenic CO_2 to the atmosphere from upgrading facilities on an annual basis, which for example could be utilized to assist in the production of wax and furfurals as new bio-products. The process will utilize the CO_2 from the biogas plants upgrading facility, in the form of supercritical CO_2 ($scCO_2$), as a solvent for the extraction of furfural and wax. The process allows to produce such bio-products ahead of other valuable usage of the residual straw e.g., energy production (Hansen, 2025) [20]. The benefits of and production of wax and furfurals are detailed below.

Furfural derived from straw serves as a promising source for future bio-products, making it a valuable platform for the development of green chemicals and bio-fuels (Li *et al*., 2016) [31]. It is touted as a "biobased alternative for the production of everything from antacids and fertilizers to plastics and paints," (Biomass, 2021) [4]. Unlike traditional furfural produced from fossil fuel petroleum products, natural furfural is extracted from lignocellulosic materials, which include lignin, hemicellulose and cellulose. To generate furfural, xylose or xylan, a component of hemicellulose, is frequently used, typically employing an acid catalyst. This process involves the hydrolysis of xylan into xylose and subsequent dehydration of xylose (pentose) to yield furfural (see Table 1). Xylan is commonly found in lignocellulosic biomass, such as cereal straw emphasized in this work, but also in maize cob, rice husk and bagasse (Matsagar *et al*., 2017) [36]. It is imperative to separate and pretreat the lignocellulosic material to extract the hemicellulose content, a crucial step that enables the conversion of this substrate into C5 sugars and, ultimately, furfural. Furfural production is a versatile chemical platform, serving as a building block for various green chemicals and construction materials, thus implies a short lived CCUS strategy, with materials being more durable and long lived. See Figure 3. This process can benefit from the use of supercritical CO_2, where supercritical CO_2 can function as the solvent for extracting furfural, replacing environmentally unfriendly mineral acids. One significant advantage of this approach is the recyclability of the solvent (Sin *et al*., 2014) [42].

Table 1: Potential outputs of wax and furfural and related benefits for Abed Biogas Plant

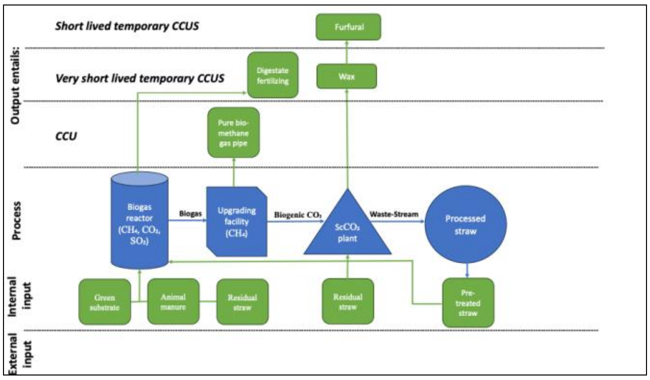
Output	Amount	Content/data
Residual straw	100.000 tn	40 % cellulose 20 % hemicellulose 25 % lignin (ii&iii)
Wax	66 tn	0,66 % extraction (i&iv)
Furfural	10.080 tn	20 % hemicellulose 70 % extraction 72 % yield (iii&v&vii)
Green substrate	89.854 tn	Pre-treated feedstock with high gas yield potentials (ii&vi)
Biogas	17,3 M m^3 methane	245 m^3 methane/tn dry matter (DM) (ii)

Source: Own table based on: Sin *et al*., 2014 [42] (i); Møller and Nielsen, 2016 [37] (ii); Matsagar *et al*., 2017 [36] (iii); Bulushi *et al*., 2018 [5] (iv); Dalvand *et al*., 2018 [13] (v); Lybæk *et al*., 2020 (vi); Biomass Furfural, 2021 (vii).

The production of wax from straw is a versatile process encompassing various substrates, including fatty alcohols, fatty acids, sterols, wax esters, and alkanes. These waxes can be derived from biomass residues, such as cereal straw in this case, and are extracted from the greasy content present on the surface of cereal straw (Bulushi *et al*., 2018) [5]. The resulting natural wax finds application in diverse fields, including food supplements, cosmetics, flavorings, fragrances and coatings (Sin *et al*., 2014) [42]. The wax implies a very short lived CCUS strategy, as the products will be utilized relatively near to its production. See Figure 3. It is environmentally friendly nature, as it serves as a substitute for petroleum-based (fossil fuel) wax, which has limitations in production scale (Bulushi *et al*., 2018) [5]. The extraction of natural wax from cereal straw involves the utilization of supercritical CO_2 as an extract-fluid/solvent, a process well-documented by Hyatt (1984) and Hunt *et al*. (2010) [23]. This approach streamlines the extraction and fractionation of wax from biomass and can be conducted in a single, internal step (Deswarte *et al*., 2006; Sin, 2012) [14, 41]. Crucially, this method stands out as an eco-friendly alternative to more traditional techniques that employ organic solvents. The use of supercritical CO_2 ensures that no solvent residues are generated, making it compliant with the strict requirements of substrates used in cosmetics and food supplements (Hunt *et al*., 2010; Sin *et al*., 2014) [23, 42].

After the extraction of wax and furfurals by the processes detailed above, the processed residual straw can be further repurposed as feedstock for biogas production, here within the co-located Abed Biogas Plant. See the output materials in Table 1. During the extraction of wax and furfural, the residual straw undergoes a pretreatment, which is exceptionally well-suited for biogas production. This significantly increases the value of residual straw as a substrate in the cascading process, leading to higher gas yields, surpassing those obtained from non-processed straw residues (Lybæk *et al*., 2020). Furthermore, this approach may result in cost savings, potentially eliminating the need for previous straw pretreatment technologies, such as macerators and choppers, as proposed by Møller and Nielsen (2016) [37]. The outcome is hence a process that creates valuable synergies. Applying the example of residual straw utilization at the Abed Biogas Plant, the production of wax and furfurals - and related benefits - are illustrated in

Table 1 above.



Source: Author

Fig 3: The Biogas Plant Case with upcycling of straw incl. CCU/CCUS profile

4.1.3 Straw for building materials (The Prefabricated Wall's Case)

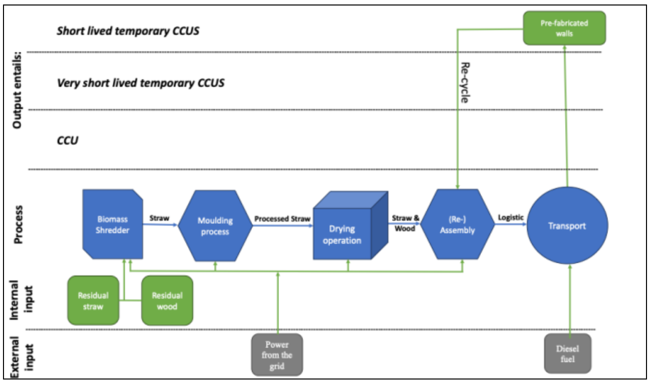
EcoCocon operates in the eastern part of Jutland, Denmark, with its headquarters in Slovakia and its production facility in Lithuania. The Danish branch was established in 2015. The company manufactures prefabricated building walls made from straw for use in contemporary construction. From the production site in Lithuania, the prefabricated elements are transported by truck to customers in Denmark. The elements are produced from natural and renewable materials, primarily residual straw with a smaller proportion of wood. According to the company, the elements undergo limited processing and are described as contributing to a high indoor air quality without releasing harmful substances. The system is designed to be breathable, allowing moisture to escape, and is reported to be windproof and free of thermal bridges, which is intended to reduce the risk of drafts and mold. The use of natural materials is described as supporting a stable indoor microclimate with relatively consistent temperatures across seasons (EcoCocon, 2025). The elements consist of 89% straw and 10% wood. In line with the aim of reducing the use of forest resources, the company states that the design minimizes wood use while maintaining structural integrity (Keller, 2025) [28]. EcoCocon sources residual straw from local farmers near the production facility and states that the production process is designed to have a low energy demand (EcoCocon, 2025).

The prefabricated elements are produced by shredding or chopping the straw it into smaller uniform pieces, based on the intended application (size of elements). Then a natural binding agent, typically a bio-based polymer or eco-friendly adhesive, is added to hold the straw particles together and provide structural integrity. The mixture of processed straw and binding agent is molded into the desired shape of the elements with compression applied for added strength. The molded elements are then allowed to cure or dry, which involves exposure to air or controlled heat, ensuring they harden and gain structural strength (EcoCocon, 2025). Quality control measures are finally employed to ensure the elements meet the required standards for strength, durability and environmental sustainability (Cornaro *et al*., 2019) [9].

The prefabricated elements are composed of the following features: Exterior: a) Wood fibre layer aids in achieving passive house standards in cold climates; b) Windproof, breathable membrane prevents heat loss and ensures moisture transfer. Elements: a) Straw insulation manufactured using multi-directional compression technology; b) Dual-load-bearing structure utilizing wood from forests; c) Tailored dimensions to suit various building designs; d) Smooth and uniform surface; e) Standard thickness of 40 cm. Interior: a) Surface for clay rendering, b) Compatible with various conventional rendering methods (EcoCocon, 2023). See Figure 4.

Source: Author

Fig 4: Cut-through of the EcoCocon prefabricated wall exposing various exterior and interior layer's



Source: Author

Fig 5: The Prefabricated Wall's Case with upcycling of straw incl. CCU/CCUS profile

The elements furthermore rely on the 'design for disassembly' principle, so that building parts and materials can be used again in other places and for other purposes in the future. Design for disassembly is a critical principle in sustainable product development (Keller, 2025) [28]. This principle involves creating products with the intent of easy disassembly, repair and recycling, ultimately reducing waste and environmental impact. By implementing design for disassembly, it is possible to extend the lifespan of renewable energy infrastructure and reduce the need for resource-intensive manufacturing. This approach promotes both economic and environmental benefits (Daly, 2023 [12]; Ottehaus, 2023). The prefabricated elements can hence be re-used and re-assembled at EcoCocons facilities or nearby its original usage. See Figure 5. Thus, a short lived temporarily CCUS strategy for residual straw can be identified, where re-cycle options exist implying that the carbon will be stored even further.

The company's long-term objective is to develop more localized production capacity, including in Denmark, to be closer to customers, contribute to local economic activity, and reduce transportation-related emissions (EcoCocon, 2025). EcoCocon states that its mission extends beyond the organization itself, describing it as part of a broader international community seeking to promote change within the construction industry. As of today, they have erected over 20.000 m² of EcoCocon prefabricated elements and have hence sequestering and stored more than 1.500 tn of CO_2. Additionally, the company will achieve CO_2 emission reductions, amounting to at least 9.000 tn over the lifespan of the building stock, primarily due to increased energy efficiency in the building design and composition of the elements (Keller, 2025) [28].

5. Discussion

This results from the exploratory case study has reviled insights from three pathways for the utilization of residual straw in Denmark: The Bio-Refinery Case, the Biogas Plant Case and the straw-based Prefabricated Wall's Case. The comparison highlights important potentials for carbon capture, utilization and storage (CCUS). The findings, however, stresses that assessing pathways solely on their CCUS performance provides an incomplete and potentially misleading picture. A more accurate sustainability assessment of straw pathways depends equally on their contribution to the circular bioeconomy (CBE) and their ability to generate cascading upcycling's'. Only by considering carbon storage, cascading value and local valorization together, can we identify pathways that genuinely advance climate and circularity goals.

The bio-refinery pathway demonstrates strong cascading value by converting straw into multiple high-value products - prebiotics, ethanol and lignin polymers - while integrating residues into energy systems. These upcycling's exemplify how straw can be elevated within the CBE and substitute fossil-based inputs. However, the CCUS potential is largely short-lived, as most products quickly release their carbon. Moreover, the high costs and limited number of facilities constrain the wider role of this pathway in Denmark. The biogas plant pathway stands out for its broad cascading profile and practical maturity. Straw is used alongside manure and green substrate to produce renewable energy, while e.g. digestate improves soil quality and stores carbon in agricultural fields. Captured CO_2 is applied in the production of furfural and wax, substituting fossil-based chemicals and thereby extending the utility of biogenic carbon. This pathway therefore not only achieves CCUS benefits but also exemplifies cascading upcycling's' across several loops: energy, soil fertility and new bio-products. With more than 100 agricultural-based biogas plants - of which more than half upgrade the biogas to methane resulting in carbon for further usage (Biogas Danmark, 2024) [3] - the biogas case provides the strongest immediate option for integrating both CCUS and CBE principles in practice. The straw-based building materials pathway offers the most durable form of carbon storage, as straw is locked into walls for decades while substituting conventional construction materials. However, this case provides essentially **one single cascading step** - straw into prefabricated elements - and does not open additional loops of valorization.

Furthermore, the production facilities are currently located outside Denmark, which undermines the principle of local valorization central to the CBE and increases transport-related emissions. Without local production, this pathway cannot be considered a fully circular or cascading solution, even if its long-term carbon storage effect remains significant. If future pathways were assessed only in terms of CCUS, the building materials case could appear to be the most promising, given its long storage horizon. However, this would neglect the lack of cascading value and local integration. Similarly, the bio-refinery's short lived CCUS profile would undervalue its contribution to high-value substitution and circular innovation. The findings therefore show that **CCUS is a necessary but insufficient single criterion** for evaluating biomass strategies. Sustainable pathways must foremostly be judged on their cascading upcycling potential and their capacity to advance the CBE in practice. For Denmark to realize the full value of its 2,6 M tn of unused straw residues, policy must explicitly promote hybrid strategies that combine CCUS and cascading upcycling. Support for bio-refineries should target innovation and market development for bio-based products. Biogas plants should be further incentivized to integrate CO_2 utilization technologies and soil-enhancing practices. Investment in local production of straw-based building materials is necessary if this pathway is to contribute meaningfully to CBE goals rather than only to carbon storage. Policies that focus narrowly on carbon accounting risk overlooking these broader systemic benefits.

6. Conclusion

The analysis demonstrates that no single pathway provides a comprehensive solution. Biogas plants today deliver the most robust cascading and CCUS profile and should be prioritized for immediate implementation. Bio-refineries hold strong cascading and substitution potential, though scaling barriers remain. Straw-based building materials contribute long-term carbon storage, but without local production and additional upcycling loops, their CBE contribution is weak. In conclusion, the evaluation of straw pathways must not be reduced to CCUS metrics alone. A balanced and forward-looking strategy requires integrating CCUS with cascading upcycling's and CBE principles. Only by combining carbon utilization, high-value product substitution and long-term carbon storage, can Denmark maximize the environmental and economic gains from its straw resources and move decisively towards climate neutrality and circular sustainability.

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