Supplementary Information for "What is the potential of bioCCS to deliver negative emissions in Norway? From biomass mapping to a window of negative emissions potential"

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Abbreviations: AD, anaerobic digestion; bioCCS, bioenergy with carbon capture and storage; DM, dry matter; EU, European Union; HHV, higher heating value; MSW, municipal solid waste; NIBIO, Norwegian Institute of Bioenergy Research; NOBIO, Norwegian Bioenergy Association; SSB, Statistisk Sentralbyrå; TMF, The Magic Factory; WtE, waste-to-energy.

1 Biomass Mapping Details

1.1 Agriculture

1.1.1 Straw

Straw is a residual biomass left after the harvesting of grains in agriculture. Although different grain (or cereal) crops produce various kinds of straw and the scale of the harvesting equipment dictates the straw collected. Of the total crop harvest, 50% of collectible straw is available for further uses [1] [2]. Norwegian agriculture produces primarily barley, wheat, oats, rye, and a smaller amount of rye wheat. According to the Norwegian Bread and Grain information office, grain production is highest in the mid-eastern counties of Viken, Innlandet, Vestfold, and Telemark, as shown in Figure 1. Conversely, grain production is lowest in the northernmost counties of Troms, Finnmark, and Vestland [3].

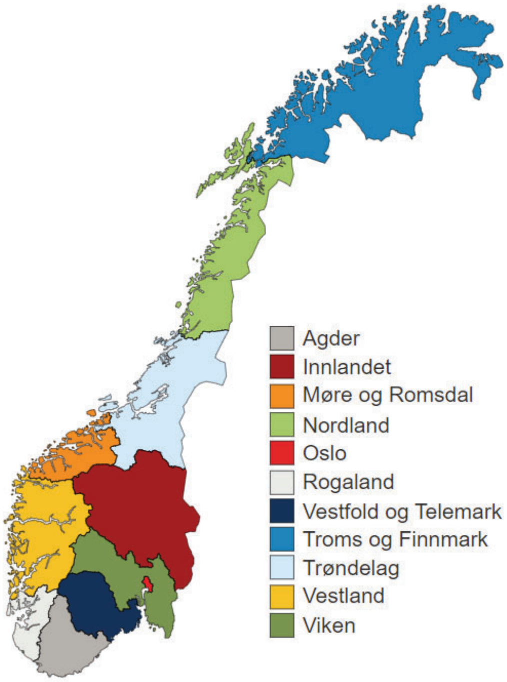

Figure 1: Counties of Norway

Despite having a relatively high heating value of 14-16 MJ/kg (dry basis), the use of straw for energy production is limited due to physical, logistical, and societal factors. For instance, it requires a long drying time in the field before it can be collected and balled, which can take up to a week to achieve the desired moisture content of 16% in European straws. Drying and storing it for efficient combustion can be expensive and challenging due to its ash content (3-5% ash), which can cause sintering and slag/deposit formation in the combustion chamber and on heat exchangers at high temperatures [2] [1]. In addition, its high chlorine and alkali metal content can lead to the formation of corrosive sodium and potassium chloride salts [1]. Moreover, farmers must leave a significant portion of straw (50-67%) in the field for soil enhancement, which enhances the carbon content and physical

	Lignin (g/kg)	Cellulose (g/kg)	Hemicellulose (g/kg)	Ash (Mass fraction of Dry solids(%))	Total Solids (%)	Volatile Solids (% of total solids)	Moisture Content (%)
Barley	86	464	220	4.7 ±0.05	92.67	95.26	7.33
Oats	64	436	236	7.7 ±0.12	92.05	92.25	7.95
Wheat	75	435	261	3.5 ±0.06	91.91	96.51	8.09
Rye and rye wheat	71	449	289	3.9 ±0.20	91.36	96.05	8.64

Table 1: Straw composition details [9].

characteristics of the soil [4] [2]. Open-air burning of straw is minimal in Norway due to regulations against it in many municipalities.

The only typical application of straw for bioenergy in Norway is heating systems at farm locations [5]. However, only 10% of the 1600 farms reported by the Norwegian Bioenergy Association (NOBIO) to receive public funding to build heating systems in the early 21st century built straw heating systems [6]. In contrast, Denmark uses one-third of its available straw as feedstock for bioenergy via centralized combustion plants, and ongoing research is being conducted in Denmark to improve biogas production efficiency with straw [7] [8]. Therefore, despite the limitations and challenges of straw as feedstock for bioenergy, it is currently well-exploited in other Nordic countries.

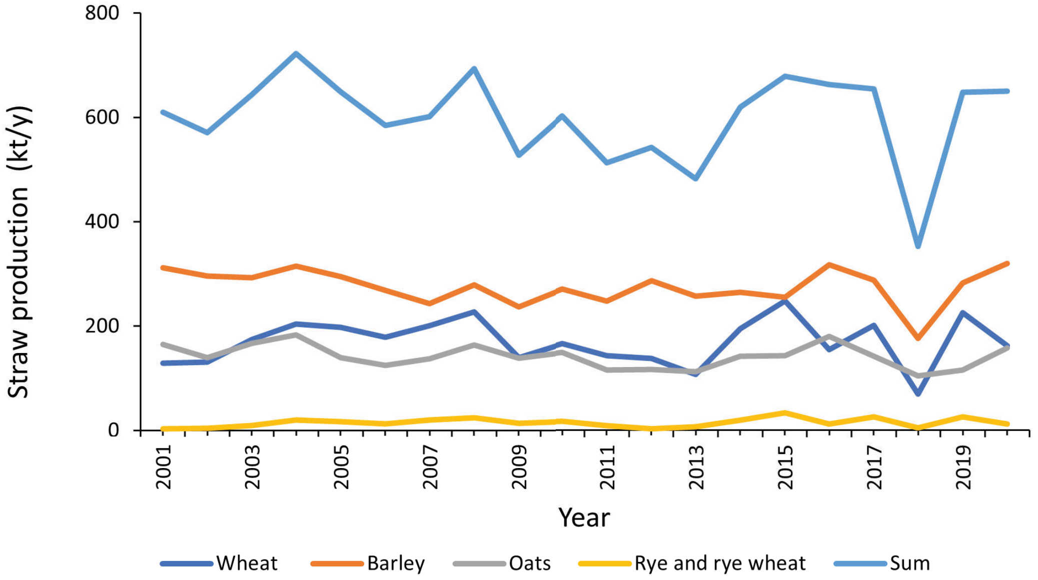

Figure 2: Production of straw in Norway from 2001 to 2020 (SSB 04607, SSB 04610). Based on two reports by the governmental reporting agency Statistics Norway (SSB) used for grain production and crop yield per acre (50% of which is the accepted estimate of crop production, which is collectable straw) (SSB 04607, SSB 04610). Values are on a wet basis with a 15% moisture content.

Norway could better exploit straw as a biomass resource for energy production. The straw production in Norway from 2001 to 2020 is shown in Figure 2. Sammut (2019) reports that 50-67 % of straw produced should remain on site to ensure good soil characteristics, while another 14% is used as livestock feed and bedding [4] [2]. Assuming Norway follows similar practices to Denmark, 40% of straw could be removed from the farm, leaving 26% (after removal of the 14% for feed/bedding) as the potential value for other applications, including energy recovery via combustion or anaerobic digestion (AD) of biogas and production of digestate and fertilizer.

Total straw production in Norway is approximately 604,000 tonnes (wet basis), with the grain types being 46% barley, 28% wheat, 23% oats, and 3% rye and rye wheat. All these cereals have similar physical properties and thus similar application potential for bioenergy production with CCS (bioCCS). With a moisture content of 15 wt% and an average carbon

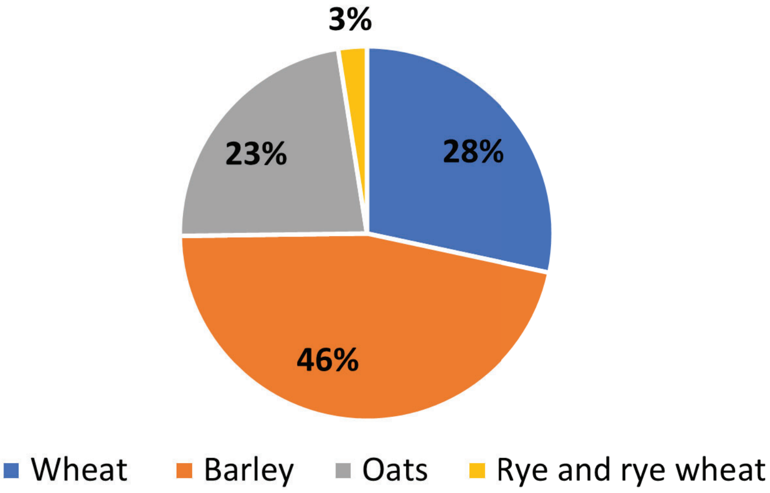

Figure 3: Distribution of types of straw within the context of the total annual straw production in Norway.

content (dry basis) of 46 wt%, the total yearly amount of carbon currently found in straw in Norway is about 254,000 tonnes. Other sources have described the moisture content of straw to be around 5-8% . However, a 15% weight-content of moisture is adopted in this study following SSB reports [10] [9].

Because the values for straw production are relatively stable over the 2001-2020 period, our estimate for both the current and the 2030 total straw production is an average value using the last 20 years. Data from 2018 is excluded from this average because of drought conditions [11]. However, if drought frequency and strength increase in Norway as a result of climate change, the 2018 estimate may become more representative.

1.1.2 Livestock manure

Despite the large availability of livestock manure in Norway, there is a lack of facilities that exploit this resource. The Magic Factory (TMF), which treated 69,500 tonnes of manure in 2019 using anaerobic digestion (AD) to produce bio-methane, was the only large-scale facility found [12]. TMF also operates an environmentally friendly greenhouse on a research scale, growing tomatoes using recycled food waste and livestock manure digestate from the factory as bio-fertilizer. Few other smaller facilities using manure, including Romerike Biogas Plants and Biokraft AS, were also found. However, Pettersen et al. [13] reported that only 1% of the energy potential offered by manure was exploited, per 2017, despite the granting of subsidies for 11,000 tonnes of livestock manure at farm-based treatment plants [12]. Based on the statistics collected by the Norwegian Institute of Bioeconomy Research (NIBIO), approximately 83,000 tonnes of livestock manure was delivered to biogas facilities in 2019, although this only represents the manure treated in state-subsidized plants, and limited information is available from other sources. The composition of manure varies by animal species, as well as additional parameters such as feeding, modes of operation, and the use of litter. In Norway, livestock manure primarily comes from pigs and cattle; its composition is shown in Table 2. Currently, the most common use of manure in Norway is storage and subsequent spreading as a fertilizer for cultivated land or approved infield grazing [4]. A large amount is stored each year due to limitations on amount of manure which can be spread per hectare of land.

	Ash (Mass fraction of Dry solids(%))	Total Solids (%)	Volatile Solids (% of total solids)	Moisture Content (%)
Cow manure (oat feed)	14	11	86	89
Cow manure (barley feed)	12	13	88	87
Pig manure	11	24	89	76

Table 2: Composition of pig and cow manure, from a study on biogas production potential in Norway [14]. The cow manure used excludes urine, but the moisture content is stated by Morken et al. [14] to be slightly lower than typical manure streams.

Livestock manure is a stable and sustainable raw material readily available, but its high moisture content makes combustion less practical. Manure type can affect yields in anaerobic digestion, depending on factors like composition and water content. Cow manure is less diluted than pig manure, requiring lower transport costs [15]. Including manure in pre-treatment or blending with other feedstocks increases gas yields [10][12].

In 2030, Sammut (2019) estimates 1,150,723 tonnes of livestock manure will be available on a dry basis, with 78% (897,563 tonnes d.b.) estimated to be usable for other applications such as bioenergy. However, only 42% is considered to have "realistic potential" for biogas production at a centralized location, based on farm type and geographical distribution [4]. Carbon Limits estimates Norway's "realistic potential" of manure to be 6,606,145 tonnes on a wet basis or approximately 660,615 tonnes on a dry basis (assuming a 10% solids content [14]), around 70% of the annual total. These two estimates average out to 780,000 tonnes of dry basis available manure. With an average carbon content of 36 wt%, that represents around 280,800 tonnes of carbon [16]. Sammut also predicts that by 2030, the number of farm animals will increase by 15% (to 19 million from the current 16.5 million), making manure a reliable and increasing feedstock for bioenergy production with CCS.

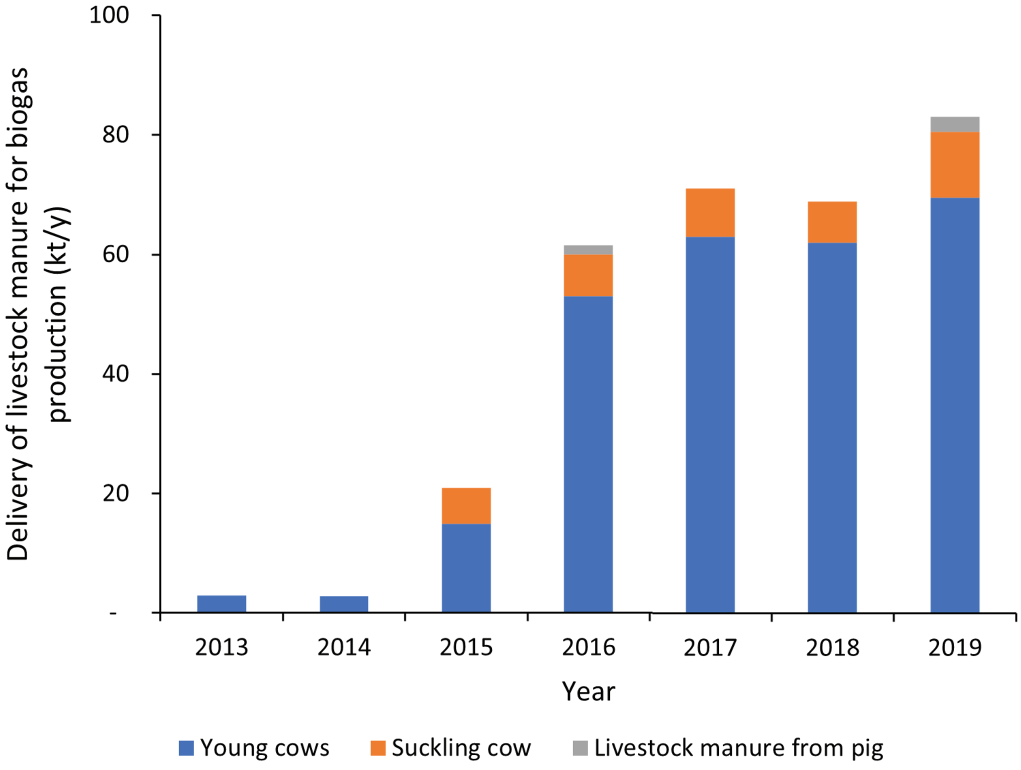

Figure 4: Origins of manure delivered for biogas production from 2013-2019 [12].

1.2 Forest

Norway's forests, including both productive and unproductive forests, occupy more than 1.1 billion cubic meters, accounting for 38% of the total area [17]. Spruce, pine, and birch make up 90% of the standing volume, with many regions of Norway being dominated by one species due to a combination of climate factors and management practices. The growth season and conditions (e.g., temperature, air quality, soil nutrients, light, etc.) are highly variable across Norwegian geography [17] [18].

Forest is reported in Norway as area with over 10% coverage of trees that are or can become at least 5 meters tall. Productive forest refers to forest that can annually produce 1m^3 of timber (bark included) per hectare under favorable conditions. Unproductive forests are areas with forest trees and forest canopy coverage that do not meet the production level of productive forest. Other wooded land has only 5-10% canopy cover of forest trees; this can include lands with more than 10% perennial shrubs and short trees (e.g., bogs and lowlands). Open areas refer to land with vegetation cover that is neither forest, water, bogs, ice, agricultural area, nor developed land, and is mostly in mountainous areas. Other areas include state-controlled open areas, military training areas, power roads, cabin fields, etc. (see more details in relevant sources [17].

Norway's forest density and area can also be variable with geography. Figure 5 illustrates the differences in forest area throughout the country, with Troms and Finnmark having the largest total area, most of which is "other wooded land" rather than productive forest [17]. Innlandet has the highest area of productive forest by both area and volume (Figure 6). Forest distribution and density generally follow terrain expectations, with the majority of forest cover located in the milder south-eastern part of the country, with flatter terrain and better shelter from wind and ocean weather.

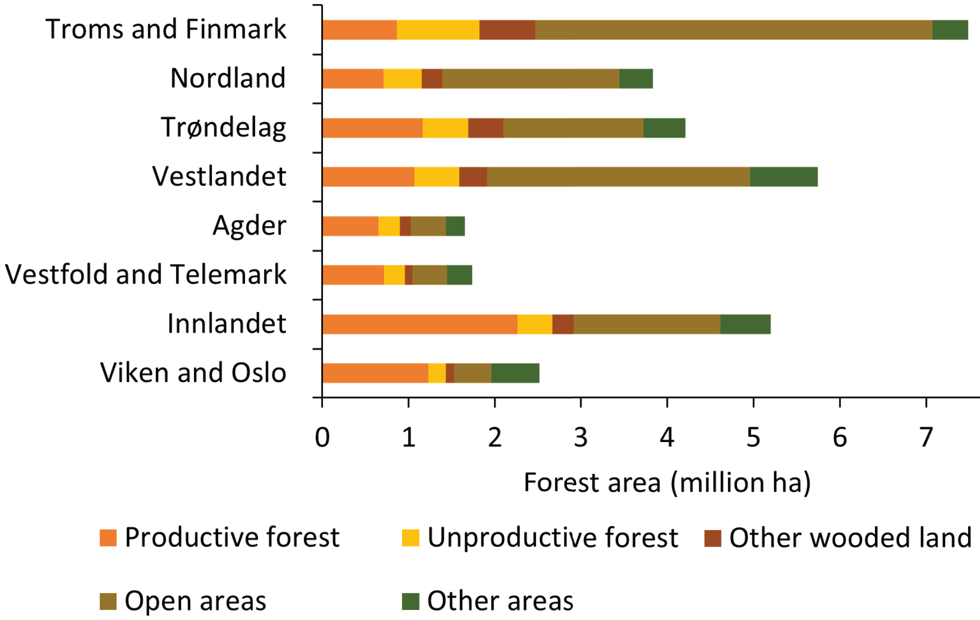

Figure 5: Forest by area, in millions of hectares, as reported by NIBIO [17][19]

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1.2.1 Spruce, Pine, Birch, and other deciduous trees

To ensure sustainable forest management, a yearly "balance quantity" limit is set as the maximum harvest quantity. It is defined as slightly less than the gross annual growth of the forest area and is already calculated each year for Norway's forest areas [17]. Because

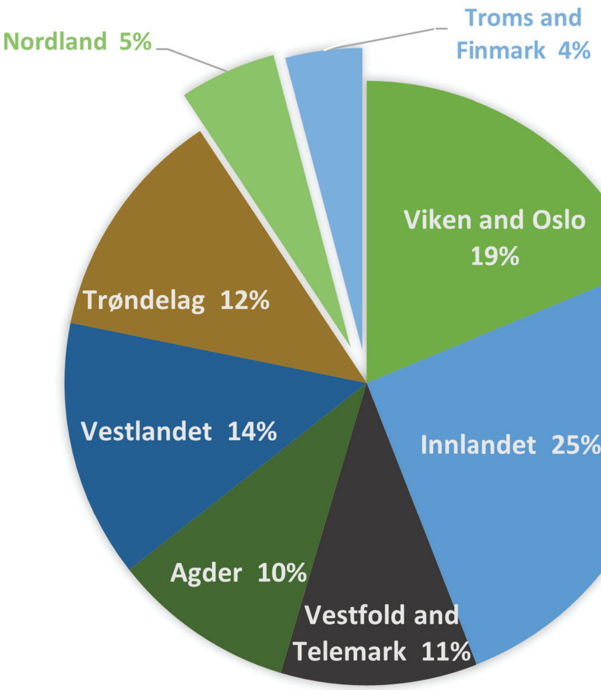

Figure 6: Distribution of forest volume by county, as reported by NIBIO [17].

extraction of forestry biomass is consistently less than the annual growth, the standing volume of forest in Norway is increasing and has been doing so for over a century. The harvesting rate is lower than the annual growth, resulting in a net increase in standing forest volume each year [19]. While there are variations in the yearly harvest rate, a report by Tømborg and Røsrstad in 2017 suggests that it is unlikely to increase significantly without a corresponding increase in the price of timber (roundwood and pulpwood) [20]. NIBIO's national forest assessment reports the standing forest volume from 1920 to 2020 (shown in Figure 7).

Although increased commercial felling may not be economically favorable in certain areas of Norway's forests due to higher harvesting costs, many forest residues can still be used for bioenergy applications. Some parts of Norway's forested areas are challenging to access and remove wood due to obstacles like waterways and steep slopes, which can result in the cost of harvesting outweighing the value of the wood [21]. Because productive forests are mainly used for primary industries such as buildings, furniture, paper, and pulp, the application of timber resources for energy purposes has a lower economic value. However, there are various forest residues, such as bark, sawdust, branches and tops, stumps, and wood residues, that are not being fully utilized in other value chains and are readily available for bioenergy applications. These residues which are easier to collect can come from various sources, including power line installation, pastures or other agricultural settings, and road and railway construction.

The NIBIO report from 2022 states that the yearly rate of growth of the forest is predicted to be greater than felling in several proposed future scenarios based on historical context, as well as changes in forest management policy. Deforestation over the last 100 years has moderately but steadily (Figure 8) while standing volume is increasing nearly exponentially (Figure 7).

Because the growth rate is higher than the felling rate [19], there is a potential for increased, sustainable tree harvesting that could be used for a variety of applications. Felling is generally not permitted for trees younger than 11 year old, and the potential increase in felling discussed here follows these sustainable harvesting practices. Based on the average

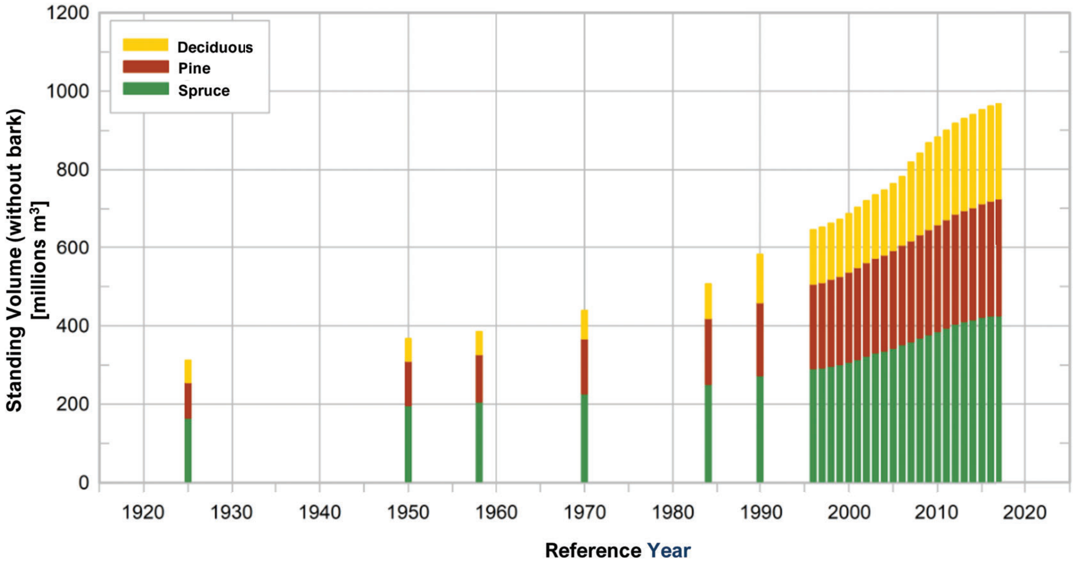

Figure 7: Standing development of forest (without bark) from 1920 to 2020. Adapted with permission from [19].

of the scenarios proposed by NIBIO, the balance quantity is approximately 20,500 km^3. This means that with a felling rate of 20,500 km^3, the forest remains healthy as defined by growth, species diversity, and as a habitat for animals. From available growth and felling numbers [17] forest growth (excluding unavailable forest on steep slopes or natural obstacles) is 26,300 km^3 per year while annual felling is 13,000 km ^{3}. This means an excess of 7,200 km^3 of forest each year could be available as part of sustainable forest management, with no reduction in overall forest standing volume. These numbers typically do not include tops and branches, stumps and roots, and bark.

A typical tree in Norway consists of 5% bark, 22% stumps and roots, 53% trunk, and 20% branches and tops [7]. The wood itself consists, on average, of 40% cellulose, about 25% hemicellulose, and 20-30% lignin. Woody dry matter consists of approximately 50% carbon, 43% oxygen, 6% hydrogen, and 1% nitrogen and ash [22]. The ash in the trunk wood of the tree is lower (0.5%) and highest in the bark (2%). In addition, bark can be polluted by sand and gravel if the timber has been extensively dragged [23].

The most common application of wood for bioenergy in Norway is by combustion in wood stoves (ca. 1.9-2 million m^3) [19] and small- to medium-scale biomass combustion plants for district heating or industrial purposes [24] using mainly timber-processing residues as feedstock (see section below). There is a long and strong tradition of wood stove utilization in Norway (both for heating and coziness). It represents about 40% of the use of biomass for energy purposes in Norway [25].

While fresh trees have an average moisture content of about 50%, the different parts of the tree have different water contents. The higher the moisture content, the lower the calorific value [26]. While some wood chip heating systems can handle a moisture content of 40-50%, others require as low as 30% moisture for burning. Additionally, other composition properties differ with species variation, resulting in different calorific values. For example, pine has the highest caloric value of the trees present in Norway due to its high resin content. When estimating potential for integration with bioenergy, both caloric value and distribution of tree species in Norway should be considered. An assumption in this report is that woody biomass is dried to 30% moisture. To include bark, we multiply the felling by a factor of 1.05.

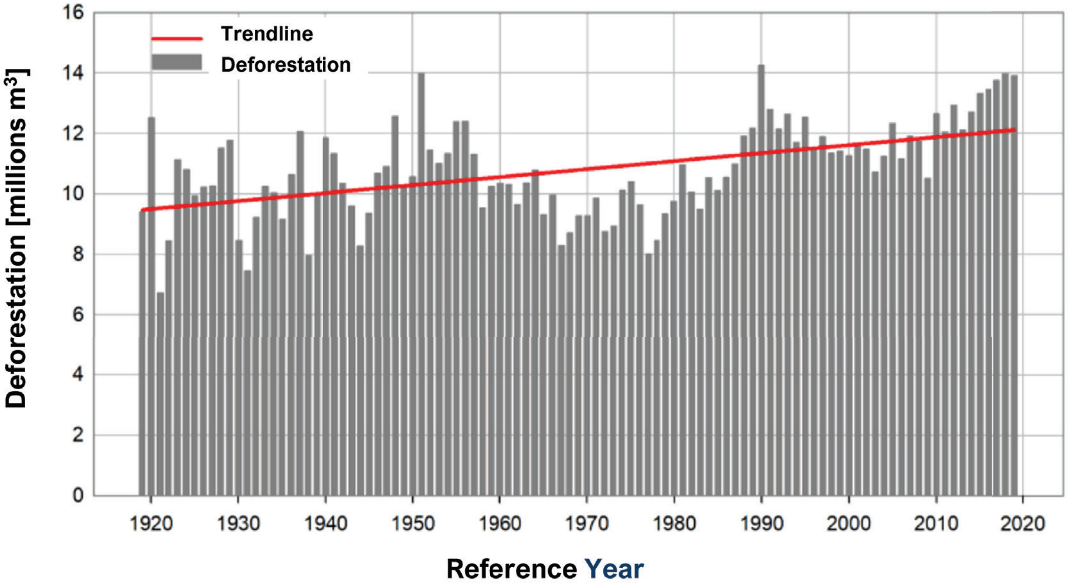

Figure 8: Deforestation of Norwegian forests, with trendline, from 1920 to 2020. Adapted with permission from [19].

1.2.2 Timber

Timber (or roundwood) is the high-value component of trees and is already well-exploited for production of paper, and building materials (planks, floors, etc.). Figure 9 provides a complete overview of the main streams concerning timber and shows the complexity of this market. Approximately 47% of timber is used for building materials, while 37% is used for pulp and paper (the remaining 15% being used in residential heating appliances) [27] [28]. About 32% of the timber is exported (net value corrected for import). When the timber residues are used for energy purposes, it is, whenever necessary, being cut and processed into different sizes/shapes depending on the installation, e.g. logs, briquettes, pellets, or chips. Chips can vary in size, and the finest chips can be smaller than 3 mm. Sticks are classified as chips longer than 15 cm, and these larger pieces can clog wood chipping systems. During the cutting of round wood, in preparation for manufacturing high-value goods, as much as 45% of the biomass is “discarded” [29] to be used by the pulp and paper industry in Norway and abroad, or energy purposes such as internal drying processes in sawmills. The average number is 25% “residues/losses” for pulp and paper (average for chemical and mechanical pulping processes) [30]. Of the round wood, only lower-quality fractions are typically considered for bioenergy integration due to the higher value of products made of timber in comparison to conversion to energy. Changes in the energy and/or building materials markets might affect this situation, but looking back at the developments these last few decades, it does not seem probable without stronger economic incentives for energy from woody biomass.

Round wood chips of lower value often result from building new areas, referred to later in this report as “fores residues from different build areas”. For example, the clearing of trees to build new housing, new or expanded pastures, power lines, or clearing areas around roads and railways. These cannot be landfilled and are thus often left onsite or sent to waste-to-energy plants. In Bernseng’s report, this fraction of Norway’s forest biomass is about 1.5%, and the collection and use of this fraction for bioenergy applications seems too costly and operationally challenging to be realistically feasible [31].

Ultimately, only the residues from timber processing are deemed to be available for integration with bioCCS.

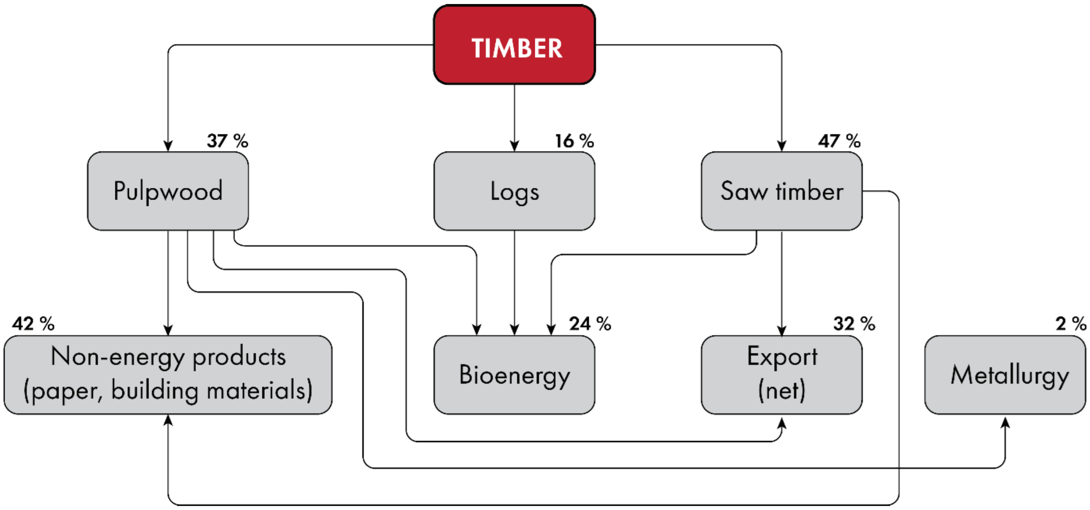

Figure 9: Illustration of the timber market in Norway, including quantities.

1.2.3 Branches and tops

During felling, the branches and tops are removed by the machinery onsite for easier collection and transport of the round wood. This fraction is also known in Norway as GROT [32]. In some countries, such as Sweden, this fraction of the tree is collected and used for energy. As of 2019, Sweden collects around 15% of branches and tops, which are used for bioenergy applications, and studies indicate that up to 50% collection is possible on a sustainable basis [33]. However, in Norway, the complete fraction of branches and tops is left in the forest. As previously mentioned, the branches and tops correspond to up to 20% of the tree. Due to financial, logistical, and environmental factors, some of this fraction must be left in the forest, as also mentioned by reports on Sweden's practices. In Bergseng's 2012 report, 50-60% is considered available for removal [31]. Another report from NIBIO considers up to 70% to be removable with consideration of logistics and environmental factors [34].

The branches and tops fraction is far from homogeneous, and the physical characteristics create additional challenges for collection. The needles contain a higher concentration of nutrients, e.g. nitrogen, which is more beneficial to leave in the forest (both for forest growth and because burning needles can cause high NOx emissions). The ash content is around 2.3% of the dry weight in branches and tops, and its moisture content is generally higher than round wood [35]. These two characteristics make branches and tops less desirable for energy applications. Finally, the percentage of fines (particles smaller than 3 mm) is higher for branches and tops than for other woody biomass fractions, as high as 25% [36]. For most heating plants, this is too high and can cause operational challenges. As a result, chip heating systems mixtures only include about 30% GROT while 70% are larger chips from timber [36]. Finally, without proper planning, branches and tops are difficult to collect. They need to be left in the forest to dry before collection, yet they are not currently gathered onsite and instead get run over by machinery. This is sometimes considered a protective measure against machine damage to the landscape, but only a small fraction is actually needed for that application [33]

Despite the downsides of collecting tops and branches for energy applications, other countries have demonstrated its feasibility. Although the practice is currently almost non-existent in Norway, it has increased in the last few years [7]. Yet, as Melbye later states, wood chip subsidies have stopped, and no further increase in branches and tops collection is expected given the current practices and framework.

Branches and tops could hence be seen as underutilized and a viable potential biomass resource that could be considered for integration with bioCCS. As previously mentioned, branches and tops are 20% of the tree volume, and the highest recommendation for collection is 70% of the fraction. Therefore about 14% of the annual felling volume is a potential resource. At today's level (13,000 km^3 per year), the fraction is 1,820 km^3, and if the felling is increased to today's balance quantity (additional 7,200 km^3 felling), the annual available fraction of branches and tops would be 2,828 km^3.

The chemical composition of branches and tops is 51% carbon and assumed a similar raw moisture content as round wood, although this can vary by species. The ash content is around 2.5%, and the HHV is 20.7 MJ/kg [32].

1.2.4 Bark

Bark makes up about 5% of the tree. Bark can be combusted with energy recovery for district heating or industrial purposes. Statistics Norway reports that bark, sawdust, and other types of wood made up one-third of the fuel for district heating in 2021 (SSB 04727, SSB 04729) [37]. Bark not used for district heating is commonly used in commercial products or as a soil enhancer to improve nutrient content and limit weed growth. Some bark is also be mixed with compost. Much of this fraction is considered to be used completely at the current rate of felling and collection. With an increase in felling to the balance quantity, more bark would be available, most probably mainly for energy purposes.

1.2.5 Residues from timber processing

During the processing of timber into products, different residues are created. For example, fiber residues discarded during paper production, or sawdust created during milling. Timber (logs), which is used in wood stoves across Norway for heating, is not included here, due to the difficulty of integrating CCS with such a decentralized system.

For timber being processed into logs or wood chips, processing takes place at sawmills where the generation of sawdust is unavoidable, as well as substantial. Up to 45% of the wood is converted to sawdust as part of the production of furniture, planks, or other wood products [29]. Current uses of sawdust in Norway include firing briquettes, animal litter, wood pellets, particle board, or feedstock production. In addition to sawdust, a range of byproducts for energy are produced with varying sizes, i.e. cutter chips, tear chips, and sawmill chips. Sawmill chips are typically used for paper production and in the smelter industry. These chips are considered the most important byproduct from the sawmills [36]. Sawmill chips have a moisture content of 55-60% when harvested, similar to fresh wood. When used for energy production, the chips require pre-drying to meet the requirements of the combustion system (previously noted to be as low as 30%). Cutter chips and tear chips are drier byproducts and are most often used for animal litter, briquettes, or wood pellets, but would also work well for bioenergy production. Sawdust has similar chemical properties to the round wood it is made from.

During paper production, waste streams include black liquor and lower-quality fibers that may be discarded based on the paper type being produced. For example, paper with a higher quality and special characteristics is more likely to have higher quantities of waste residues than newspaper products. Of the total timber logged from the Norwegian forest, 47% is sent to the sawmills for processing, 38% goes to the paper and pulp industry, and about 15% is used in wood stoves for heating homes [30]. Within the paper and pulp fraction, yields are 90-95% for mechanical pulping and 40-70% for chemical pulping [30]. Since both of these pulping techniques are applied in Norway, an average of 75% conversion was applied, resulting in the classification of 25% of the pulp and paper fraction of timber as waste residues. Reported "timber-processing residues" in the present work is the combination of wastes from both pulp and paper plants, and processing and sawmills after timber (logs) used in wood stoves is excluded.

1.2.6 Stumps and roots

Stumps and roots comprise around 22% of the tree, and this fraction is nearly always left in the forest after felling. Although it could be possible to use this fraction for bioenergy production, removing it from the felling area in a sustainable way is complex. Additionally, it has been shown that, for the biological diversity of the forest, most stumps and roots should remain after felling [4]. A study conducted in Sweden on the environmental impact of removing stumps and roots indicated that a maximum of 5-10% of stumps and roots can be removed with minimal biodiversity impact [38]. Another study from 2019 estimates 20% to be the maximum removal of stumps and roots, considering primarily the species diversity impacts [33]. Finland uses even larger percentages, arguing that the entire stump and root fraction can be removed efficiently and used for bioenergy [39].

However, considering that the available fraction that can be removed without impacting biodiversity is small, that the removal process can be costly, and difficult in Norway, due to the areal distribution of forest, this work does not include it as a potential biomass resource for bioCCS applications in Norway.

1.2.7 Summary and Future Trends in Forest Biomass

The price of round wood has been relatively stable in recent history while the felling rate only increases moderately per historical trends (Figure 8). Unless wood prices increase, the trend suggests a similar level of felling and an increasing rate of growth in forests. Within the fraction of timber that is felled, a portion is exported. In 2019, for example, more than 700 km^3 was exported [28]. Most of the exported wood (60%) goes to Sweden, Denmark and Belgium. The demand in these countries is therefore also highly relevant for the potential for increasing harvesting to the balance quantity.

1.3 Marine

Marine biomass is vast and diverse, including both plant and animal organisms. Sustainable biomass for bioCCS applications should only include fractions which do not harm the ecosystem. Similarly, marine biomass for energy applications should not compete directly with human food sources. Preferably, they are fast-growing sources that can be redirected to bioenergy applications at reasonable costs. Both fish farming wastes and byproducts, as well as algae, fit this description well. In this overview of biomass potential in Norway, we focus on residues from the fish farming and processing industry (addressed in subsection 1.4) and algae. Within algae, there is a separation between microalgae (single-celled photosynthetic organisms like cyanobacteria and phytoplankton) and macroalgae (commonly in the form of multicellular protists like seaweed and kelp).

1.3.1 Microalgae

Microalgae is often cultivated in either photobioreactors (i.e. onshore) or large open ponds. Due to Norway's mountainous terrain and large seasonal weather changes, photobioreactors are the more applicable cultivation technique. Most production of microalgae by this technique is done in Norway on a small scale; for example, in research contexts. Although R&D projects exploring microalgae production are under progress, the high start-up costs of photobioreactor cultivation systems can generally be prohibitive to widespread implementation at an industrial scale, at least, in the near future (Project AlgScaleUp, SINTEF). For these reasons, microalgae is not considered a notable biomass resource for Norway, nor is it expected to increase greatly in the coming decade.

1.3.2 Macroalgae

Macroalgae is easier to cultivate in coastal environments and is considered a viable biomass resource, especially in upcoming years. The most common macroalgae currently grown in Norway is *Saccharina lattissima*, commonly referred to as sugar kelp [40]. Sugar kelp cultivation has increased in recent years and is expected to increase greatly in the coming years [41][42].

Unlike other photosynthesizing biomass on land, which remove CO_2 from the atmosphere as they grow, algae does not displace agricultural space that could otherwise be used for agriculture. Coastal waters with suitable depths along Norway's coastline are vast, and many areas are currently either underutilized or not in use at all for industrial applications. In contrast to fish farming, there is little waste generation. Instead, algae can use wastes and byproducts from fish farming as nutrients for growth. According to Handå's report, the wastes from the salmon and rainbow trout farmed fish industry (28,000 tonnes of Nitrogen emissions in 2006) could be used as feed, resulting in 10-20 million tonnes of seaweed [43]. Seaweed forests filter pollutants from water passing by, promote marine diversity, and increase fish populations by providing a habitat. Because algae grow faster than land plants, they are also more efficient in removing CO_2 from the atmosphere for biomass synthesis [44]. While trees store carbon over their multi-year lifetime, algae can be used in a variety of products and is quickly re-generated each year.

Seaweed has diverse applications,. Human consumption of seaweed has become more common worldwide, and the nutrient profile makes seaweed a good animal feed. Additionally, seaweed is a component in several high-value products such as bioactive components, additives, and pharmaceuticals. Therefore, even if not all the seaweed produced is available for integration with bioCCS, there are wastes and by-products leftover after production of commercial products that could be well-suited to bioenergy applications.

Macroalgae could, in principle, be used for either thermal energy conversion processes (combustion, hydrothermal liquefaction and gasification, pyrolysis, etc.) after appropriate pre-processing, or it can fermented and used for bioethanol or biogas production. Due to the high water content of seaweed, it takes large amounts of energy to dry. The most promising applications of thermal conversion of seaweed are those that benefit from a high water fraction, such as hydrothermal processes. Hydrothermal liquefaction and hydrothermal gasification utilize water as a reactant and catalyst in conversion to a high-energy liquid fuel or a syngas. Fermentation of seaweed for ethanol or methane does not require drying either. Bioethanol, methane, bio-oil, and syngas present the advantage of being able to make use of existing transport infrastructures. However, since many of these technologies do not currently exist on an industrial scale, it is might be challenging to deploy them at a large scale in the near term. The by-products from biofuel production from seaweed could be used in animal feed, fertilizer, or soil improvement products [43].

At present, sugar kelp is not being produced at a large industrial scale. However, seaweed cultivation has increased rapidly in recent years (Figure 10), and Norway had the 9th highest seaweed production (farmed and wild) worldwide in 2019. Yet, of Norway's production (about 163 thousand tonnes), less than 1% is from cultivation, while China's production (around 20 million tonnes) is more than 99% from cultivation. After China, Indonesia was ranked 2nd in production quantity, with about 10 million tonnes [45]. The main difference between Norway and those higher on the list is the higher cost of labor and lack of established infrastructure. However, several new companies have emerged in recent years with the goal of large-scale production of sugar kelp along Norway's coastline. A large focus in many of these applications involves automation wherever possible. For example, the Norwegian Center for Seaweed and Kelp Technology was established in 2011 with the goal of industrial-scale seaweed cultivation. During data collection for this article, around 30 companies in Norway were found to do business for cultivation, harvesting, research and development of seaweed growth. Many are in raw material markets, but some are in food production for humans, animals, or technology development. According to Brekke et. al. (2017) and Kyst.no (2018), 4 million tonnes are expected to be produced in Norway in 2030 and up to 20 million tonnes by 2050. At a moisture content of around 86% and carbon content (dry basis) of around 32%, the 2030 estimate of seaweed production would result in nearly 165,000 tonnes of biogenic carbon [46] [47].

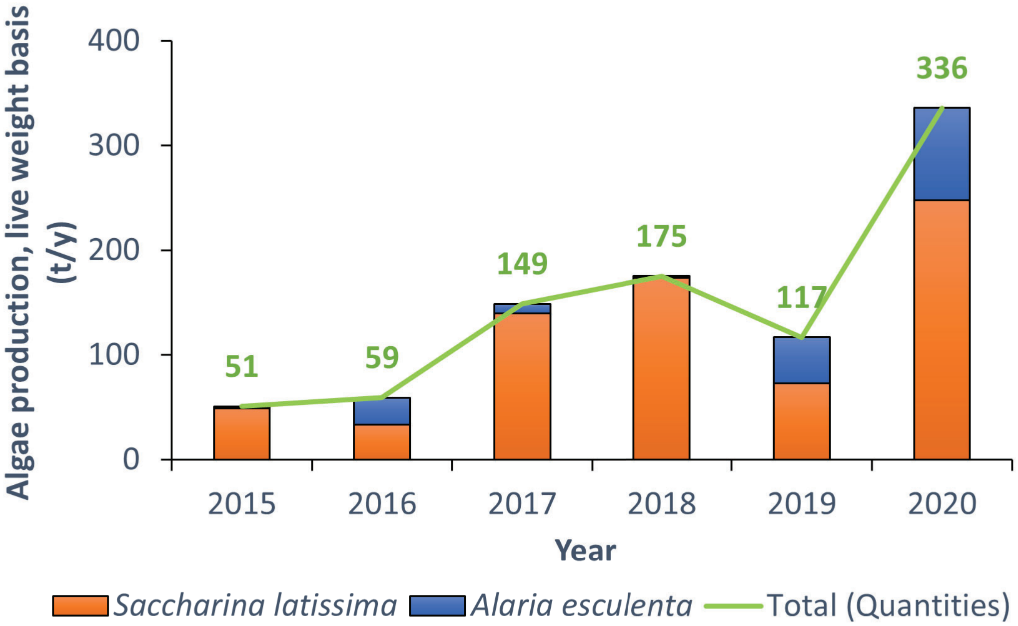

Figure 10: Norway's macroalgae production quantities for the period 2015-2020 as live wet weight, separated by species. Based on data collected by Food and Agriculture Organization of the United Nations [45].

1.4 Wastes

According to Art. 3 of the European Union Waste Framework Directive 2008/98/EC "waste means any substance or object which the holder discards or intends or is required to discard". Although this definition seems simple enough, there is great variation between sources on what is defined as waste (as well as different classes of wastes, from inert to hazardous) and how it could be utilized or valorized. For Norway's biomass potential, the wastes considered here were wood waste, silage, and sludge from on- and offshore fish farming, sewage sludge, and food waste from households, commercial, and industrial sources. Exported wastes fractions and municipal residual waste (a mixture of biogenic and fossil waste) are also discussed.

1.4.1 Wood Waste

The different kinds of wood wastes and their relative distribution are shown in Figure 12. The chemical composition is generally comparable to that of the timber described in subsubsection 1.2.2, containing 50% carbon [26]. Woods that are treated with impregnation coatings (e.g., using heavy metals, creosotes, or copper) will have a slightly different composition; however these waste fractions are usually considered hazardous waste, a fact that makes their utilization and disposal more delicate [48].

In 2016, the wood waste was reported as 792,000 tonnes [48] and this amount was stated to be consistent over time. Yet, SSB statistics show there has instead been a steady increase, nearly 100,000 tonnes more in 2020 than in 2012 Figure 14.

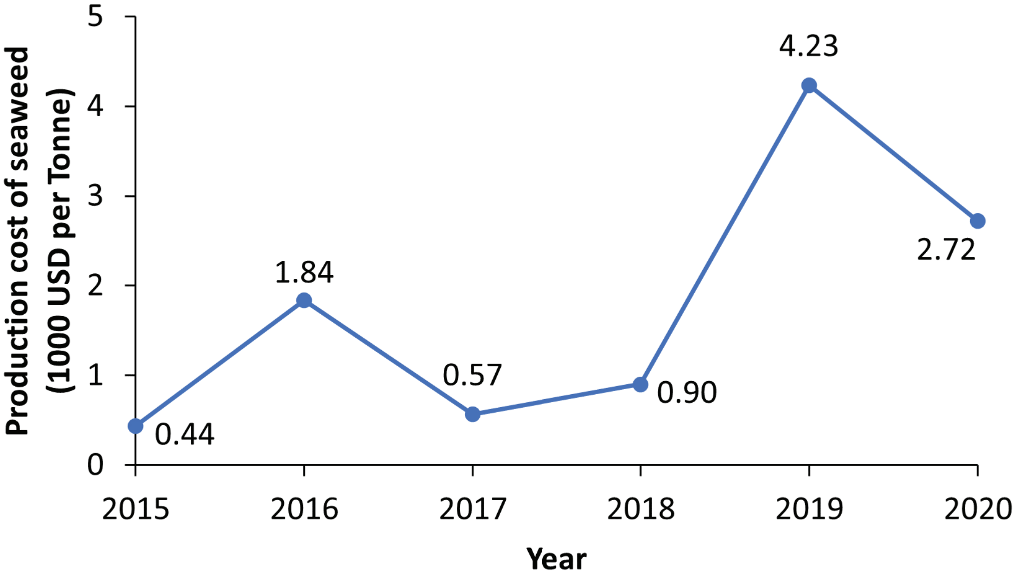

Figure 11: Cost per tonne of live seaweed. Based on data collected by Food and Agriculture Organization of the United Nations [45].

Wood waste is currently often combusted with energy recovery. SSB reports that 674,000 tonnes of wood waste were combusted in 2020 (usually in WtE plants together with other waste fractions such as MSW), while composting and biogas production treatment each only accounted for 3,000 tonnes of wood waste Figure 13. Norway has banned the landfilling of biodegradable waste since 2009, so waste that are not treated must otherwise be combusted with energy recovery for district heating or electricity production. This waste could thus be integrated with bioCCS. Thus, this waste fraction can be considered a slow-growing yet substantial source of biomass for bioenergy and CCS applications. The fraction of the wood waste that was combusted in 2019 resulted in around 137,000 tonnes of CO_2, a large possible resource for CCS applications.

1.4.2 Sewage Sludge

Sewage sludge is a residual product of wastewater treatment, containing organic matter, nutrients such as nitrogen, phosphorous, and an array of other elements (including metals) from both the material being processed and the micro-organisms involved in the wastewater treatment process. These materials are useful in the sense that they could be valorized via agriculture, bioenergy production with CCS. Yet, the composition of this waste stream can vary widely from municipality to municipality, and require pre-treatment to destroy any toxins or infectious agents, before its use [49]. The presence of heavy metals may also be a problem when considering various applications.

Sewage sludge is currently, in large part, treated biologically in methods like composting to make natural fertilizer or anaerobic digestion to generate biogas. After biogas production, depending on the composition, the remaining digestate can in most cases be used as a natural fertilizer in agriculture. The digestate is divided into classes based on the heavy metal content, shown in Table 3, where classes 0-2 can be applied to agricultural areas and class 3 can only be applied to other green areas. For 2017, NIBIO states that about 50-60% of digestate from biogas production was used for agriculture [26]. This percentage is consistent with SSB's report for 2021, where 55% (68,741 tonnes) of digestate was used for agriculture (SSB-10513).

Besides the category of agriculture, sewage sludge utilization or disposal is classified by SSB into other categories. The categories and values for how sewage sludge was disposed

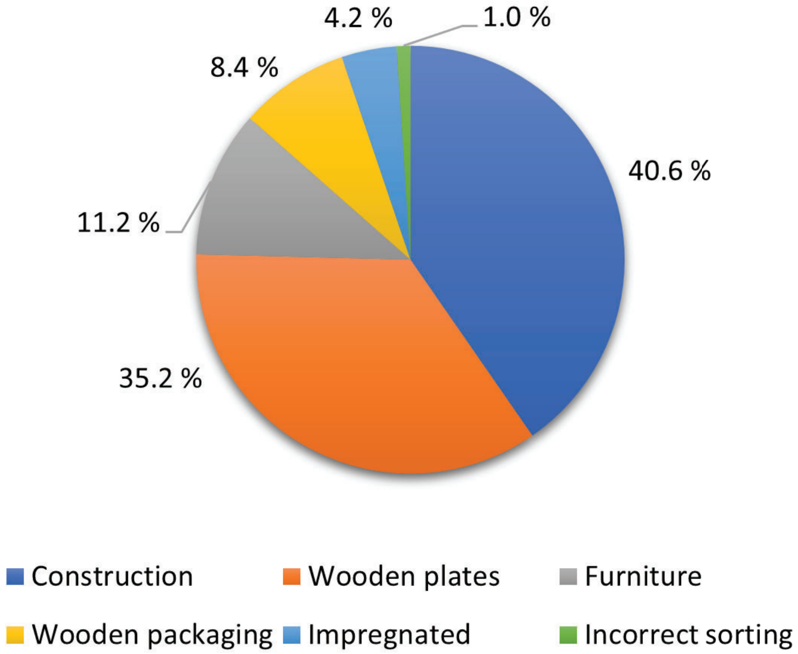

Figure 12: Types of wood waste.

of in Norway in 2020 are shown in Figure 16.

The largest disposal method, biological treatment, has also grown for sewage sludge and other organic wastes in recent years. In their report for the Norwegian Environmental Agency, Carbon Limits created a comprehensive review of the organic waste streams from 2017 to 2020 [49]. Their findings show sewage sludge is the largest single waste type delivered for biological treatment (40% of the organic waste produced). The produced biomass has increased by about 100,000 tonnes from 2017 to 2020, and the number of biogas processing plants has increased from 31 to 35. During this period, the amount of biogas produced has increased by 65%, and the fraction of biogas that is further upgraded to fuel quality has more than doubled.

The production of sewage sludge is, understandably, correlated to the population, and it is expected to grow at the same pace [4]. Using SSB predictions for population (SSB-13603, SSB-13599, SSB-13604, SSB-13602), a projection on sewage sludge production is included with the historical overview in Figure 15.

With a sewage sludge production in 2020 of around 146,000 tonnes (dry basis) and a carbon content of 28%, this results in about 41,000 tonnes of biogenic carbon.

Quality class	**0**	**1**	**2**	**3**
	mg/kg dry matter			
Cadmium (Cd)	0.4	0.8	2	5
Lead (Pb)	40	60	80	200
Mercury (Hg)	0.2	0.6	3	5
Nickel (Ni)	20	30	50	80
Zinc (Zn)	150	400	800	1500
Copper (Cu)	50	150	650	1000
Chromium (Cr)	50	60	100	150

Table 3: The different classes of sewage sludge based on their heavy metal content. Described by the Norwegian Water board, retrieved August 2022 [50].

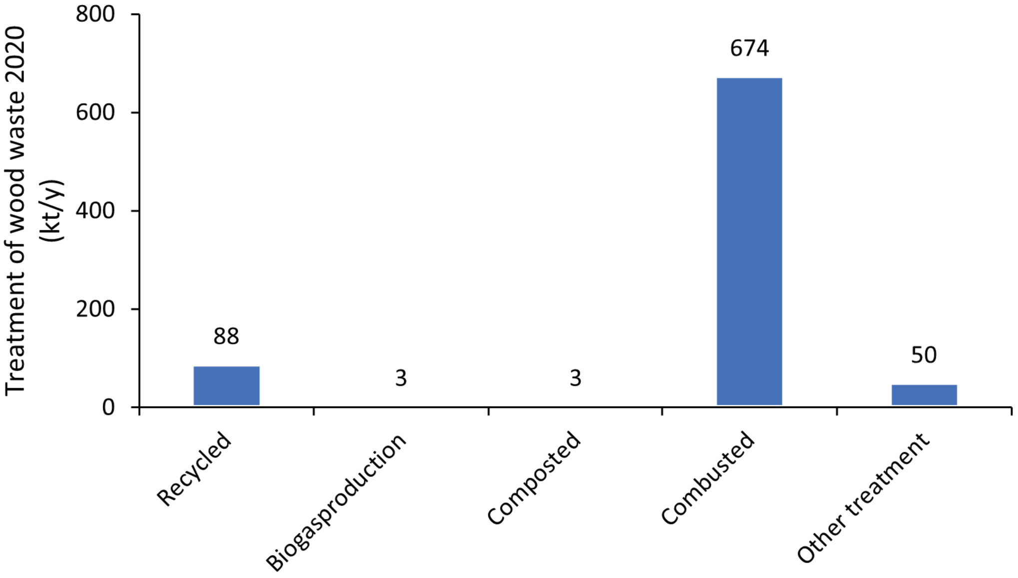

Figure 13: The treatment for waste wood in Norway for the year 2020. by Statistics Norway (SSB-10513), retrieved August 2022.

1.4.3 Fish waste and Silage

Fish waste is divided into three categories of quality which affect how they can be used [51]. Category 1 is that which is hazardous for health and cannot be used for animal feed, consumption, or biological treatment but can be combusted with energy recovery. Category 2 is made from fishes that have died accidentally but with no signs of disease, and it can be used for biogas, compost, soil improvement, or animal feed for fur-production animals. Category 3 is made of fish processed for human consumption, specifically the excess biomass left after the slaughtering process, and is the only category suitable for animal feed to animals for food production. In this framework, category 2 can be considered as easily applicable to a variety of biological treatments to produce energy and other products (silage) while category 1 can be suitable for bioenergy production with CCS [4].

Fish Silage can be made from fish parts or whole fish that are not sold as food (or otherwise treated); it is a liquid product from the enzymatic/acidic liquefaction of the fish biomass [52]. Fish that die accidentally are processed in this way. Bacteria, acids, or enzymes can be added, but the liquefaction is primarily carried out by enzymes endogenous to the fish. The addition of acids can improve enzyme activity and prevent spoilage. Fish silage has a high concentration of proteins and free amino acids, which can be problematic in traditional biogas fermentation. However, when fish silage is co-digested with manure, methane production has been shown to increase by 100% compared to manure alone [53]. Additionally, the co-digestion of fish-oil refinery by-products with fish silage increases the methane yield [54]. Silage can also be dried with additives like rice bran to create a powder silage with increased nutritional value (for example, for use as feed) and longer shelf life [55]. Silage production is lucrative, creating a high-value product, which does not require access to established fishmeal production plants [56]. This is a common practice in Norway for category 2 and 3 silage from salmon farming. Companies like Hordafor and Scanbio specifically buy fish biomass from salmon farms to produce and sell the silage. In the 2019 Carbon Limits report [4], the authors assume that only category 2 is a viable source for biogas production, yet their report focuses primarily on biological (rather than thermochemical) conversion, i.e. fermentation.

On one hand, silage is a high-value product which are typically excluded from our calculations, but it is also used for energy production via biogas. There is already marginal

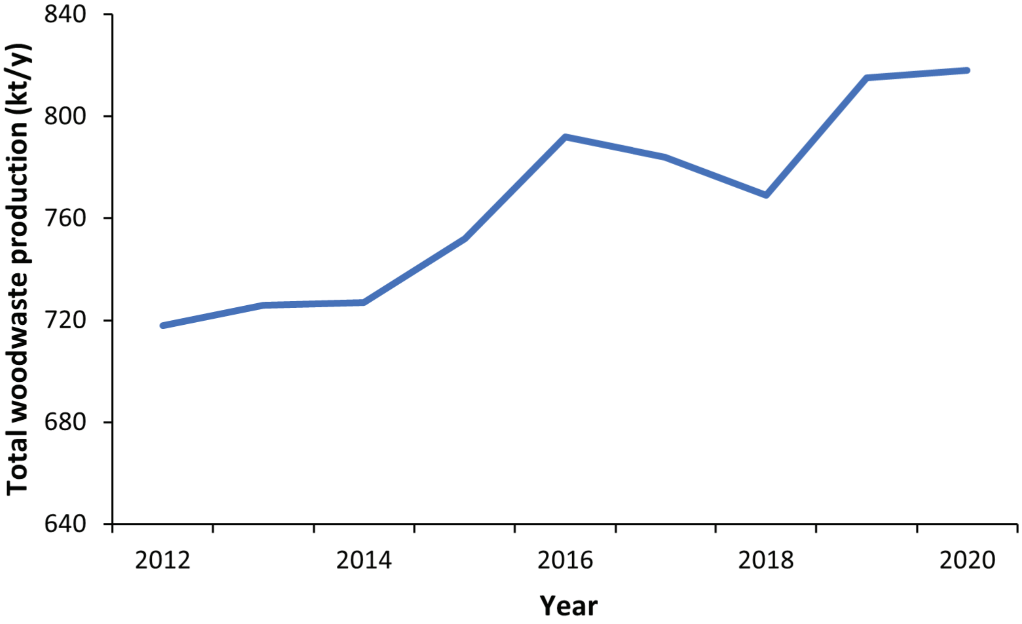

Figure 14: The total wood waste produced per year in Norway. as reported by Statistics Norway (SSB-10513), retrieved August 2022.

use of fish silage to biogas production, yet this could be increased. Sammut reports only around 27% of the silage from 2018 was used for biogas [4]. The only other use for this category of fish silage is feed for fur animals, and in 2018 just under 30% of the calculated fish silage was used for this purpose, and the percentages not applied for biogas nor feed was discarded as waste [57]. However, that market will disappear in Norway no later than February 2025 due to animal welfare concerns, and the fur animal business is arguably a significantly lower priority market than bioenergy production at this time. Therefore, increased use of this waste stream for bioCCS may be relevant.

If silage is not considered for bioCCS applications, this leaves only residual wastes that are not utilized. These values are annually tracked by SINTEF Ocean. Through a project called Restråstoffanalyser, an interactive web tool was developed between 2020 to 2022 with historical data on utilization of fish wastes from 2012 to 2021. For 2020, the portion of fish waste (not utilized) was 157,000 tonnes (wet basis). The moisture content of fish silage is approximately 75% [55][58][56]. Therefore, there is 39,250 tonnes of dry fish waste not otherwise used as a product, containing 45.33% carbon (17,662 tonnes).

If silage is considered for integration with bioCCS, the following addition could be made. The amount of fish silage in Norway was estimated using SSB data on annual slaughtered fish and factors from Carbon Limits and SINTEF reports [4] [59]. Sammut reports a 5% annual increase from 2007 to 2019 [4]. Category 2 silage is, by definition, based on the slaughtering of fish for human consumption. SINTEF estimated this value to be 6.6% of the fish produced for food in Norway over the period of 2013-2016. In 2020, the amount of fish silage is estimated to be 100,687 tonnes (wet basis). With the previously mentioned moisture content of 75% [55] [58] [56], the fish silage on a dry basis in 2020 is estimated as 25,235 tonnes. Fish silage is reported to have 45.33% carbon [58], meaning the fraction of carbon in this waste fraction for 2020 alone was approximately 11,349 tonnes. If silage production were combined with fish waste not currently utilized, this fraction becomes just over 29,000 tonnes of carbon.

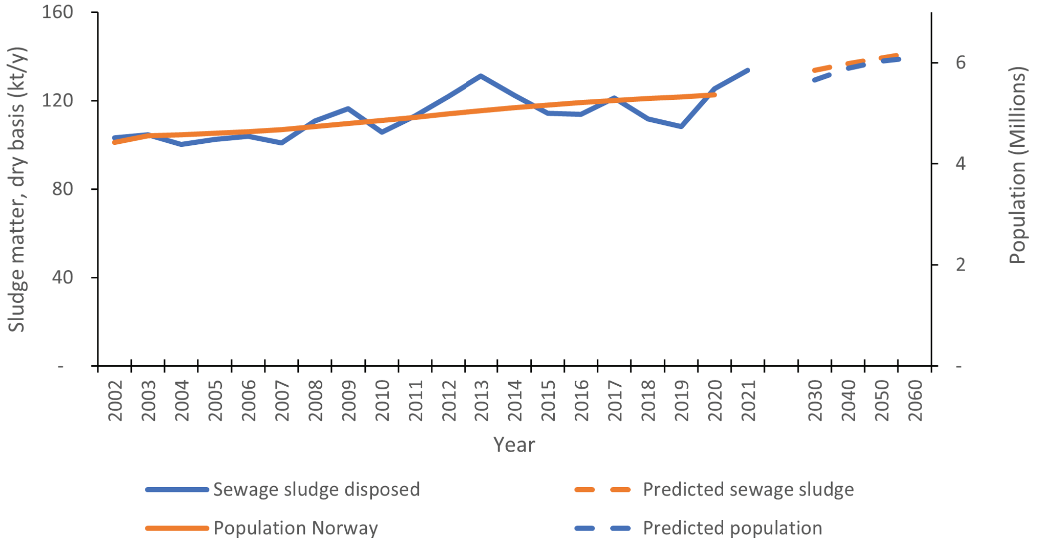

Figure 15: Amount of sewage sludge disposed over time in Norway alongside predictions for population by (SSB-13603, SSB-13599, SSB-13604, SSB-13602). The population predictions were used to predict sewage sludge disposal by applying a similar growth rate with respect to 2020.

1.4.4 Fish sludge

Fish sludge is a waste stream that consists of fish feces and feed remains. This waste can be a large source of various emissions to marine or freshwater environments that have to be monitored and as limited as possible according to the Norwegian Environment Agency [60]. In Norway today, marine fish farms are not obligated to treat the fish sludge, but fish farms on land must dispose of it [50]. Companies like Bioretur AS process fish sludge from fish farms for production into a dry product that can be applied, for example, as a fertilizer [53]. However, standards for "certified organic" farming often prohibit the use of fish sludge as a fertilizer, which can also limit export potential to other european countries [61] [62]. According to their website, Bioretur also provides the farms with reports on the contents of the sludge (i.e. heavy metals and nutrient composition), which can inform end-users who may consider employing the biomass for energy production. They accept sludge at varying moisture contents but adjust the material to a specific fraction of dry solids to accommodate their processing equipment, up to 90% dry matter in the final product. In addition to use as a fertilizer, fish sludge can be processed into biogas by anaerobic digestion. Subsequent use of the digestate as fertilizer or feedstock can also be applied to thermochemical conversions to energy. Additionally, as with fish silage, co-digestion with other waste streams like manure are found to be beneficial [53].

The amount of fish sludge produced in Norway annually seems to vary greatly depending on the source. Some reports are based on calculation of sludge dry matter (DM) with respect to fish quantities [4] [63] and others report wet values tied to Norwegian industry contacts [64]. Although there are many descriptions of fish sludge quantities available online, they are incomplete and/or lacking sources. Biogass Bransjen reports that in 2017, more than 2 million tonnes of fish sludge was produced, and 25% of this is left in the ocean; the post lacks sources, but the statement that 25% is not collected indicates the number is calculated rather than measured [65]. In a project called Slamdunk with Bioregion and Norce, salmon and trout alone are reported to produce 2.1 million tonnes of fish sludge in 2017, and they predict a sludge production of 11 million tonnes by 2050 [66]. Again, that website article lacks sources as well as the moisture content of those millions of tonnes. Avfall Norge references a report by NIBIO from 2017 and states that 1 million tonnes are produced annually, additionally commenting on Bioretur's capabilities to process fish sludge from 1% DM to 90% DM yet not confirming the DM content of their reported sludge value [67]. The

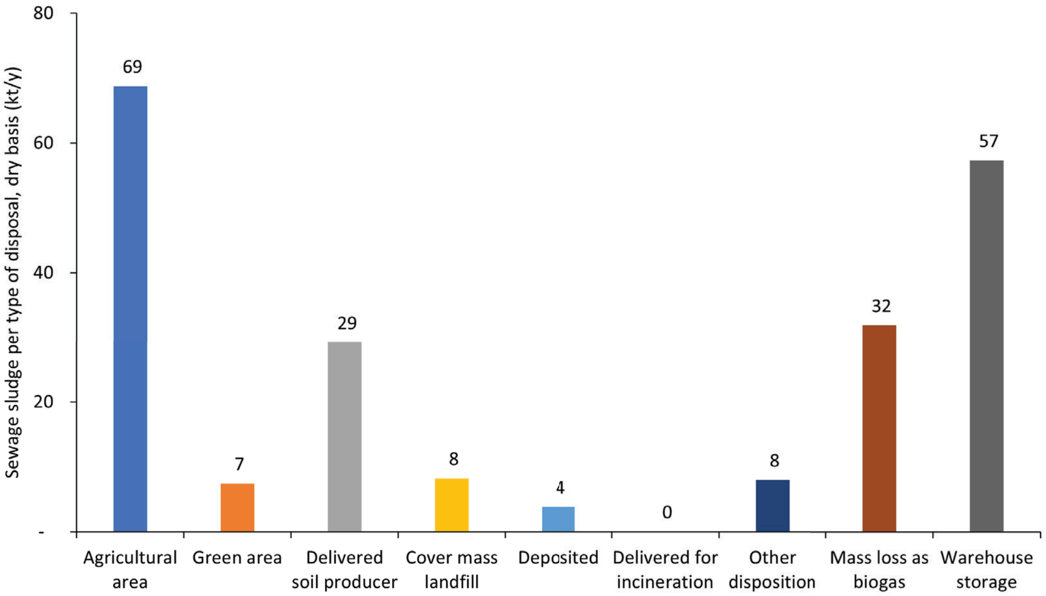

Figure 16: Distribution between disposal types for sewage sludge (SSB-05279). Mass loss as biogas can refer, for example, to flaring or utilization as heat.

Global Seafood Alliance states that the Greig Seafood Finnmark company produces 20-200 tonnes on a dry basis [68]. Since fish sludge can vary greatly in DM, the lack of detail on composition and great variety in reported values only creates confusion about Norway's production values.

While no directly reported quantities (with DM content) were found, a strategy that has been applied in some Norwegian reports involves the estimation of sludge using the total weight of all fish or on a per-fish basis. This allows for the inclusion of fish sludge produced both in the ocean and on land. Sammut calculates the amount of sludge is 0.306 grams (dry basis) per gram of fish (weighing on average 90 grams), based on a study by Nofima [63]. A more recent study by Nofima published in 2018 reports an increase in weight in juvenile fish [69]. Juvenile salmon in Norway have increased from 80 grams in 2010 to around 135 grams in 2017. With unavoidable uncertainties, the current report follows calculations similar to Sammut's report.

The current report applies the 0.306 gram dry fish sludge per g fish calculation approach for annual fish sludge in Norway, using fish production values from Statistics Norway. The factor from Summut, based on 90 gram fish, is applied to reported annual quantities of sold smolt and juvenile fish from Statistics Norway. Fish sludge production in 2020 is therefore estimated to be 12,604 tonnes on a dry basis containing just under 6,000 tonnes of biogenic carbon (assuming 45% carbon content). Using an estimate of 90% water, the raw quantity of sludge before drying would be just over 126,000 tonnes [70]. The average annual increase over the last 20 years is 4% per year, which is used to estimate 2030 values. Both fish silage and sludge historical estimates and future predictions are shown in Figure 17.

1.4.5 Wet Organic Wastes (Includes Food Wastes): Household and Services/ Industry

Wet organic waste is a fraction that includes, for example, food waste from households, food waste from services/industries (i.e., grocery, dairy, bakeries, catering, agriculture, etc.), garden wastes from households and public green areas, fishery wastes (which can include fish sludge), slaughterhouse and butchery wastes, and prepared food and snack industries [71]. Wet organic waste can be treated in a hierarchy of ways: internal use (within the industry creating it), redistribution, use as ingredients in new food production, animal feed, bio-

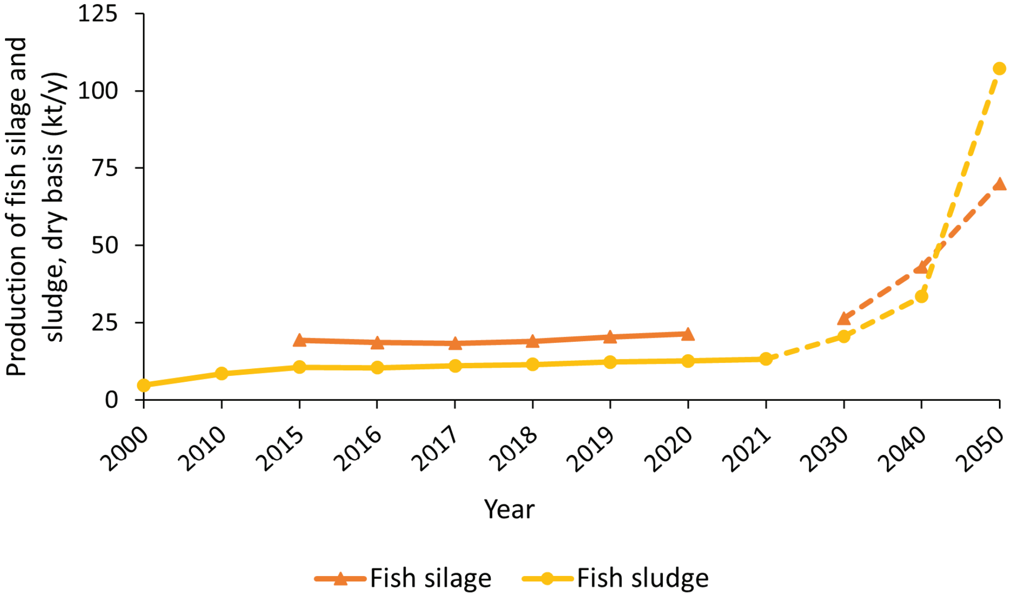

Figure 17: Fish wastes, separated into the categories of silage and sludge [4]. Fish silage is category 2 silage calculated by fish production in Norway each year and a factor (6.6%) provided in other biomass quantification reporting [4]. Fish sludge is calculated using fish greater than 90 grams and another factor (0.306 grams sludge per fish) [4]. Note the Y-axis includes future estimates at 10-year intervals rather than 1 year for 2030, 2040, and 2050.

prospecting, biogas/bio-ethanol/bio-diesel production, compost, or combustion with energy recovery [71].

Today, there are no official, national statistics accurately characterizing the quantities of wet organic waste from industries vs. from households (and similar wastes from businesses/services), nor is there accurate tracking for the fraction of the residual/mixed waste stream containing wet organic waste (that could potentially have been separated or collected separately). Reports on this topic therefore create estimates, for example, on a per-inhabitant basis for household organic wastes or based on data collection from industries working with wet organic materials. While SSB provides values for "wet organic wastes", several reports argue that these values are much lower than the true amount [71] [72]. SSB reports wet organic waste in 2021 was 489,000 tonnes, with 210,000 tonnes of this total coming from households (SSB-10513). Yet a report by Østfoldforskning estimates the household organic waste fraction alone was around 400,000 in 2014, of which 182,000 tonnes were separated for biological treatment [71]. They additionally analyzed reports of organic waste generation on a per-inhabitant basis, determining an average of 78.8 kg per inhabitant per year. In our study, this factor is applied to quantify household wet organic waste from 2015 to 2017. From data gathered more recently in areas where food waste sorting/separate collection systems are in place, 81.2 kg per inhabitant is reported [71]. The current report applies this factor for 2021 and an evenly increasing increment from 78.8 to 81.2 kg per inhabitant per year for the years 2017-2020. Using that figure and the total population, household food waste in 2021 would be 441,366 tonnes in Norway.

Using the aforementioned factors, household wet organic waste, consisting primarily of food waste, was estimated for the period of 2015 to 2021, shown in Figure 18. Less than half of the estimated production of wet organic waste is collected separately and further treated, about 44-49% during this period. It is considered most likely that this gap is due to the absence of sorting systems in many areas of Norway, much of the household food waste is discarded with residual mixed waste ("restavfall" in Norwegian), which is'combusted with energy recovery in WtE plants. Starting in 2019, there is a shift in treatment preference:

increased biogas production and decreased composting.

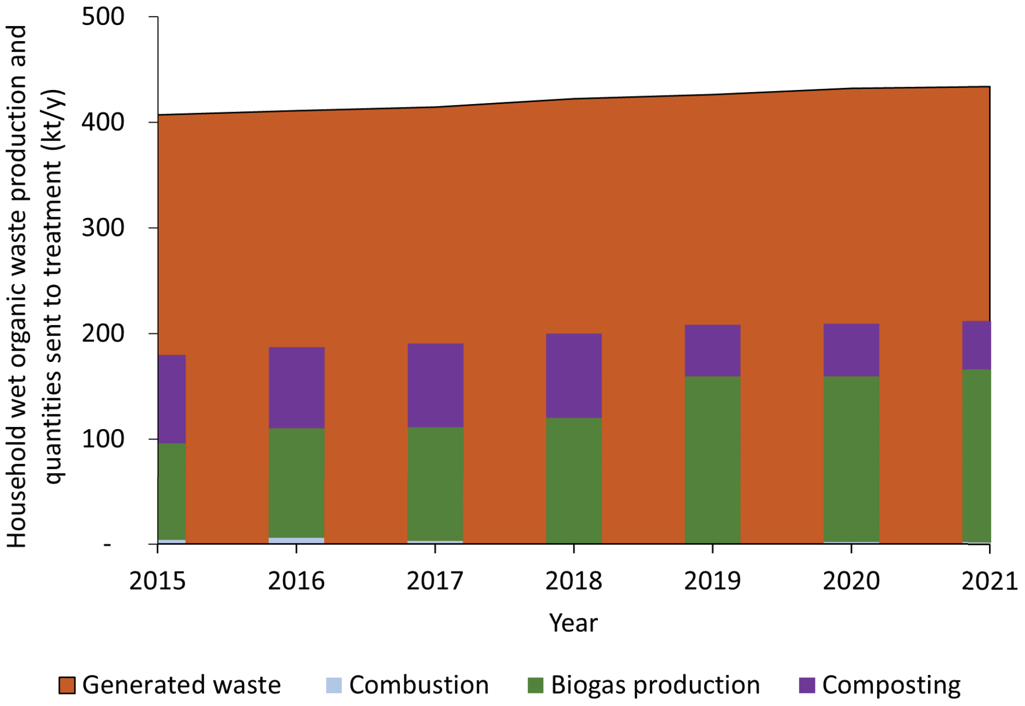

Figure 18: Estimated production of household wet organic waste and the amount which is reported as treated (SSB-10513). Production estimates are calculated using population statistics from SSB and reported factors of waste generation per person per year.

Organic wastes can produce biogas only if properly separated. If mixed with other waste fractions, the only option becomes combustion with energy recovery for district heating or electricity [40]. Starting January 1st, 2023, food wastes from households and businesses must be collected separately (or otherwise separated) by municipalities and private actors to be sent to recycling facilities (material recovery) as part of a circular economy [73]. This regulation aims to align Norway with the ambitious EU goals for material recycling of waste and is part of a far- and wide-reaching framework that includes several waste fractions. Amongst several targets, the new regulation requires 70% of food and plastic waste to be sorted out by 2035 (to enable recycling), a significant increase from today's situation.

For industrial wet organic wastes, the national statistics from SSB also reports lower amounts than other reports on this topic. Of the 489,000 tonnes reported, SSB classifies 101,000 tonnes as originating from service industries (SSB-4, 2021). Two other reports from 2008 calculate the annual production as high as 2 million tonnes [74], and the Mepex report from 2012 estimated this fraction to be 880,000 tonnes [72]. The large difference between the two reports can be attributed to the classification of dairy waste as "unavailable", stating that it is used to a large extent for feed, which agrees with the "realistic potential" classification outlined in a 2016 Østfoldforskning report [71]. The totals and realistic potential in tonnes from that report are shown in Figure 19. Other minor sources of wet organic waste not included here are breweries, used cooking oils or fats, vegetables or fruit residues in value chains other than food production, and coffee wastes. In addition, other industry sources of wet organic waste are included in other sections of this work, e.g., fish waste.

Wet organic wastes from both industrial and household origins are expected to continue to increase; the household fraction with population increase, and the industrial fraction by about 0.2% each year [4]. The locations of these wastes are not easy to specify or characterize, but will be understandably higher in areas of higher population or associated with industrial presence. It is therefore difficult to assess logistical challenges for different applications, but, as an example, locations closer to cities or relevant industrial plants are likely to require lower transport costs. As some of these materials are already processed into biogas, the potential to process more organic wastes primarily depends on increased and improved separation and collection methods. Assuming development of a greater treatment capacity in Norway (locally or centralized), the new regulations requiring separation of food wastes will offer new opportunities for utilization, including bioenergy production with CCS. However, it is important to keep in mind that the focus from 2023 will be on material recycling, so treatment alternatives not delivering on this point will not be preferred.

The composition of wet organic waste can vary greatly. Greenhouse gas emissions for food waste in Norway alone were 978,000 tonnes of CO2 in 2015 [75].

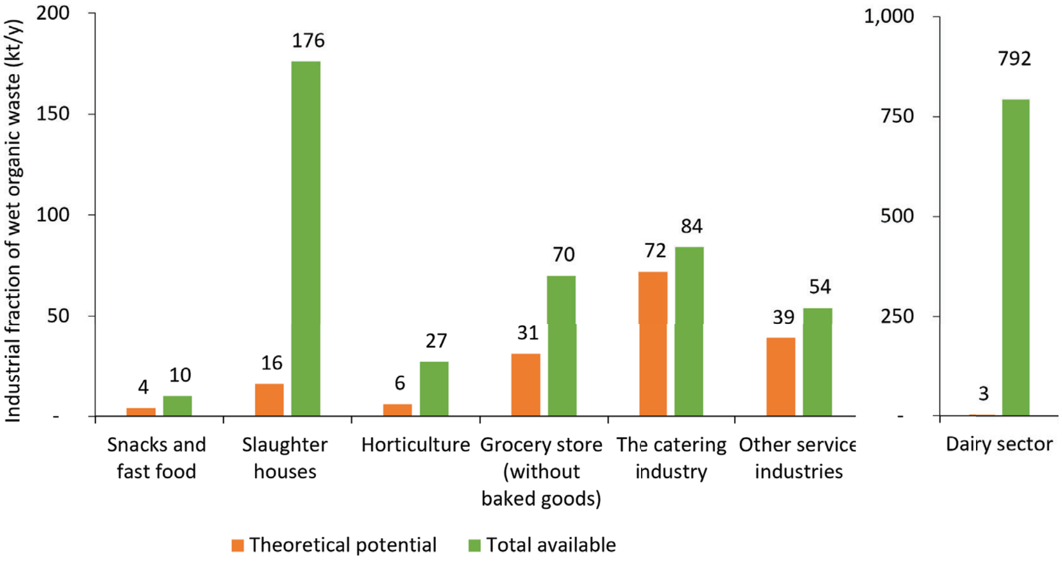

Figure 19: Industrial fraction of wet organic waste separated by source category and reported in average tonnes per year, reported in 2016 [71]. Dairy sector shown on a separate y-axis (also in 1000 tonnes), the majority is not considered available because of its reported primary use as feed. Theoretical potential is based on classification by the source.

1.4.6 Exported Waste

The majority of waste streams in Norway are handled within Norway, yet a significant portion, including biogenic fractions, are exported, primarily to Sweden. The landfill ban for biodegradable waste in Norway in 2009, led to the increase of the amount of MSW being incinerated at WtE facilities from ca. 1.1 to ca. 1.8 million tonnes by 2015 and has been stable since [7] [8] [76]. Throughout Norway, these facilities have the capacity to handle about 2 million tonnes of waste. Furthermore, a significant amount of waste has been exported to Sweden (Data about exported waste retrieved from the Norwegian Environment Agency, direct communication, summer 2022) for many years, mainly because of lower gate fees [77]. Though waste treatment in Sweden can be considered an acceptable solution from economic perspective, it could be argued that a modern, wealthy country such as Norway should treat all of the waste it generates as a matter of principle. As a general rule, international transport of wastes, albeit allowed, shifts the responsibility elsewhere, and is therefore considered a temporary solution employed while national treatment capacity (for material or energy recovery) is increased [78].

Norwegian export of wastes from 2013 to 2021 is given by destination country in Figure 21 based on information from the Norwegian Environment Agency (direct communication, summer 2022). The top countries receiving the most of Norway's exported wastes,

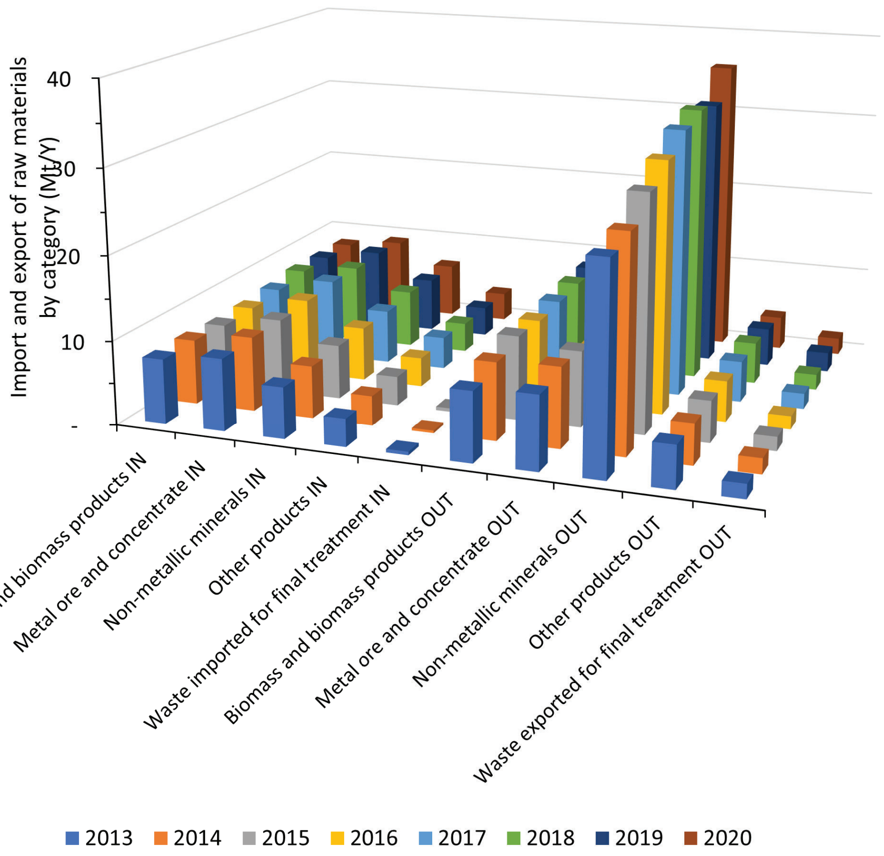

Figure 20: Import and export of raw materials by category for years 2013-2021 (SSB-10321).

with 2020 percentages as a reference, are Sweden (68%), Denmark (14%), Latvia (5%), and the United Kingdom (3.5%). Germany, the Netherlands, and Lithuania have also accepted 2-4% of the Norwegian exported wastes over this time period, depending on the the year. The received wastes are further treated in the destination country according to the categories described in Figure 22. The countries importing the smaller fractions of Norwegian waste use it primarily in recycling or recovery processes of various materials. However, Sweden, the recipient of more than half of Norway's waste exports, uses 90% as fuel for energy production, primarily district heat. In 2021, just over 1 million tonnes of Norwegian waste was used to produce energy in Sweden.

This category can therefore be seen as a huge missed opportunity for the Norwegian economy, especially regarding energy production. Several hundred thousand tonnes of Norwegian waste have been sent to energy recovery outside of Norway each year over a long period. Within Sweden, the top categories within the "use for fuel..." category are wood wastes and other combustible waste (Figure 23). The categories listed within "combustible waste..." is only further defined as about 50% "wastes collected from households", 1% "residues from industrial waste disposal operations", and 49% "other" (Norwegian Environment Agency, direct communication, summer 2022).

Since other "combustible waste" is a rather broad category and can include a wide variety of materials, we do not attempt to break it down by physical composition as for the other potential biomass sources. Yet a large part of this waste is wood, and can be considered similar to the wood properties described in subsection 1.2. The geographical origins of the exported waste were difficult to quantify, yet transport out of the country can easily be in the order of several hundreds of kilometers. Local waste treatment is likely to result in lower transportation costs, less energy use, and decreased emissions. At present, however,

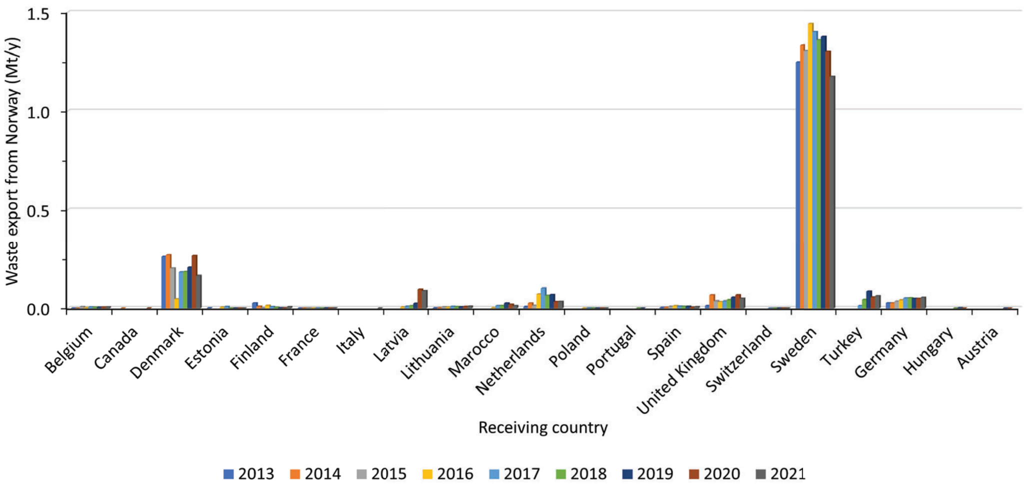

Figure 21: Waste export from Norway from 2013 to 2021 by destination country. Data retrieved from the Norwegian Environmental Agency in August 2022 via direct correspondence.

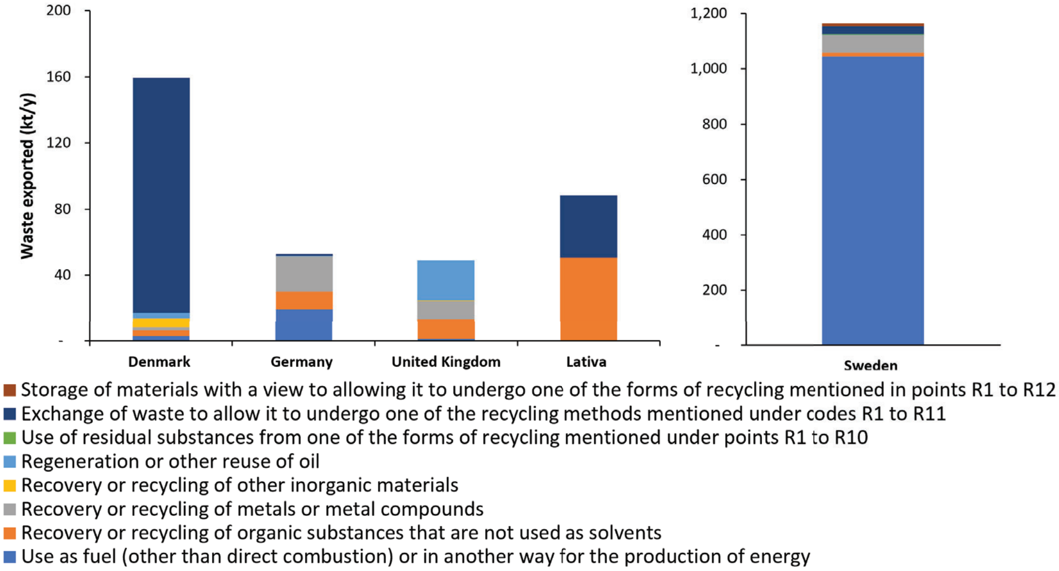

Figure 22: Treatment of exported Norwegian waste in the receiving country in 2021. Note the separate y-axis for Sweden, also in tonnes. The smaller axis is shared for data on exports to Denmark, Germany, the United Kingdom, and Latvia.

Sweden's processing capabilities and large number of facilities make the export of waste to Sweden a cheaper alternative, and there has not been any substantial motivation to build new Waste to Energy plants in Norway. However, treatment of this waste within Norway via bioCCS could enable further low-carbon energy production and negative emissions. If the exported waste was instead integrated with waste-to-energy production with CCS, up to 1 million tonnes of CO_2 per year could be captured, with at least half of it being of biogenic origin [77]. Material recycling is also expected to increase in the coming years. This is probably a low estimate as a large fraction of the exported waste discussed in wood.

1.4.7 Textiles

Another (partially) biogenic waste fraction has attracted a lot of attention these last years: textiles/clothing. This has mainly been due to negative reasons such as environmental (spread of micro-plastic), international (improper disposal of European textile wastes out-

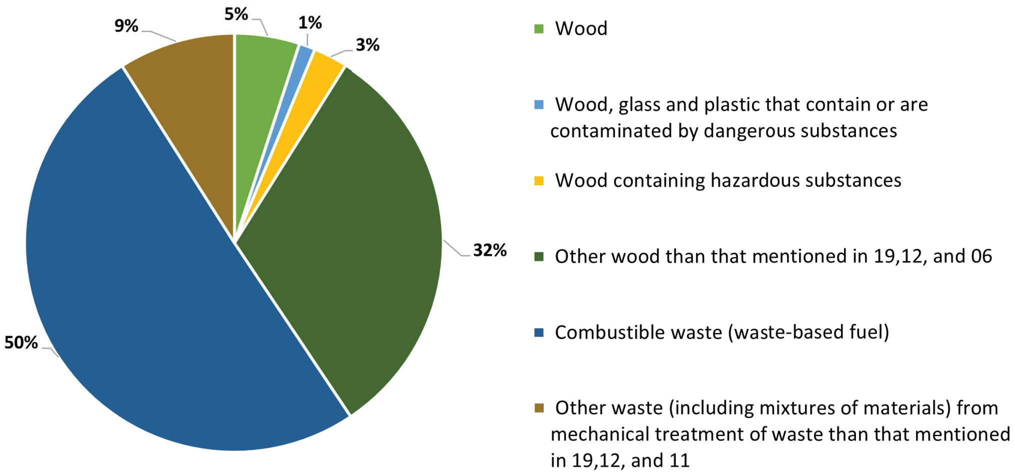

Figure 23: The largest fractions (greater than 1% of the total) for the category "used as fuel (other than direct combustion i.e. combustion without energy recovery) or in another way for the production of energy" of Norwegian waste exports to Sweden. The categories are as described by the Norwegian Environmental Agency. Data collected by direct communication with agency in August 2022. The total amount is 1,044,506 tonnes.

side of the EU) and societal (throw-away culture/consumption) concerns. Textiles can be of synthetic (i.e., fossil-based) or natural (cotton, wool) origin. 60-70% of textiles are currently made of synthetic material in Europe, including mixed synthetic-natural [79]. The yearly consumption of new textiles and clothing in Norway is about 80,000 tonnes/year (15 kg/inhabitant) [80]. More than half of the used textiles, approx. 30-35,000 tonnes, are thrown in the residual waste bin by households (and hence become part of the residual waste being incinerated). 97% of the used clothes/textiles (approx. 30,000 tonnes in total) collected separately (e.g., by charities) are being exported outside of Norway, making their ultimate fate difficult to track. This means that less than 3% of the used textiles are sold on the secondhand market via charities (and hence not including the blossoming person-to-person market)[80]. The separate collection of textiles will be mandatory from 2025 in the EU. Several initiatives are currently developing (fiber-to-fiber) material recycling of textiles [81].

Both cotton and wool fibers are made of about 50 wt% carbon, so using the aforementioned statistics, about 5,000 tonnes biogenic carbon are being exported out of Norway in the form of clothes/textiles every year, while a similar amount could be integrated with CCS as it is currently incinerated in Norwegian WtE.

1.4.8 Residual, mixed waste going to Norwegian Waste to Energy plant

A last stream to consider is the fraction that constitute municipal waste (including from households and other sources) going to Waste to Energy (WtE) plants in Norway. This waste stream is a complex, heterogeneous fraction including both fossil (plastic, textiles, etc.) and biogenic sub-fractions (food, wood, paper, etc.). Ideally, this waste should include only non-recyclable and/or materials containing compounds that must be destroyed and/or removed from circulation (e.g. heavy metals). Some of these biogenic sub-fractions are included in prior sections of this work, such as food waste, but this distinction is only possible for properly separated streams. Others (e.g. paper) have not as they are meant to be recycled when collected separately (even though rejects or process losses are to be expected).

The situation (as reported in 2017) of the WtE sector in Norway can be summarized as such: ca. 1.8 million tonnes MSW [82] are incinerated and produce ca. 1.8 million tonnes CO_2 per year, 60% being biogenic [83].

The evolution of the sector is difficult to predict given the increasing focus on recycling, but it is reasonable to assume that the amount of MSW being incinerated will remain stable in the coming decade, mainly due to population and wealth evolution [84]. Several WtE-CCS projects are underway in Norway, the most famous one being the full-scale CCS installation being under construction at the Celsio Klemetsrud WtE plant in Oslo that should be in operation in 2027 [85] and be connected to the Longship project to ensure permanent storage of the captured CO_2[86].

2 Biomass Mapping to maximum negative emission potential into 2030: Summary of the 3 Scenarios

For each of the 2030 scenario outlined in the manuscript, the biomass quantities and potential level of integration with bioCCS were extrapolated based on the respective scenario definitions. The correspoding data for these scenarios can below with a summary of the scenario definitions for context:

- Table 4: "Business-as-usual" scenario: where the result obtained for the 2020 situation are updated to represent the 2030 situation assuming annual increase/decrease in quantities using historical statistical data and considering an unchanged state-of-play concerning biomass uses and the fractions that are possible to integrate with bioCCS
- Table 5: "Expansion" scenario: which, in addition to the "business as usual" scenario, includes that three main events take place 1) the forest is harvested to its balance quantum (i.e., all growth is taken out and goes to the same applications as today) 2) seaweed production takes off according to currently forecasted estimates, 3) combustible waste fractions currently exported to Sweden are assumed to be treated (i.e. incinerated with energy recovery) in Norway.
- Table 6: "BioCCS-driven expansion" scenario: where the aforementioned events take place but are solely motivated by bioCCS, meaning that, for example, all the additional biomass from the quantum harvesting of the forest is integrated with bioCCS.

Table 4: 2030 potential – Business-as-usual scenario

Category	**Biomass fraction**	**Total carbon (kt)**	**Share integrable with bioCCS* (%)**	**Negative emissions potential (ktCO$_2$)**	**Evolution short description**	**Yearly increment 2020-2030 (of reference year)**
Agriculture	Livestock manure	354	42	545	Estimate	0.3%
	Straw	262	26	250	Historical data	0.3%
Forestry	Timber to non-energy products (incl. export)	3144	0	0	Historical data (forest growth)	2.8%
	Bark	305	100	1120	Historical data (forest growth)	2.8%
	Timber-processing residues and logs	945	34	1178	Historical data (forest growth)	2.8%
	Residues from urban expansion	93	100	342	Historical data (forest growth)	2.8%
	Branches and tops	1501	70	3853	Historical data (forest growth)	2.8%
	Stumps and roots	1636	0	0	Historical data (forest growth)	2.8%
Marine	Macroalgae	0.6	0	0	Estimate	50%
Waste	Wood waste	201	82	605	Historical data	2%
	Sewage sludge	44	100	162	With population	0.7%
	Fish waste	18	100	65	Historical data	0%
	Fish silage	14	30	15	Historical data	2%
	Fish sludge	8	100	29	Estimate	4%
	Wet organic waste from households	68	50	125	With population	0.7%
	Wet organic waste from industry	201	13	96	With population	0.7%
	Mixed waste to Waste-to-Energy	491	60	1080	Estimate	0%
	Exported waste	299	0	0	Estimate	1%

* Same uses and availabilities as estimated for 2020

Table 5: 2030 potential – Expansion scenario

Category	**Biomass fraction**	**Total carbon (kt)**	**Share integrable with bioCCS* (%)**	**Negative emissions potential (ktCO$_2$)**	**Evolution short description**	**Yearly increment 2020-2030 (of reference year)**
Agriculture	Livestock manure	354	42	545	Estimate	0.3%
	Straw	262	26	250	Historical data	0.3%
Forestry	Timber to non-energy products (incl. export)	3783	0	0	To forest balance quantum ->	54% over the whole period
	Bark	367	100	1347	To forest balance quantum ->	54% over the whole period
	Timber-processing residues and logs	1137	34	1418	To forest balance quantum ->	54% over the whole period
	Residues from urban expansion	93	100	342	To forest balance quantum ->	54% over the whole period
	Branches and tops	1806	70	4636	To forest balance quantum ->	54% over the whole period
	Stumps and roots	1968	0	0	To forest balance quantum ->	54% over the whole period
Marine	Macroalgae	165	20	121	Estimate for 2030	n.a.
Waste	Wood waste	201	82	605	Historical data	2%
	Sewage sludge	44	100	162	With population	0.7%
	Fish waste	18	100	65	Historical data	0%
	Fish silage	14	30	15	Historical data	2%
	Fish sludge	8	100	29	Estimate	4%
	Wet organic waste from households	68	50	125	With population	0.7%
	Wet organic waste from industry	201	13	96	With population	0.7%
	Mixed waste to Waste-to-Energy	491	60	1080	Estimate	0%
	Exported waste	299	60	658	Estimate	1%

* Same as 2020 except for *Macroalgae* (20% rejects estimated to enter bioCCS applications) and *Exported waste* that is not exported anymore (100% WtE in Norway, 60% biogenic).

Table 6: 2030 potential – bioCCS-driven expansion scenario

Category	Biomass fraction	Total carbon (kt)	Share integrable with bioCCS* (%)	Negative emissions potential (ktCO$_2$)	Evolution short description	Yearly increment 2020-2030 (of reference year)
Agriculture	Livestock manure	354	42	545	Estimate	0.3%
	Straw	262	26	250	Historical data	0.3%
Forestry	Timber to non-energy products (incl. export)	3783	35	4855	To forest balance quantum ->	54% over the whole period
	Bark	367	100	1347	To forest balance quantum ->	54% over the whole period
	Timber-processing residues and logs	1137	56	2335	To forest balance quantum ->	54% over the whole period
	Residues from urban expansion	93	100	342	To forest balance quantum ->	54% over the whole period
	Branches and tops	1806	70	4636	To forest balance quantum ->	54% over the whole period
	Stumps and roots	1968	0	0	To forest balance quantum ->	54% over the whole period
Marine	Macroalgae	165	20	121	Estimate for 2030	n.a.
Waste	Wood waste	201	82	605	Historical data	2%
	Sewage sludge	44	100	162	With population	0.7%
	Fish waste	18	100	65	Historical data	0%
	Fish silage	14	30	15	Historical data	2%
	Fish sludge	8	100	29	Estimate	4%
	Wet organic waste from households	68	50	125	With population	0.7%
	Wet organic waste from industry	201	13	96	With population	0.7%
	Mixed waste to Waste-to-Energy	491	60	1080	Estimate	0%
	Exported waste	299	60	658	Estimate	1%

* Same as 2020 except for *Timber and Timber-processing residue and logs*: all the additional harvesting (to forest balance quantum) is considered to be integrated with bioCCS applications.

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References

[1] H. Belbo, “Halm som biobrensel”, 2011.

[2] M. Spöttle, S. Alberici, G. Toop, D. Peters, L. Gamba, S. Ping, H. van Steen, and D. Bellefleur, “Low ILUC potential of wastes and residues for biofuels Low ILUC potential of wastes and residues for biofuels”, Tech. Rep., 2013, p. 168.

[3] *Kornproduksjon i Norge*, 2022. (visited on 08/05/2022).

[4] F. Sammut, I. Isakova, K. Voss, V. Vandenbussche, and J. Morken, “Ressursgrunnlaget for produksjon av biogass i Norge i 2030 - Sammenfatning av kunnskap og oppdaterte analyser”, *Carbon Limits M-1533—2019*, pp. 1–97, 2019.

[5] L. L. Granlund and H. Midtskogen, “Gardsvarmeanlegg – en byggeveileder”, Tech. Rep., 2012, p. 38.

[6] Klimasmart Landbruk, *Norske halmstrå kan varme en hel by*, 2017. [Online]. Available: `https://klimasmartlandbruk.no/klima-og-landbruk/klimalosninger-energi-og-teknologi/norske-halmstra-kan-varme-en-hel-by%7B%5C#%7D:%7B~%7D:text=%E2%80%93%20Vi%20installerte%20et%20helautomatisk%20halmfyringsanlegg,for%20store%20mengder%20CO2-utslipp.` (visited on 01/01/2023).

[7] A. M. Melbye, P. K. Rørstad, and M. Killingland, *Bioenergi i Norge*. Norges vassdrags- og energidirektorat, 2014, ISBN: 9788241009907.

[8] T. D. Remøy, “Virkemidler for økt bruk og produksjon av biogass”, Tech. Rep., 2020, p. 161. [Online]. Available: `https://www.miljodirektoratet.no/publikasjoner/2020/mars-2020/virkemidler-for-okt-bruk-og-produksjon-av-biogass/`.

[9] K. Fjørtoft, J. Morken, J. F. Hanssen, and T. Briseid, “Pre-treatment methods for straw for farm-scale biogas plants”, *Biomass and Bioenergy*, vol. 124, no. January 2017, pp. 88–94, 2019, ISSN: 18732909. [Online]. Available: `https://doi.org/10.1016/j.biombioe.2019.03.018`.

[10] R. Singh, S. Behera, Y. K. Yadav, and S. Kumar, “Potential of wheat straw for biogas production using thermophiles”, *Recent Advances in Bio-Energy Research*, no. May, pp. 242–249, 2014.

[11] B. Bjøtlo, *Halverte kornavlinger etter tørkesommer*, 2019. [Online]. Available: `https://www.ssb.no/jord-skog-jakt-og-fiskeri/artikler-og-publikasjoner/halverte-kornavlinger-etter-torkesommer` (visited on 07/08/2022).

[12] I. Ålund and E. van Weeghel, “Husdyrgjødsel til biogass”, Tech. Rep., 2020, p. 56.

[13] I. Pettersen, A. Grønlund, A. E. Stengsgård, and F. Walland, “Klimatiltak i jordbruk og matsektoren”, Tech. Rep. 2, 2017, pp. 1–100. [Online]. Available: `https://www.miljodirektoratet.no/globalassets/publikasjoner/M660/M660.pdf`.

[14] J. Morken, S. Ayoub, and Z. Sapci, “Revision of the Norwegian model for estimating methane emission from manure management”, p. 10, 2013.

[15] J. Liebetrau, R. O'Shea, M. Wellisch, K. Lyng, G. Bochmann, B. McCabe, P. Harris, C. Lukehurst, P. Kornatz, and J. Murphy, *Potential and Utilization of Manure to Generate Biogas in Seven Countries*, June. 2021, 1–52 PP – ISBN: 978–1–910154–88–5 (eBook electroni, ISBN: 9781910154885. [Online]. Available: `https://www.ieabioenergy.com/wp-content/uploads/2021/07/Potential-utilization%7B%5C_%7DWEB%7B%5C_%7DEND%7B%5C_%7DNEW.pdf`.

[16] Q. Ma, L. Han, Q. Li, S. Ma, and G. Huang, "Applicability of two separation methods for elemental analysis of typical agricultural biomass in China", *BioResources*, vol. 12, no. 2, pp. 4302–4313, 2017, ISSN: 19302126.

[17] A. Svensson, R. Eriksen, G. Hylen, and A. Granhus, *Skogen i norge. Statistikk over skogforhold og skogressurser i Norge registrert i perioden 2015-2019*, 142. 2021, vol. 7, p. 85, ISBN: 9788231101642.

[18] O. Finstad and A. Kjellsen, "Skogbruket fra A til Å", Tech. Rep. April, 2011, pp. 0–17. [Online]. Available: `https://www.allskog.no/upload/2011/11/09/skogbruket-fra-a-til-a.pdf`.

[19] G. Hylen, C. Antón, A. Granhus, D. Skog, and A. Landsskogtakseringen, "Skogressurser i Norge; Status og framtidsscenarier", Tech. Rep. 85, 2022.

[20] E. Trømborg and K. Rørstad, "Råstofftilgang – hvor mye biomasse og til hvilken pris?", Tech. Rep., 2017, p. 13.

[21] A. Granhus, N. von Lüpke, R. Eriksen, G. Søgaard, S. Tomter, and R. Antón-Fernándes, Clara Astrup, *Tilgang på hogstmoden skog fram mot 2045.* IV. 2014, vol. 03/2014, p. 31, ISBN: 03/2014.

[22] J. Koppejan and S. van Loo, *The Handbook of Biomass Combustion and Co-firing.* 2007, p. 464.

[23] NIBIO, *DE VIKTIGSTE EGENSKAPENE TIL BRENSEL FRA SKOGEN*, 2023. [Online]. Available: `https://www.nibio.no/tema/skog/bruk-av-tre/bioenergi/brenselflis/%7B%5C_%7D/attachment/inline/4ee83240-694a-4c15-9399-748be7c9cef1:bab1742f62dd3f0a871b331d36b23c90feb5a416/2%20-%20De%20viktigste%20egenskapene%20til%20brensel%20fra%20skogen.pdf` (visited on 05/01/2023).

[24] Ø. Skreiberg, M. Bugge, and N. E. L. Haugen, "GrateCFD Enabling optimum Grate fired woody biomass and waste to energy plant operation through", Tech. Rep., 2021, pp. 1–24. [Online]. Available: `https://www.sintef.no/globalassets/project/gratecfd/a4%7B%5C_%7Dhandbok-gratecfd%7B%5C_%7Dv4%7B%5C_%7Denkeltsider.pdf`.

[25] ——, "WoodCFD: Clean and efficient wood stoves through improved batch combustion models and CFD modelling approaches", Tech. Rep., 2018, pp. 1–20.

[26] S. Gjølsjø, *Trevirkets brennverdi*, 2017. [Online]. Available: `https://www.nibio.no/tema/skog/bruk-av-tre/bioenergi/trevirkets-brennverdi` (visited on 12/10/2022).

[27] S. sentralbyrå, *Skogbruk Arealbruk og arealressurser*, 2016. [Online]. Available: `https://www.ssb.no/jord-skog-jakt-og-fiskeri/faktaside/skogbruk` (visited on 03/20/2023).

[28] A. Svensson and L. S. Dalen, "Bærekraftig skogbruk i Norge", Tech. Rep., 2021. [Online]. Available: `https://www.skogbruk.nibio.no/tilvekst-og-skogavvirkning`.

[29] I. Aarø, "Skog En viktig del av klimaløsningen", Tech. Rep., 2018.

[30] P. Bajpai, "Pulp and Paper Production Processes and Energy Overview", *Pulp and Paper Industry*, pp. 15–49, Jan. 2016.

[31] E. Bergseng, T. Eid, P. K. Rørstad, and E. Trømborg, *Bioenergiressurser i skog.* 2012, p. 48, ISBN: 9788241008207.

[32] K. Q. Tran, M. Z. Alonso, L. Wang, and Ø. Skreiberg, "Simultaneously Boosting the Mass and Fixed-carbon Yields of Charcoal from Forest Residue via Atmospheric Carbonization", *Energy Procedia*, vol. 105, no. 1876, pp. 787–792, 2017, ISSN: 18766102. [Online]. Available: `http://dx.doi.org/10.1016/j.egypro.2017.03.390`.

[33] IRENA, *Bioenergy from boreal forests: Swedish approach to sustainable wood use.* 2019, ISBN: 9789292601195.

[34] A. Granhus, "Potensial for uttak av GROT fra sluttavvirkninger i Innlandet", Tech. Rep., 2022, pp. 1–12.

[35] E. Nordhagen and S. Gjølsjø, "FLIS OG FLISEGENSKAPER En undersøkelse av brenselflis i det norske flismarkedet", Tech. Rep., 2013.

[36] G. Alfredsen, K. M. Sandland, L. R. Gobakken, and E. Bergseng, "Sekundærråstoff fra trebaserte verdikjeder i Norge", Tech. Rep. 93, 2018.

[37] N. Fjernvarme, *Statistikk om Urban Energi i Norge*, 1. [Online]. Available: `https://www.fjernvarme.no/fakta/statistikk` (visited on 06/18/2023).

[38] T. Persson and G. Egnell, "Stump Harvesting", Tech. Rep., 2017.

[39] P. Hakkila, *Developing technology for large-scale production of forest chips.* 2004, vol. 6, p. 102, ISBN: 952-457-151-X. [Online]. Available: `http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.136.2946%7B%5C&%7Drep=rep1%7B%5C&%7Dtype=pdf%7B%5C%%7D5Cnhttp://www.tekes.fi/en/document/43249/wood%7B%5C_%7Denergy%7B%5C_%7Dfinal%7B%5C_%7Dpdf`.

[40] A. Brekke, E. Soldal, S. Saxegård, and E. Svanes og Hanne Lerche Raadal, *Klimavirkninger av ikke-skogbasert bioenergi.* 2017, ISBN: 9788241016011. [Online]. Available: `www.nve.no`.

[41] A. Sørensen, C. Banet, M. Bjordal, M. Bjørndal, J. Fuhrman, D. O. Hessen, M. S. Hole, F. Levihn, C. Merk, K. M. Mistry, P. Moss, F. Ramos, S. Roussanaly, J.-K. S. Røttereng, J. Skjermo, A. Torvanger, K. Weber, and A. Tomasgard, "Negative Emissions and Carbon Dioxide Removal (CDR) Including Ocean Scenarios", *NETI Policy Brief*, no. 01/2022, 2022.

[42] A. Vincent, "Hidden champion of the ocean", Tech. Rep., 2020, p. 60.

[43] A. Handå, S. Forbord, O. J. Broch, R. Richardsen, J. Skjermo, and K. I. Reitan, "Investigation into the cultivation and use of kelp, with a special focus on bioenergy in the northern regions", Tech. Rep., 2009.

[44] D. Erlandsen, *Taredyrking kan binde CO2*, 2022. [Online]. Available: `https://biocosmos.no/taredyrking-kan-binde-co2/`.

[45] Cai, J.and Lovatelli, A.and Aguilar-Manjarrez, J. and Cornish, L. and Dabbadie, L. and Desrochers, A. and Diffey, S. and Garrido Gamarro, E. and Geehan, J. and Hurtado, A. and Lucente, D. and Mair, G. and Miao, W. and Potin, P. and Przybyla, C. and Reantaso, M. and Roubach, R. and Tauati, M. and Yuan, X., "Seaweeds and microalgae: an overview for unlocking their potential in global aquaculture development", Tech. Rep., 2021. [Online]. Available: `https://www.fao.org/documents/card/en/c/cb5670en`.

[46] S. L. Holdt and S. Kraan, "Bioactive compounds in seaweed: Functional food applications and legislation", *Journal of Applied Phycology*, vol. 23, no. 3, pp. 543–597, 2011, ISSN: 09218971.

[47] G. Roesijadi, S. B. Jones, and Y. Zhu, "Macroalgae as a Biomass Feedstock : A Preliminary Analysis", *Analysis*, no. September, pp. 1–50, 2010, ISSN: PNNL-19944; Other: BM0204010; TRN: US201106%%96. [Online]. Available: `http://www.pnl.gov/main/publications/external/technical%7B%5C_%7Dreports/PNNL-19944.pdf`.

[48] T. Wågønes, G. A. Sørensen, and F. Syversen, "Material recycling of reclaimed wood", Tech. Rep., 2018.

[49] I. Ålund, "Treatment and disposal of sewage sludge and other organic waste in Norway", Tech. Rep., 2021.

[50] Lovdata, *Forskrift om begrensning av forurensning (forurensningsforskriften); Del 5, Kapittel 17*, 2023. [Online]. Available: `https://lovdata.no/dokument/SF/forskrift/2004-06-01-931/KAPITTEL%7B%5C_%7D6%7B%5C#%7DKAPITTEL%7B%5C_%7D6`.

[51] Ø. Bækken and S. Bekkevold, *Håndbok i Ensilering*. 1993, ISBN: 8299308909.

[52] N. D. Palkar, J. Koli, S. Patange, S. Sharangdhar, R. Sadavarte, and A. Sonavane, "Comparative Study of Fish Silage Prepared from Fish Market Waste by Using Different Techniques", *International Journal of Current Microbiology and Applied Sciences*, vol. 6, no. 12, pp. 3844–3858, 2017, ISSN: 23197692.

[53] L. Solli, O. Bergersen, R. Sørheim, and T. Briseid, "Effects of a gradually increased load of fish waste silage in co-digestion with cow manure on methane production", *Waste Management*, vol. 34, no. 8, pp. 1553–1559, 2014, ISSN: 18792456. [Online]. Available: `http://dx.doi.org/10.1016/j.wasman.2014.04.011`.

[54] S. Sarker, "By-products of fish-oil refinery as potential substrates for biogas production in Norway: A preliminary study", *Results in Engineering*, vol. 6, no. May, p. 100 137, 2020, ISSN: 25901230. [Online]. Available: `https://doi.org/10.1016/j.rineng.2020.100137`.

[55] U. Hossain and A. Alam, "Production of powder fish silage from fish market wastes", *SAARC Journal of Agriculture*, vol. 13, no. 2, pp. 13–25, 2016, ISSN: 1682-8348.

[56] J. Toppe, R. Olsen, O. Peñarubia, and D. James, "Production and Utilization of Fish Silage", *Food and Agriculture Organization*, pp. 1–28, 2018. [Online]. Available: `http://www.fao.org`.

[57] T. Guneriussen, "Kvalitet av ensilasje og ensilasjeprodukter fra restråstoff etter sløying av torsk og laks", Ph.D. dissertation, 2018. [Online]. Available: `https://munin.uit.no/handle/10037/16085`.

[58] S. Kannan, Y. Gariepy, and G. S. Raghavan, "Optimization and characterization of hydrochar produced from microwave hydrothermal carbonization of fish waste", *Waste Management*, vol. 65, pp. 159–168, 2017, ISSN: 18792456. [Online]. Available: `http://dx.doi.org/10.1016/j.wasman.2017.04.016`.

[59] R. Richardsen, R. Nystøyl, G. Strandheim, and A. Marthinussen, "Analyse marint restråstoff, 2016.", Tech. Rep., 2016, p. 55.

[60] Miljødirektoratet, *Akvakultur*, 2023. [Online]. Available: `https://www.miljodirektoratet.no/ansvarsomrader/vann-hav-og-kyst/Akvakultur-fiskeoppdrett/` (visited on 07/06/2023).

[61] G. Mathisen, *Norsk fiskeslam kan hjelpe på matmangel, men EU vil ikke gjødsle med det*, 2022. [Online]. Available: `https://forskning.no/fisk-landbruk-mat/norsk-fiskeslam-kan-hjelpe-pa-matmangel-men-eu-vil-ikke-gjodsle-med-det/1991742` (visited on 07/06/2023).

[62] I. Ahuja, E. Dauksas, J. F. Remme, R. Richardsen, and A. K. Løes, “Fish and fish waste-based fertilizers in organic farming – With status in Norway: A review”, *Waste Management*, vol. 115, pp. 95–112, 2020, ISSN: 18792456. [Online]. Available: `https://doi.org/10.1016/j.wasman.2020.07.025`.

[63] L. Matias del Campo, P. Ibarra, X. Gutierrez, and H. Takle, “Utilization of sludge from recirculation aquaculture systems”, Tech. Rep. March, 2010, p. 64. [Online]. Available: `www.nofima.no/filearchive/Rapport%2009-2010.pdf`.

[64] E. Pedersen, “Oppsummering av anbefalinger fra BioDigSirk-prosjektets konseptfase”, 2022.

[65] NIBIO, *Biogass fra fiskeslam*, 2022. (visited on 03/03/2023).

[66] D. Kleinegris, *SLAM-DUNK: the SLudge Appraisal teaM – Developing a sUstainable value chaiN from tanK to product*, 2021. [Online]. Available: `https://www.norceresearch.no/en/projects/slam-dunk-the-sludge-appraisal-team---developing-a-sustainable-value-chain-from-tank-to-product` (visited on 08/04/2023).

[67] O. K. Korneliussen, *Utnytter slam fra oppdrettsindustrien*, 2021. [Online]. Available: `https://avfallnorge.no/bransjen/nyheter/utnytter-slam-fra-oppdrettsindustrien` (visited on 08/04/2023).

[68] B. Waycott, *Bioretur converts farmed fish sludge into a powder fertilizer as demand for ‘circular economy’ technologies grows*, 2021. [Online]. Available: `https://www.globalseafood.org/advocate/sludge-report-finding-value-in-norways-aquaculture-waste/%7B%5C#%7D:%7B~%7D:text=It%20reduces%20the%20waste%20of,dried%20fish%20sludge%20each%20year` (visited on 08/04/2023).

[69] A. Iversen, Ø. Hermansen, R. Nystøyl, A. Marthinussen, and L. D. Garshol, “Kostnadsdrivere i lakseoppdrett 2018 Fokus på smolt og kapitalbinding”, Tech. Rep., 2018, p. 43.

[70] E. Brod, J. Oppen, A. Ø. Kristoffersen, T. K. Haraldsen, and T. Krogstad, “Drying or anaerobic digestion of fish sludge: Nitrogen fertilisation effects and logistics”, *Ambio*, vol. 46, no. 8, pp. 852–864, 2017, ISSN: 16547209.

[71] H. L. Raadal, A. E. Stensgård, K.-A. Lyng, and O. J. Hanssen, *Vurdering av virkemidler for økt utsortering av våtorganisk avfall og plastemballasje.* 2016, p. 107, ISBN: 978-82-7520-739-3. [Online]. Available: `http://www.miljodirektoratet.no/Documents/publikasjoner/M522/M522.pdf`.

[72] J. (Martinsen, “Økt Utnyttelse Av Ressursene I Våtorganisk Avfall”, Tech. Rep., 2012.

[73] Miljødepartementet, *Strengere krav til kildesortering av avfall*, 2022. [Online]. Available: `https://www.regjeringen.no/no/aktuelt/strengere-krav-til-kildesortering-av-avfall/id2917708/` (visited on 01/01/2023).

[74] H. L. Raadal, V. Schakenda, and J. Morken, “OR 21.08: Potensialstudie for biogass i Norge”, Tech. Rep., 2008, p. 55.

[75] A. E. Stensgård and O. J. Hanssen, *Food Waste in Norway 2010-2015, Final Report from the ForMat Project (OR.17.16).* 2016, p. 63, ISBN: 9788275207508.

[76] Ø. Holm, S. Jarstein, and B. Fram, “The bioenergy potential of industrial waste”, Tech. Rep., 2013.

[77] M. Becidan, L. Wang, M. Fossum, H. O. Midtbust, J. Stuen, J. I. Bakken, and E. Evensen, “Norwegian Waste-to-Energy (WtE) in 2030: Challenges and opportunities”, *Chemical Engineering Transactions*, vol. 43, pp. 2401–2406, 2015, ISSN: 22839216.

[78] R. Østgårdsgjelten, M. E. ValvikJournalist, and S. Bjørnestad, "Billig og miljøvennlig å frakte søppelet over til Sverige, mener myndighetene", *Aftenposten*, p. 5, Oct. 2015. [Online]. Available: `https://www.aftenposten.no/okonomi/i/jajn/billig-og-miljoevennlig-aa-frakte-soeppelet-over-til-sverige-mener-myndighetene`.

[79] EEA, "Plastic in textiles : towards a circular economy for synthetic textiles in Europe Key messages", *European Environment Agency*, pp. 1–12, 2021.

[80] D. Watson, S. Trzepacz, S. Rubach, and F. M. Johnsen, "Kartlegging av brukte tekstiler og tekstilavfall i Norge", Tech. Rep., 2020. [Online]. Available: `https://norsus.no/wp-content/uploads/or1120-kartlegging-av-brukte-tekstiler-og-tekstilavfall-i-norge%7B%5C_%7DVersjon-2-1.pdf`.

[81] B. Kopstad, S. Eggen, and H. Lystad, "Materialgjenvinningsmuligheter for tekstiler i IVAR-området", Tech. Rep., 2020, pp. 1–31. [Online]. Available: `https://s3-eu-west-1.amazonaws.com/avfall-norge-no/dokumenter/MatGjenvMuligheter-Tekstiler-i-IVAR-omr%7B%5Caa%7Ddet.pdf?mtime=20210204133128%7B%5C&%7Dfocal=none`.

[82] S. Bjørnerud, F. Syversen, and A. Dalen, "Avfallsmengder fram mot 2035; Energigjenvinningens rolle i sirkulærøkonomien", Tech. Rep., 2019, pp. 1–23.

[83] CEWEP, "Waste-to-Energy Climate Roadmap The path to carbon negative", Tech. Rep., 2022, pp. 1–20.

[84] L. Wang and M. Becidan, "MSW in a Circular Economy: 2020-2035 Scenarios for the City of Oslo, Norway", *IOP Conference Series: Earth and Environmental Science*, vol. 691, no. 1, 2021, ISSN: 17551315.

[85] Hafslund Oslo Celsio, *Karbonfangst i Oslo realiseres*, 2022. [Online]. Available: `https://kommunikasjon.ntb.no/pressemelding/karbonfangst-i-oslo-realiseres?publisherId=17848166%7B%5C&%7DreleaseId=17936591` (visited on 01/24/2023).

[86] Norwegian Ministry of Petroleum and Energy, "Longship – carbon capture and storage", Tech. Rep., 2020, p. 92. [Online]. Available: `https://www.regjeringen.no/en/dokumenter/meld.-st.-33-20192020/id2765361/`.