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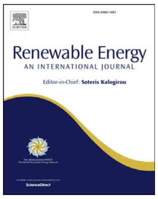

The role of sustainable bioenergy in a fully decarbonised society

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ABSTRACT

With the Danish government's goals of decreasing 70% of CO_2 emissions by 2030 and reaching a fully decarbonised society in the years after, this paper aims to identify the role of sustainable bioenergy in achieving this goal. The methodology and approach presented are relevant for other countries heading in the same direction. The focus is on strategies to further develop the sustainable biomass resources and conversion technologies within energy and transport paired with CCUS (carbon capture utilisation and storage) to coordinate with other sectors and achieve a fully decarbonised society. By using hourly energy system modelling and a Smart Energy Systems approach, it is possible to create a robust multiple technology strategy and keep the sustainable bioenergy levels. The results are presented as principles and guidelines on how to include the use of sustainable biomass in the individual country as an integrated part of global decarbonisation.

1. Introduction

The decarbonisation of society has not only been a highly recognised necessity on the political agendas worldwide but has also been a subject of interest in the research community. The combustion of fossil fuels is the main driver of climate change, and with the energy sector emitting e.g. 78% of the total greenhouse gas (GHG) emissions of the European Union [1], it still holds the key to any strategy for achieving a fully decarbonised society. While GHG emissions have decreased in the majority of the sectors, the transport sector is an exception with the continuous growth of demand and lack of action on the decarbonisation measures. Decarbonisation of the energy sector represents many challenges [2]. The challenge to reduce GHG emissions involves the combination of reductions in the energy demand, increases in energy efficiency, electrification of the end-use and establishment of a high share of renewable energy [3]. However, there is no global measure to cut emissions, and each country has to put individual measures into action. Such individual country strategies will have to coordinate their efforts to properly address common issues such as the global use of sustainable biomass resources and the necessity for implementing carbon capture, utilisation and storage (CCUS).

With biomass resources representing a direct substitute to different fossil sources, all energy sectors compete for the same sustainable biomass resources and even at maximum levels of sustainable bioenergy production, cross-sectoral competition is high [4] within the energy system, but also in the broader perspective [5]. Recent evidence [6] highlights the issues of the biomass demands in energy system modelling, showing that a bioenergy focused renewable energy system leads to biomass demands 6–10 times higher than the projected global potential of 10–30 GJ/person/year. Carbon capture and storage (CCS) has been indicated as necessary by some [3,7] for the decarbonisation plans, but it is also visible that policy and political support for CCS are not consistent [8]. Rogulj et al. [9] point out that even though fossil fuels combined with CCS are sometimes used as bridging solutions, their use in achieving a 1.5-degree target should be limited as it results in residual emissions. On the other hand, the carbon capture and utilisation (CCU) technologies can help secure the energy supply as they reduce dependence on fossil fuels [10] by enabling the potential to produce fuels, chemicals, and plastics.

A growing body of literature has examined the modelling of the future energy systems for different countries worldwide [10], Europe [11–14] and also global models [15–18]. Among the former, Denmark is a frontrunner in renewable energy, aiming towards becoming carbon neutral in 2050 according to its Climate law [19].

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Consequently, much research on the future Danish energy system has been conducted [20–26]. Denmark is also one of the richest biomass regions in the EU [27], and sustainable use of biomass has been a focal point of some analyses [6,28–30]. However, there are still some issues, such as the coordination with other GHG emitting sectors and the relation between Denmark and the rest of Europe.

The Danish Climate law [19] and the political climate agreement from 2020 [31] impose a set of initiatives, including sustainability requirements for biomass for energy production, green transport, support for biogas and other green gases, as well as support for power-to-x (PtX) technologies and carbon capture. Recently, the Danish government published both a handbook on meeting biomass sustainability requirements [33] and a new CCS agreement with a roadmap for storing CO_2 [34]. This CCS agreement announces that the strategy will also include the CCU options paired with PtX [32].

In this paper, Denmark is used as a case to provide the national strategy for decarbonisation of the energy sector supported by a set of guidelines and methodologies that address both sustainable biomass use and the role of CCUS. The approach and methodology are likely relevant for most countries on a global level, while the result of the analysis will depend on the context and available biomass resources in the specific country. The presented work is part of IDA's Climate Response 2045, a proposal on how to meet the political goals prepared by the authors in close collaboration with the Danish Society of Engineers (IDA) and inputs from experts within different technical areas. Similar proposals were put forward by the same collaboration between researchers and IDA in 2006 [21], in 2009 [23,33] and 2015 [24]. Previous analyses have shown that a 100% renewable energy system is possible and feasible for Denmark, but also that what appear as suitable individual measures are not necessarily best for the overall system [34]. Therefore, the Smart Energy System concept was developed [35,36] and used to create this decarbonisation strategy. It was previously highlighted [21] that it is important to consider the degree to which countries should rely on biomass or primarily on wind power combined with PtX technologies, which will bring a certain inefficiency in the system design, and this analysis attempts to address these matters.

2. Methodology and guiding principles

The technical design of IDA Climate response 2045 has been developed by the use of advanced hour-by-hour modelling in the energy system analysis tool EnergyPLAN, where the hourly energy balances and possible sector integration and storage options for the entire energy system are considered [37]. Detailed comparison of different energy system tools, including EnergyPLAN, is provided by Ref. [38]. In addition, the inclusion of Smart Energy Systems as a modelling concept was discussed in Ref. [39] and theoretical considerations on using the simulation tool when designing future energy systems are presented in Ref. [40].

A country can convert to 100% renewable energy or be fully decarbonised in many ways. However, if the world should succeed in doing so at the global level, within the limits of sustainable biomass, each country should fulfil its objective of renewable energy and CO_2 reductions in a way that fits well into a context where the rest of the world will be able to do the same. Such overall guidelines can be used in the design of several choices and issues. In the case of Denmark, some of the most important are that: (1) the Danish share of *international aviation and shipping* is considered even though it is not included yet in the UN's way of calculating CO_2 emissions; (2) the Danish share of *worldwide sustainable biomass* should not be exceeded; (3) Denmark should contribute to establishing *flexibility and reserve capacity* to integrate wind and solar into the *European electricity supply*.

The design of the Smart Energy System for Denmark in IDA's Climate Response 2045 fulfils all these principles to achieve a carbon neutral solution within the energy and transport sector. To remain within the limits of the Danish share of global sustainable biomass resources, there is a strong need to convert both biomass resources and CO_2 together with electrolytic hydrogen [41] via PtX pathways [42–44] or biomass resources by advanced biofuel pathways to different end-fuels. These fuels can then be used for parts of the transport demand not suitable for electrification due to the requirements for high energy density fuels such as heavy-duty road transport (long-haul), marine and aviation [45,46]. Even though the demands for liquid and gaseous fuels will overall decrease in the future, due to the high levels of electrification, the gas demands for the electricity production are expected to increase in comparison to the existing systems [47], highlighting that the production of green gaseous products needs to be aligned with the available biomass resources.

Several different biomass conversion technologies are relevant to minimise biomass use and generate needed fuels. In addition, some PtX pathways with CCU are needed to relieve the biomass demand. However, many of these technologies are not yet commercially ready at the relevant scales [48,49]. Furthermore, biomass demand for the production of different kinds of fuel poses competition as the same biomass types are used to produce electricity [6]. In the study, efficiencies and cost, including handling costs, are based on the Danish Technology Catalogue [50] and thus, the likely and expected development of each technology was taken into account.

Fuel pathways that can use feedstocks, like waste biomass that would otherwise not be utilised, bring new possibilities to the system [51]. Biomass resources with low net CO_2 emissions should be prioritised. Such resources are e.g. biogas produced on manure having additional greenhouse gas emission advantages for the agricultural sector. The production implies the need to transform diverse bio-resources into liquid or gaseous fuels, which poses challenges in process development to improve conversion efficiency and overall sustainability while decreasing production costs. For these reasons, IDA's Climate Response 2045 scenario promotes multiple technology solutions, focusing on using different biomass technologies and PtX technologies by enabling synergies between them and the energy system. This results in a robust multiple technology strategy in which one technology can replace another in case some of these are not commercially ready at the proper time. For example, the scenario shown later in Fig. 3 has three major pathways for the conversion of biomass straw. If one fails, the resource can be converted by the two others as illustrated later in Fig. 4. However, in general, if more pathways are available options, this will be better to design a suitable, efficient and effective system.

Consequently, IDA's Climate Response 2045 has formulated the following principles for the use of sustainable biomass:

- Keeping the biomass within the limits of the Danish share of global sustainable biomass resources;
- Biomass resources and technologies with low net CO_2 emissions are given priority;
- Solutions integrated with hydrogen from flexible electrolysis plants are given priority;
- Due to uncertainties related to future technological development, priority is given to robust multiple technology pathways;
- Priority is given to technical solutions that provide negative CO_2 emissions, i.e. both CCS and biochar.

3. Analysis

3.1. Sustainable biomass levels

The limits for how much biomass globally can be used sustainably for energy purposes are still being debated [52]. Following the Danish Energy Agency estimations [53,54], the future amount of sustainable biomass is estimated to be somewhere between 100 and 300 EJ/year, equal to 10–30 GJ/capita annually in a scenario with 10 billion global inhabitants. However, other estimates point out that, in the long run, it will only be around 100 EJ/year [55,56]. It is forecasted that approximately 14–46 EJ of bioenergy will be available in the European Union [57]. Similar estimates can be found in other sources (see Fig. 1).

In their Smart Energy Europe study [57], the authors assumed that a future 100% renewable energy system might consume a maximum of approximately 14 EJ/year of bioenergy, which is the identified minimum forecast from all studies. 14 EJ/year for the EU28 corresponds to 27 GJ/capita annually, while the global bioenergy resources for 2050 are expected to be 33 GJ/capita annually. By limiting the EU28 bioenergy consumption to a similar level as the global availability, the EU28 contribute to a sustainable global solution. It should be emphasised that the amount of sustainable biomass in a specific country and at the global level depends on whether or not an active policy is conducted [58]. This is also illustrated by the wide range in the estimates. In the case of Denmark, it is possible to increase the harvesting of sustainable wood by increasing the share of forest (as elaborated in Table 1). Similarly, the option of coordinating with biochar production and other types of CO_2-sinks also exists. In IDA's Climate Response 2045, the Danish contribution to global sustainable biomass resources is estimated, as illustrated in Table 1.

Energy crops are not included in Table 1 and can be an additional resource. The estimate of wood chips depends on increases in forestry in Denmark. This study has chosen to base the numbers on an increase of 100,000 acres of productive forest, which is aligned with the current political plans [53]. Under such an assumption, the potential in 2045 is 40 PJ of wood chips. Including an additional resource of firewood, wood pellets, and waste wood of approximately 15 PJ in 2045, the sum of potential sustainable wood becomes 55 PJ in 2045. The 45 PJ of straw can be reached either by supplying 75 PJ to a biogas plant with a return of 30 PJ to the fields or by supplying 45 PJ directly to other technologies such as combustion or thermal gasification.

The 158 PJ represent the potential Danish input to the global amount of sustainable biomass resources (see Fig. 2). However, in its strategies for achieving a zero-carbon solution, Denmark should still limit itself to the Danish share of sustainable biomass. 158 PJ biomass correspond to approximately 26 GJ/capita, which is within the range of potential sustainable biomass on the global level, yet likely at the high end. Therefore, a Danish strategy should try to limit its use of biomass for energy purposes and leave some of it for potential export to other countries, where sustainable biomass resources are less plentiful.

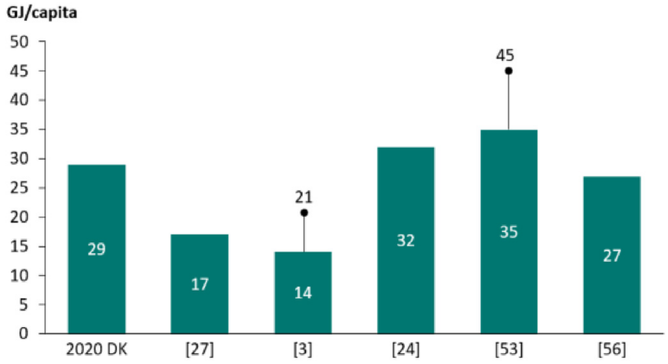

Fig. 1. Comparison of different estimates of biomass per person. Black dots represent range reported in the specific studies.

3.2. A robust multiple technology conversion approach

In order to make the best use of the available sustainable biomass, IDA's Climate Response 2045 proposes a combination of the following conversion technologies, also described below: biogas plants, thermal gasification, pyrolysis, hydrothermal liquefaction, combustion and CCUS. All investments in biomass technologies are decided as inputs to the EnergyPLAN model. The EnergyPLAN model is used to calculate the operation and consequences in the context of a fully sector-integrated smart energy system as described in Ref. [62].

3.2.1. Biogas plants

Biogas plants are a well-established technology in Denmark, with its first biogas plant inaugurated in 1920 [63]. Currently, around 20% of the Danish natural gas demands distributed in the Danish natural gas grid is green gas based on upgraded biogas from biogas plants [64]. Moreover, it is projected that in 2030 the whole Danish gas demand will be supplied by biogas [65]. This makes Denmark the European country with the highest share of biogas in gas consumption. In Denmark, biogas production is primarily based on manure and various types of organic waste. In the future, straw might be a promising additional resource to boost biogas production. The inclusion of straw calls for a relatively small increase in reactor volume and consequently involves only minor additional investments [59]. The production of biogas with the addition of straw results in equal shares of methane and CO_2; while, for traditional manure-based biogas, the relation is typically 35% CO_2 and 65% methane [59]. The cleaning and upgrading of biogas with physical or chemical upgrading methods are energy and chemical intense [66] but necessary to increase the calorific value of the gas, as the gas' energy content is in the methane part. Separated CO_2 can be captured and utilised in CO_2 intensive industries, reacted with the addition of electrolytic hydrogen in methanation units [67] or stored with CCS. In this regard, Korberg et al. [68] analysed the prioritisation of biogas use in the system, demonstrating that biogas should be used directly, when possible, or in the form of biomethane primarily for power and heat production or for meeting the industry demand. In addition, Jensen et al. [69] stress that upgraded biogas should not be neglected for decarbonising electricity and district heating systems.

3.2.2. Thermal gasification

Thermal gasification is one of the biomass conversion technologies that can decompose dry biomass as woody products and straw into syngas in the presence of controlled amounts of oxygen or steam at relatively high efficiencies [50]. Ren et al. [70] give an overview of different gasification technologies and see methane or synthetic natural gas (SNG) production via biomass gasification as an economical technology in the future. Furthermore, output gas generated by gasification is rich in carbon and is well suited as a PtX pathway with hydrogenation and further conversion into liquid electrofuels such as methanol, DME or jet fuel. However, thermal gasification is still at the demonstration level [71,72]. Demonstration of the coupling of biomass gasification and electrolytic H_2 has not yet been realised but has been modelled for methanol production [73–75] with high potential for flexible operation and

Table 1
An estimate of the Danish potential for Sustainable Biomass in 2045.

Biomass type	[PJ/year]	Notes and source
Biogas based on manure, deep bedding, industry and residual waste, discarded crops and green agricultural waste	49	The estimate is based on [59]. In this assessment, the potential changes over time and the numbers shown are valid for the year 2040. This potential should be regarded as an upper limit.
Straw	45−75	The estimate is based on [59]. The potential is an upper limit, however, without straw use for cows. Historically, typically 20–25 PJ has been used for energy purposes. The potential of 75 PJ could be converted into approx. 45 PJ biogas with a return of 30 PJ to the fields. The net CO_2 emissions are more or less the same as if all 75 PJ were put directly on the fields.
Wood such as wood chips, firewood, wood pellets and wood waste	40−80	The potential for wood chips is based on [60] and is an estimate of the waste product that has to be removed from the forest. The potential includes power-cultures, i.e. fast-growing trees such as e.g. larch trees. A potential of 35 PJ is based on the current forest area, while 60 PJ include an increase in forest areas of 200,000 acres. 90,000 m^3 of wood is allocated to improving biodiversity. Additional to wood chips, there will also be a potential for firewood equal to the current level of 3−4 PJ [61] plus a similar contribution from rural areas and a potential of 2.7 PJ of wood pellets and 9 PJ of wood waste.
Waste	13	Waste resources are estimated based on the current level of 40 PJ/year being reduced due to the recycling and subtraction of organic waste.
Total	**160−220**	Estimated maximum potential.

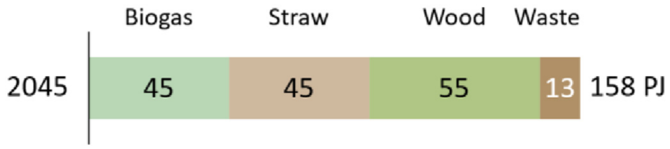

Fig. 2. Sustainable biomass resources for 2045.

carbon conversion. Hannula et al. [76] find that the efficiency of biomass gasification to methanol or methane is highly sensitive to the type of gasifier even with the use of the same biomass resources, which may add up to the uncertainty of the technology if some gasifier designs do not deliver on the expected technical performances. Nevertheless, previous energy system analyses showed that the production of electrofuels via gasification could lower the energy system costs and improve the system efficiency [43,44].

3.2.3. Pyrolysis

Pyrolysis is another thermochemical process that decomposes organic matter in the absence of oxygen into bio-oil and a solid residual coproduct named biochar. Slow pyrolysis is employed to maximise the solid product yield, while fast pyrolysis is used to maximise the liquid product yield [77]. Both of these use the same type of dry feedstocks as gasification, i.e. primarily woody biomass and straw. The amount and distribution of products it generates depend on the pyrolysis temperature, resource composition and heating rate [78], but the main product is bio-oil, which can directly replace fossil oil in regular refining processes and is also the main appeal of this technology. However, the pyrolysis bio-oil has a high oxygen and low-energy content; thus, it requires integration with deoxygenation processes based on hydrogen addition to upgrade the fuel to a higher quality [79]. The pyrolysis off-gases, a combination of CO and CO_2, may also be used for permanent storage or for producing additional fuels via PtX, in which case more hydrogen will be needed than during the regular deoxygenation process [80].

Biochar from pyrolysis may be used as carbon sink, a technical solution that has been discussed for decades, and studies report different levels of global carbon sequestration potential of biochar at 0.7−1.8 Gt $CO_2-C_{(eq)}$ yr [81]. The most commonly applied utilisation of biochar is soil amendment, however, other potential utilisation pathways can be considered and eventually improve both the economic viability and environmental sustainability [82]. In addition, some research investigated the economic and environmental impacts of pyrolysis technologies and studied the broad scope of the biofuel value chain [80,83–85], or even the overall energy system [86]. In general, pyrolysis is likely to involve lower investments and costs than thermal gasification, but the output of liquid and gaseous fuels is lower [50].

3.2.4. Hydrothermal liquefaction of biomass

Hydrothermal Liquefaction (HTL) is a thermochemical conversion of biomass into liquid fuels in a hot pressurised environment [87]. A recent literature review on this topic [88] looked into various aspects of HTL, such as the types of processes, different feedstocks, advantages/disadvantages and energy efficiency. The results show that HTL is best used for processing high-moisture biomass as it does not have any moisture-level requirements, being able to process a wide variety of biomass and waste feedstocks from industrial, food and forest industries, swine manure, algae, arboreous crops and sewage sludge. The process can also convert plastic to oil [89], which is particularly good in situations in which plastic and similar waste products are to be removed before organic waste is returned to the fields. One of the by-products of HTL is CO_2, which can either be sequestrated or reacted together with process gas and electrolytic H_2 via a PtX unit to methanol. In this way, the additional demand for hydrogen is higher than the regular upgrading process, which also uses hydrogen to remove oxygen. This concept, therefore, brings the benefit of cross-sectoral integration. Hansen et al. [90] present the results of a techno-economic analysis to evaluate the feasibility of developing an electrofuel system based on HTL, pointing out that the HLT derived electrofuels are cost-competitive with other alternative fuels. The HTL process can be designed for various combinations of outputs.

3.2.5. Combustion

Biomass incineration has typically been used in Denmark for processing waste feedstock in incineration plants, which are in most cases combined heat and power (CHP) plants connected to district heating networks. Combustion is also likely to be a part of future solutions, especially to convert those types of biomass which are hard to utilise using other technologies. These processes can be combined with CCUS, either for storage purposes or by utilising CO_2 for fuel production.

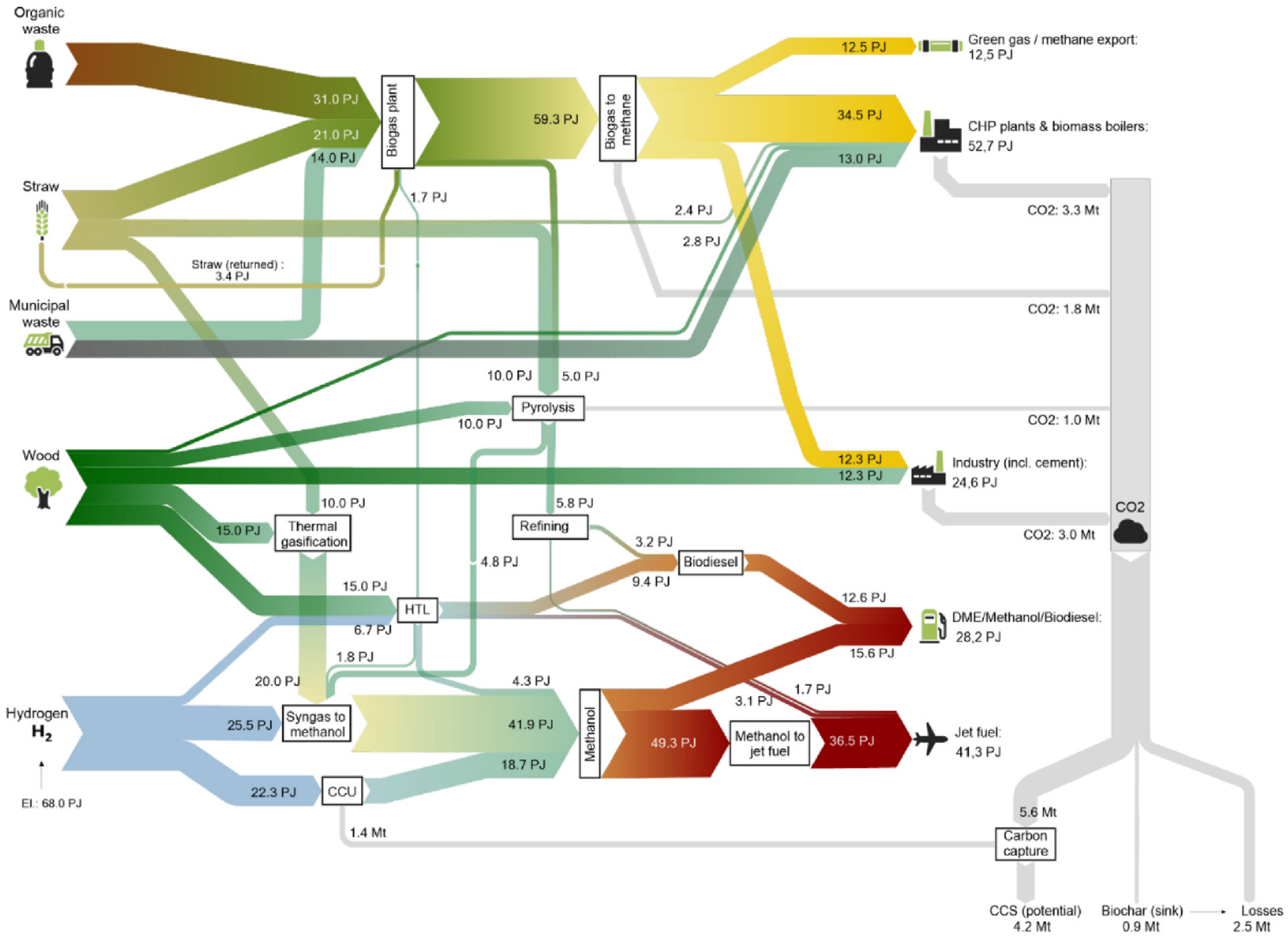

Fig. 3. Overview of the use of Biomass in IDA's Climate Response scenario of Denmark year 2045 (153 PJ minus export 13 PJ = 140 PJ equal to 23 GJ/capita).

3.2.6. Carbon capture, utilisation and storage (CC, CCU, CCS or CCUS)

Carbon can be captured from different biomass conversion processes, combustion plants or industrial processes such as cement industries. While the CCU concept is aligned with circular economy principles and treats CO_2 as a resource rather than waste, most CCU options do not entail the permanent sequestration of carbon [91]. The use of CCU via PtX pathways to generate various electrofuels, such as methane, methanol or even jet fuels, could also bring economic benefits [92] and also support the electricity grid balancing, thereby reducing the need for direct electricity storage. On the other hand, CCS as a technology has been criticised as an enabler for the prolonged use of fossil fuels and not fitting into renewable energy systems [57]. The authors [93] have reviewed the lifecycle assessment (LCA) impacts of CCU and CCS technologies, concluding that the global warming potential of CCU is higher than CCS, but that CCS has higher environmental impacts. Müller et al. [94] recently published guidelines for conducting LCA on CCU technologies to improve the comparability of LCA studies through clear methodological guidance.

3.3. Sustainable CCUS levels

The assessment of the potential for carbon capture in IDA's Climate Response 2045 is based on a calculation of the gross CO_2 output combined with assumed utilisation shares, as shown in Table 2. The low shares of CHP and power plants in the system illustrate that these plants, in a future renewable energy system, will likely have very few operating hours since they will mostly produce in peak hours or hours with little to no production from variable renewable electricity sources. The gross potential also includes an output from industrial processes in the Danish cement industry as an industrial emitter with continuous emissions. This results in a gross potential of approximately 8 Mt CO_2/year and a net potential of approximately 6 Mt/year. These estimates align with other similar estimates in Denmark, reaching a potential in the range of 5–10 Mt/year [95].

3.4. Sustainable use of biomass and CCUS in IDA's Climate Response scenario 2045

In IDA's Climate Response 2045, biomass resources are converted into green gaseous and liquid fuels using the previously presented conversion processes, as illustrated in Figs. 3 and 4. The multi-technology approach is implemented in close connection with the biomass potential and availability identified in Section 3.1, and the mix of technologies is therefore aligned with the resource availability and demands that need to be supplied with different fuel products. Two scenarios were constructed, one with a biomass consumption of 23 GJ/capita (Fig. 3) and one with 20 GJ/capita

Table 2
Assessment of the Danish carbon capture potential in the energy system of IDA's Climate Response scenario year 2045.

Input	Gross potential Mt CO_2/y	Share of utilisation	Net Potential Mt CO_2/y
Biogas	1.75	0.9	1.57
Combustion in industry	2.03	0.8	1.63
Waste incineration	1.32	0.8	1.06
Green gas CHP and power plants	1.93	0.3	0.58
Industrial processes (cement industry)	1.00	0.8	0.80
Total	**8.04**		**5.64**

(Fig. 4). These figures also illustrate the potential for CCUS in these scenarios.

Both scenarios include biomass and its relation to the use of hydrogen and CO_2 sink potentials from CCS and biochar. The gaseous and liquid fuel outputs cover most of the needs of the Danish transport sector, including the Danish share of international shipping and aviation. In the scenarios, approximately 5% of the total transport demand is met by direct use of hydrogen and parts of the marine demand are covered by ammonia; however, this is not included in the two figures as they focus on the biomass and CCUS energy flows.

In IDA's Climate Response 2045 scenario, Denmark will contribute to the global sustainable biomass resources with 153 PJ of biomass, of which 140 PJ is used to cover Danish energy demands, including the Danish share of international shipping and aviation, and the rest is exported in the form of green methane. Moreover, the strategy provides a potential for CCS and biochar equivalent to 4–5 Mt/year that can be used to compensate for the flight contrails and greenhouse gasses from other sectors than energy and transport, such as agriculture, land use, land-use change and forestry (LULUFC) and industrial processes. Due to the high agricultural activities in Denmark, the biochar is assumed to be applied as soil amendment to improve soil health.

In 2045, the use of straw and wood chips in boilers and CHP plants will be reduced as the existing biomass-fired plants cease; however, smaller amounts of waste and solid biomass will still be used in CHP plants. 14 PJ of municipal waste is used as an input for biogas production, while the rest is supplied by organic waste, including manure supplemented with straw. There is an increased demand for gas in the peak and reserve load power and heating plants, which is supplied by upgraded biogas. In industry, part of the existing consumption of fossil fuels is displaced by biomass and upgraded biogas. The transport demand is met by bio-based electrofuels and CCU electrofuels paired with electrolytic hydrogen together with hydrothermal liquefaction (HTL) and pyrolysis. Aviation fuels are met either by methanol-to-jet fuel pathways or by refining bio-oil from pyrolysis and HTL.

However, as illustrated in Fig. 4, the scenario can also be accomplished with less biomass input, with a reduction of the total biomass consumption of 36 PJ, which as a consequence provides a lower potential for carbon capture and biochar production. In the first scenario, biomass consumption is based on the current Danish agricultural and animal production structures with regards to the cultivation of fields and the number of livestock, etc. If the agriculture sector changes direction to more organic farming and reduces animal husbandry, the potential for sustainable biomass for energy purposes may be reduced. It should also be mentioned that the transition in Fig. 4 can – to a certain extent – be adapted if e.g. one technology should be commercially available at a large scale sooner than another.

4. Conclusion

This paper has presented the methodology and results of identifying the role of sustainable bioenergy in a fully decarbonised society.

The methodology is based on the basic principle that if the world should decarbonise within the limits of global sustainable biomass resources, each country should fulfil its objective of renewable energy and CO_2 reductions in a way that fits well into a context where the rest of the world will be able to do the same.

Such overall principle has been used in the design of several choices and issues. Designing a decarbonised energy system is a complex matter, especially when accounting for international aviation and shipping (navigation) and their additional fuel demands. The current UN GHG inventories do not include international shipping nor aviation when accounting for total emissions. This reduces the focus on the emissions from these parts of the transport sector. Moreover, it also eliminates the consideration of the biomass demand for fuel production for these transport modes. Furthermore, the decarbonisation of the energy and transport sectors will have to align with the emission of climate gasses in the other sectors to achieve a climate neutral society. Since it may not be possible to reduce climate gasses to zero in the other sectors, such coordinated actions involve sinks in terms of CCS and biochar.

Using the case of Denmark, this paper has applied these principles and guidelines on a concrete proposal on a strategy for the utilisation of bioenergy in a fully decarbonised society.

Such a strategy involves (1) that the Danish share of international aviation and shipping is considered even though it is not included yet in the UN's way of calculating CO_2 emissions; (2) that the Danish share of worldwide sustainable biomass is not exceeded; and (3) that the use of bioenergy provides sinks to compensate for other sectors and is an integrated part of a broad spectrum of renewable energy sources to fully replace the use of fossil fuels in the entire system.

In order to achieve the best role for bioenergy, it is recommended to implement a multiple technology solution with a focus on the use of different biomass technologies by enabling synergies between them and the energy system. This results in a robust multiple technology strategy in which one technology can replace another in case some technologies are not commercial ready at the proper time. In order to make the best use of the available sustainable biomass, as a result of energy system analysis, this paper proposes a combination of the following conversion technologies: biogas plants, thermal gasification, pyrolysis, hydrothermal liquefaction, combustion and CCUS.

With this in mind, the specific balance between these and other relevant technologies may differ between countries and should be adjusted on an ongoing basis as the technologies are subject to further development.

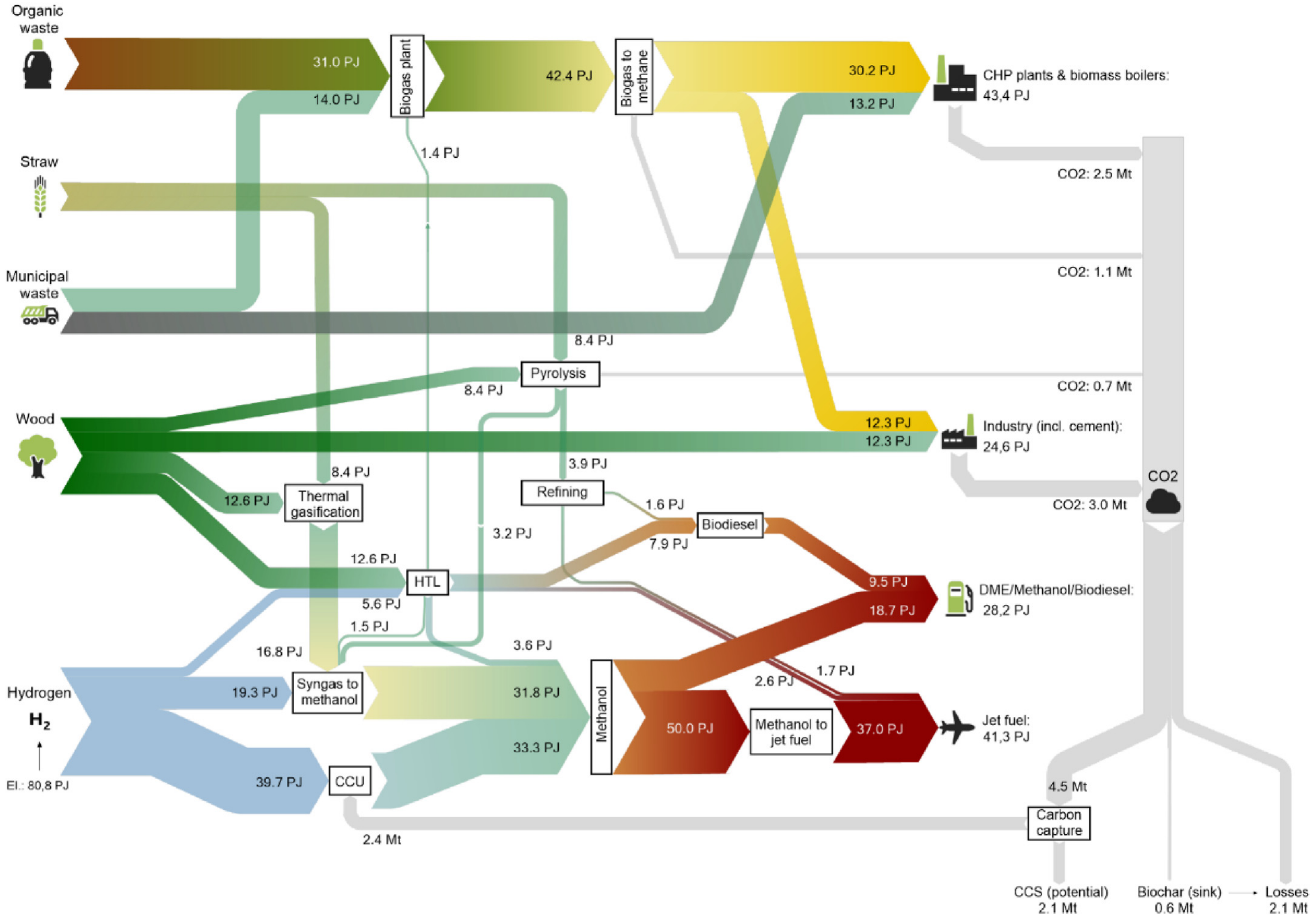

Fig. 4. Overview of the use of Biomass in IDA's Climate Response alternative scenario of Denmark year 2045 (117 PJ equal to 20 GJ/capita).

CRediT authorship contribution statement

Henrik Lund: Conceptualization, Methodology, Data curation, Writing – original draft, Writing – review & editing. **Iva Ridjan Skov:** Methodology, Visualization, Writing – original draft, Writing – review & editing. **Jakob Zinck Thellufsen:** Methodology, Data curation, Formal analysis, Methodology, Validation. **Peter Sorknæs:** Methodology, Data curation, Formal analysis, Methodology, Validation. **Andrei David Korberg:** Writing – review & editing. **Miguel Chang:** Visualization, Writing – review & editing. **Brian Vad Mathiesen:** Conceptualization, Methodology, Writing – review & editing. **Mikkel Strunge Kany:** Data curation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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