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REVIEW
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Bioenergy as climate change mitigation option within a 2 °C target—uncertainties and temporal challenges of bioenergy systems

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Abstract

Bioenergy is given an important role in reaching national and international climate change targets. However, uncertainties relating to emission reductions and the timeframe for these reductions are increasingly recognised as challenges whether bioenergy can deliver the required reductions. This paper discusses and highlights the challenges and the importance of the real greenhouse gas (GHG) reduction potential of bioenergy systems and its relevance for a global 450 ppm CO_2e stabilisation target in terms of uncertainties and temporal aspects. The authors aim to raise awareness and emphasise the need for dynamic and consequential approaches for the evaluation of climate change impacts of bioenergy systems to capture the complexity and challenges of their real emission reduction potential within a 2 °C target. This review does not present new research results. This paper shows the variety of challenges and complexity of the problem of achieving real GHG emission reductions from bioenergy systems. By reflecting on current evaluation methods of emissions and impacts from bioenergy systems, this review points out that a rethinking and going beyond static approaches is required, considering each bioenergy systems according to its own characteristics, context and feedbacks. With the development of knowledge and continuously changing systems, policies should be designed in a way that they provide a balance between flexibility to adapt to new information and planning security for investors. These will then allow considering if a bioenergy system will deliver the required emission saving in the appropriate timeframe or not.

Keywords: Bioenergy, Emission reductions, Cumulative emissions, Climate change, Uncertainties, Temporal aspects, 450 ppm CO_2e stabilisation target, 2 °C target

Review

Bioenergy is given an important role in reaching national and international climate change targets [1, 2]. Within the EU, it is considered that by 2020, 10 % of the EU's primary energy requirements could be supplied by biomass [3], significantly contributing to climate change mitigation. Bioenergy is linked to a number of challenges, such as real emission reduction, environmental impacts, sustainability, land use, food security, wider socio-economic impacts and financial incentives [1, 4]. Past research showed large variation in the emission intensity of various bioenergy systems [5–8]. Considering the urgency of climate change mitigation, the net climate impacts of bioenergy systems must be within set emission thresholds, delivering the necessary emission reduction within the given timeframe. Otherwise, it is questionable if bioenergy can be justified as a mitigation option.

This paper is focusing on the greenhouse gas (GHG) mitigation potential of bioenergy in terms of uncertainties regarding its real emission reduction potential within the necessary emission budget and timeframe. In order to stabilise global GHG emissions at a level consistent with avoiding "dangerous" climate change, it is imperative that bioenergy systems achieve minimum GHG saving thresholds without negatively affecting sustainability [4, 9]. Considering current global emission trends with continuously increasing GHG emissions, which are in line with the latest

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IPCC RCP8.5 scenario with a temperature increase range of 3.5–6.2 °C in 2100 [10, 11], staying below these minimum thresholds becomes more urgent. Bioenergy systems are related to uncertainties regarding their mitigation potential, which require special attention to investigate the potential options to handle these uncertainties [8, 12] and consider the available timeframe when emission reductions need to take place.

This paper discusses and highlights the challenge and importance of the real GHG reduction potential of bioenergy systems and its relevance for a 450 ppm CO_2e stabilisation target in terms of uncertainties and temporal aspects. By this, the authors aim to raise awareness and emphasise the need for dynamic and consequential approaches for the evaluation of climate change impacts of bioenergy systems to capture the complexity and challenges of their real emission reduction potential within a 2 °C target. The following sections will flag up some of the main challenges but make no claim to be complete. This paper also does not present new research results.

Cumulative emission framing

The concept of cumulative emissions describes the amount of long-lived GHG emissions released and accumulated in the atmosphere. The timeframe and lifespan of these emissions in the atmosphere matter, because this determines the total amount of emissions that can be released for staying within a specific climate change target. The more GHG emissions are released now and in the near future and do not peak in the short term, the more stringent the emission reductions have to be in the future to stay within the given budget [13]. The available budget therefore determines the timeframe of the extent when emission reductions are required (e.g. in short, medium and long-term).

Currently, global GHG emissions continue to rise at a high rate [14]. To date, around two thirds of the available carbon budget for staying below 2 °C global warming has already been used [14]. By failing to reduce emissions in short term, even higher emission reductions are required in the future to stabilise global GHG emissions at a level consistent with avoiding "dangerous" climate change (450 ppm CO_2e) [11].

This emphasises the importance and urgency of significant and real GHG emission reductions from the bioenergy sector. Considering current global emission pathways and the cumulative emission budget, uncertainties related to bioenergy systems and temporal aspects are two of the main challenges in achieving these required reductions within the necessary timeframe.

Challenges of the real GHG reduction potential of bioenergy system

Uncertainty is often defined as a lack of knowledge or limited knowledge about an existing state or future outcome. There are two types of uncertainty, both relevant to bioenergy systems: epistemic uncertainty, which is systematic uncertainty based on imprecise, unavailable or even unmeasurable knowledge and data [15]; and aleatoric uncertainty, which refers to statistical uncertainty describing variations in single values [15] and is therefore measurable. GHG emission-related uncertainties are usually categorised into four groups: natural variability, data uncertainty, knowledge uncertainty and model uncertainty [15]. *Natural variability* relates to uncertainties regarding external impacts on and internal process within environmental and climatic systems [15]. Additionally, it takes processes within the socio-economic system into account, such as the behaviour, choices and decisions by supply chain actors and direct and indirect stakeholders [15]. These factors and their societal and environmental outcomes are therefore hardly predictable. *Data uncertainty* is understood as the lacking knowledge of a single value. This is the result from natural processes being inherently different due to different source, location and time where and when data is collected [15, 16]. Additionally, limited accuracy of measurements is causing errors and variation in data [15, 16]. *Knowledge uncertainty* is based on lacking understanding of processes and interfaces between systems and consequently their outcomes [15, 16]. This can relate to the development and dynamics of physical, biological, ecological, social, economic and political systems and processes. Even though *model uncertainty* is often categorised as a part of knowledge uncertainty [15], it can have a significant impact on the understanding of the emission impact of bioenergy systems as it is determined by what methodology and how input data, parameters, sources, assumptions, definitions and methodologies are chosen and how results are interpreted [15, 17, 18].

In the case of bioenergy systems, the described categories of uncertainty cannot be simply grouped, as they span across the different types and sources of uncertainty. Apart from variations and errors in collected data, parameters and effects related to natural variation [19–23], lacking knowledge and understanding of processes and the availability of context specific, verified and independent data is a major challenge. Biomass production might be well understood and analysed for one location but not for another. Moreover, conditions within a system might change within or between seasons. This applies to various stages within and varies between bioenergy systems. For example, arable production systems with direct soil emissions in the form of nitrous oxide as a major climate change concern are sensitive to factors such as soil type and characteristics, weather conditions, yields or management practices [19–24], leading to significant uncertainties. In the case of perennial crops and forest systems, the main sources of uncertainty relate to carbon sequestration, soil carbon content, management practices and local climatic conditions. Additionally, timeframes when the carbon is sequestered and released play an important part in evaluating the real level of emissions [7, 8]. In the biomass processing stage aspects such as drying, GHG emissions during storage and handling losses are major sources of emission uncertainties [8, 25]. Large amounts of biomass used in the EU are imported [26]. Overseas and long-distance transport emissions vary significantly regarding vessel size, type and speed [27, 28]. The large variety of feedstock types, their quality, characteristics and properties as well as the different technologies through which the biomass is converted and then is used in different applications [4, 29, 30] adds to the overall uncertainty of the bioenergy system.

Additionally, emission uncertainties occur when modelling GHG balances due to the choices which can be made regarding input data, parameters, counterfactuals or chosen methodology such as defining scope, goal, system boundaries and allocation method of the investigated supply chain [17, 31–33]. Various recent assessments, in particular of forest-based bioenergy systems, have shown that the emission profiles can range widely depending on the methodological choice of the assessment and included factors. These factors were mainly related to aspects such as type and location of the forests, albedo changes after harvesting, level of climate intensity, harvest frequency, rotation length, conversion technology or type of systemic feedback and direct and indirect impacts [5–7, 34–36]. This and above named factors show the challenges related to natural variability, supply chain and activity characteristics, wider often indirect impacts and methodological choices. It shows that bioenergy systems are subject to significant uncertainties relating to the different type and source within the different supply chain stages from biomass production to combustion. To deal with the uncertainties related to GHG emissions from the bioenergy systems, it is therefore important to define the range and likelihood of the emission reduction potential. It is necessary to understand that every bioenergy supply chain has its own characteristics and should be analysed independently as different aspects of uncertainty occur within supply chains and different bioenergy options. While some sources of uncertainty can be measured and numerically evaluated, others such as behaviour, choices and decisions of supply chain actors as well as systemic feedback and indirect impacts are often impossible to quantify or not even to grasp appropriately. Nonetheless, with a better understanding of measurable uncertainties and an awareness of the potential range of the emission intensity of processes, behaviour and decisions can be guided and further reduce these uncertainties. Quantification and better understanding of uncertainties within bioenergy systems needs to happen on a case-by-case basis. This will improve decision-making regarding if a particular feedstock, production system, processing or conversion technology is a feasible emission reduction option and should therefore be utilised.

Challenges of the timeframe of GHG reduction within a carbon budget

Some bioenergy systems are related to time constraints when carbon is sequestered and released. Biomass is a hydrocarbon material and when that hydrocarbon is converted to simpler compounds (ultimately CO_2 and water), energy is released. There is usually a significant point source release of GHGs at the point of biomass conversion to energy, predominantly in the form of CO_2. This release has a global warming potential and affects the dynamics of the climate system in exactly the same way as a unit of CO_2 from fossil fuel combustion [34, 36, 37].

Biomass grows and accumulates carbon via photosynthesis and the carbon contained within the biomass plant has originally been sequestered from the atmosphere [37]. This means that there is a removal of a unit of CO_2 at a point in time. Then at a subsequent (later) point, that unit of CO_2 is returned to the atmosphere. In the case of annual crops, these sequestration and release events may be very closely spaced (months apart). The lifetime of CO_2 in this case is short and hardly contributes to any net long-term increase in GHG concentrations [38] unless there is a very significant imbalance, i.e. suddenly a much greater proportion of the photosynthetically stored carbon is being returned to the atmosphere than is being sequestered. This could happen for example if there was a fall in planting rates or an increase in the proportion of biomass which is degrading (e.g. if less land was being farmed or an existing market for forest products declined sharply). In case of forest-based biomass, the picture changes as at the point of harvest a large amount of CO_2 is released into the atmosphere and its sequestration takes a much longer time [5, 38].

In order to get a more accurate assessment, we must take into account the fact that release and sequestration are involved at different points in time. [5]. The issues associated with the timing of the CO_2 fluxes can be appreciated most clearly by considering some simplified examples:

1. Annual harvest of perennial crop, e.g. miscanthus—CO_2 is sequestered from the atmosphere during a 9-month growth period, then stored for typically 6 months before release
2. Harvest of short rotation coppice on a 3-year cycle—CO_2 is sequestered from atmosphere over a 3-year period with most sequestration correlating with the fastest growth period near the start, then

harvested and released at a point typically 6 months later

3. Removal of forest residues—CO_2 is sequestered from atmosphere over several decades with greater accumulation near the start, but with small sequestration steps over a long period of time. Sequestration then stops when a tree is felled and the carbon in the roundwood is locked up in solid wood products for commercial purposes, but some carbon is released when residues, such as tree tops and branches, are used within 6 months for energy and some when post-consumption wood waste is used for energy purposes [39].

It is readily apparent that the carbon flux and therefore the climate change impacts for each of these systems have to be considered over very different periods of time [5]. Recent research has shown that the assumption of carbon neutrality is not given in forest-based bioenergy systems due to the decay time of CO_2 in the atmosphere [5], direct and indirect impacts, alterations in plant growth for bioenergy and systemic feedbacks [34, 36, 38]. These different aspects play an important role in the evaluation of the real emission profile of bioenergy as alteration can lead to significant variations in the results [5, 6, 34, 36, 38, 40–42].

It can be presumed that biomass continues to grow and is harvested more than once across all three examples, which will have an impact on the long-term emission profile of each system. Hence, at a specific point in time, emissions are released when biomass is used for energy. This will increase the amount of atmospheric CO_2 at this particular point in time and this amount will then have a specific decay time in the atmosphere [5] as well as will be to some extent sequestered by re-growing biomass.

The objective of many climate change policies is to address a rise in atmospheric concentration of anthropogenic GHGs that has occurred since the start of the industrial revolution and is usually framed as avoiding release of carbon that has been "locked" up for a long time in the terrestrial sphere. Clearly, systems 1 and 2 above do not impact negatively upon that objective but provide energy and so could be viewed positively. System 3 is more challenging to assess, as the timeframe in which sequestration has occurred is longer and it does involve re-release of carbon that was sequestered a long time ago and would have been used for other things or could have stayed in place often for several years, with a much slower carbon release (e.g. through decomposition), if not used for bioenergy provision [7, 39, 43, 44]. If the activity was solely releasing carbon, this would be unsustainable; but where there is simultaneous forest regeneration, it is possible to argue that there is re-sequestration within a relevant timeframe [7, 38]. The assessment then depends on what would have happened if the feedstocks were not used for energy—an assessment that cannot be based purely on the science of climate change or bioenergy systems but requires a holistic approach and considering wider impacts.

If the utilisation of biomass for energy leads to a long-term, net increase in the atmospheric concentration of CO_2, then that will exacerbate climate change impacts and should not be encouraged. However, in order to determine whether that actually is the case, it is necessary to look beyond the point in time when the combustion products are released to the atmosphere and assess the net and long-term change.

Recent research has presented large ranges of results regarding the long-term emission profile of forest-based biomass. While some studies see a long-term reduction potential [5, 34], others show that if wider impacts, e.g. continuously increasing biomass demand for energy, changes in forest and harvesting management and increasing climate change impacts lead to a significant increase in emissions even over a long-term time horizon [6, 35, 45].

To date, life cycle assessment (LCA) and similar approaches have focused on assessing the net emissions to atmosphere, i.e. subtracting the sequestered CO_2 from the released CO_2 in order to evaluate the net emissions over a period of time. LCA focuses on process and system analysis and so commonly examines the timeframe of construction, operation and decommissioning of a process plant, with individual changes within this period assumed to offset each other. Nevertheless, utilising biomass for energy is much more complex than releasing CO_2 through energy conversion processes. There exist many interdependencies between the natural system as such but also socio-ecological factors, like land use, flows of biomass within and between the nature and human society and wider ecosystem services, which lead to not necessarily equal changes between atmospheric and sequestered carbon [34].

Discussion

As described above, the evaluation of life cycle emissions has various sources of uncertainties and very often the focus lies on generating a single value compared to an acceptable emission level. Even though standardised emissions evaluation methods exist, the scope and boundary of the system is based on assumptions and can therefore change from case to case and does not guarantee harmonised and comparable results even for the same bioenergy system. Single values in the best case can describe a trend of environmental impacts of a bioenergy system but need to be considered and understood within the given context. There are variations in values along bioenergy supply chains and up-to-date emission evaluations and system assumptions are often based on best estimates, global or regional averages or theoretical values. These values are not necessarily specific in time, space and scale. This lack of data is often a huge challenge if not a barrier in many emissions models and calculations. What is required for future analysis is to identify these specific knowledge gaps and the most significant uncertainties in systems and to do the actual analytical and experimental work to generate the knowledge and real and context-relevant data.

Recent research around assessing carbon release and sequestration of forestry-based biomass shows how limited our knowledge and ability to fully and correctly assess bioenergy systems is regarding natural processes, feedbacks, supply chain practices and socio-economic frameworks as well as wider direct and indirect impacts.

Current emission evaluation methods, and with this policy instruments, do not focus on the possible emission range and the system-specific context of a bioenergy. While carbon models consider the stock of terrestrial carbon and its possible transfer to the atmosphere, emission assessment methods like LCA cannot appropriately include this. Often, generic factors are used [6, 38, 42], partly because methods focused on emissions are perceived as an easier way to measure, report and control transfer rates of terrestrial to atmospheric carbon.

In order to incentivise change, the IPCC targets are framed as a reduction to emission levels compared to 1990 values. Applying this current emission and policy framings to bioenergy systems becomes even more challenging as the considered timeframe of carbon sequestration and release might not be coherent with the actual timeframe of the required biomass growth. For example, for forestry-based bioenergy systems, the sequestration can have taken place before the set timeframes. It could be argued that it is unsustainable to re-release any carbon that has been sequestered prior to 1990, but that release of carbon sequestered since then is acceptable; or at least that the amount of carbon sequestered before 1990 and released after should be sequestered again, to maintain the total standing timber and therefore sequestered carbon level of 1990.

The logic of cumulative emissions is based around the idea that there is a tolerable atmospheric concentration of GHGs and efforts must be made to stay within that. Considering the uncertainties and the actual timeframe of when emissions are released and the fact that the available emissions budget for a 2 °C target is rapidly shrinking makes it very urgent that we (a) understand the sources of emission uncertainties and (b) consider at what point of time what emissions are released or sequestered.

The fact that we have already used up two thirds of our emission budget means that it does matter when a unit of carbon is emitted or sequestered. Near-term carbon reductions are “worth more” than long-term ones because they mean we will not ultimately have to cut as sharply as we approach 2050 target points [13]. Within the remaining timeframe, renewable energy systems, e.g. forest-based systems, where carbon sequestration takes place first, while this carbon is then release later when the energy is provided could actually support emission targets more likely than technologies or systems where emissions take place first and energy is generated later.

There also may be cases where we cannot afford to wait for the net benefit to be achieved that is associated with the balance of sequestration and emission release within the timeframe of a bioenergy system. Once the GHGs are resident in the atmosphere sufficiently long, they will have had an irreversible impact on the climate. This would also increase the uncertainties regarding supply chain emissions and sequestration options due to stronger climate change impacts and climate intensity. It would also add to the uncertainties related to the timeframe when emission benefits actually will be achieved and therefore affecting the overall emission budget.

Recent research has shown that a growing forest-based biomass utilisation can lead to net short- and long-term emission increases [6, 45]. This emphasises the urgency of the need for a better understanding of systemic feedbacks and system interdependencies as well as harmonised assessment methods considering these.

Conclusions

Bioenergy must deliver the necessary emission reductions to support the 2 °C target. For this, we need to establish an understanding and knowledge about the actual amount and time of emission releases and sequestrations. This requires the generation of actual emission data from bioenergy systems within the specific context, time, location and scale. It is important that we rethink current evaluation methods, go beyond static approaches and consider each bioenergy system according to its own characteristics, context and feedbacks. Additionally, we need to understand the sequestration and emission dynamics as well as emission ranges of these bioenergy systems alongside the tolerable atmospheric burden as these will support decisions on choosing bioenergy options that deliver the required emission thresholds.

To make the right decisions and set appropriate incentives, decision-makers in the commercial sector and policy require reliable scientific-based information. This paper shows the variety of challenges and complexity of the problem of achieving real GHG emission reductions from bioenergy systems. National and international policies can set emission thresholds related to the cumulative emission budget and define overall sustainability standards. Local policy and business decisions should then address more case- and context-specific aspects to maximise the mitigation and sustainability potential of specific bioenergy systems along the full supply chain. As knowledge permanently develops and systems continue to change, policies should be designed in a way that they provide a balance between flexibility to adapt to new information and planning security for investors [12]. These will then allow considering if a bioenergy system will deliver the required emission saving in the appropriate timeframe and if biomass should be at all harvested now or in the near future if we need to stay within the available emission budget.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

MR and PT wrote and edited the manuscript in collaboration, led by MR. The intellectual contributions are based on experiences and findings from their past and ongoing research projects. Both authors read and approved the final manuscript.

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