IEA Bioenergy
Technology Collaboration Programme

Roles of bioenergy in energy system pathways towards a “well-below-2-degrees-Celsius (WB2)” world

Workshop report and synthesis of presented studies

IEA Bioenergy: ExCo

July 2020

Roles of bioenergy in energy system pathways towards a "well-below-2-degrees-Celsius (WB2)" world

Workshop report and synthesis of presented studies

A Strategic Inter-Task Study carried out with cooperation between IEA Bioenergy Tasks 40, 43, 44 and 45

Edited by Daniela Thrän, Annette L. Cowie and Göran Berndes

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Executive Summary

The central aim of the Paris Agreement is to strengthen the global response to the threat of climate change by limiting a global temperature rise this century to well below 2 degrees Celsius (WB2) above pre-industrial levels, and to pursue efforts to limit the temperature increase to 1.5°C (UNFCCC 2015). Many scenarios that limit global warming to well below 2 (or 1.5) degrees Celsius (WB2 world) include a significant and increasing contribution of biomass-based energy supply (bioenergy), often in combination with carbon capture and storage (CCS) to remove CO_2 from the atmosphere and store it underground in depleted oil and gas fields or deep saline aquifers (Bioenergy with CCS, BECCS). Scenarios may also include other options for CO_2 removal (CDR) such as afforestation/reforestation for in-forest carbon storage and direct air capture of CO_2. In the absence of CDR, WB2 scenarios may include more bioenergy since larger fossil fuel emissions reductions will then be needed to limit the temperature increase.

Achieving the level of bioenergy and BECCS deployment found in many global WB2 scenarios will require a large increase in the biomass supply for energy and also establishment of CCS infrastructure to enable BECCS. However, most countries and regions have not investigated potential BECCS pathways in detail. This may be considered a reflection of inadequate ambition, but it also reflects the difficulties of transposing global agreements into national or regional strategies, policies and regulations. In addition, there are concerns that large scale deployment of bioenergy and BECCS for reaching the WB2 target is difficult to reconcile with the achievement of the sustainable development goals (SDGs).

Under the IEA Bioenergy Inter-task project *The Role of Bioenergy in a WB2/SDG world*, a workshop was held in Berlin, on 25th November 2019. The objective of the workshop was to examine, synthesize and disseminate information from recent studies that investigate how bioenergy and associated technologies may contribute to achieving the reductions in greenhouse gas (GHG) emissions that are needed to meet the WB2 target. This report summarises the workshop contributions and discussions, assesses the role of bioenergy in WB2 strategies, identifies the current state of knowledge as well as gaps in knowledge that need to be addressed.

Studies come to widely different conclusions concerning the future bioenergy supply potential, due to using different methods and data when estimating the size and availability of biomass resources. It is not possible to specify the future bioenergy supply potential to a narrow range due to inherent uncertainties concerning critical factors, including priorities among a multitude of societal objectives. But studies employing improved databases and modelling capacity have over time improved the understanding of how various factors influence the supply potential, e.g., future diets, crop yields, cropping intensity and land use efficiency in meat and dairy production, and land reservation for nature conservation. They have also shown that both positive and negative effects may follow from increased biomass use for energy. We propose that 100-250 EJ/a can be used as a first approximation concerning the global bioenergy potential in the 2050-2100 time frame, while acknowledging that studies also report smaller and larger supply potentials.

Bioenergy provision is embedded in national and regional energy systems, industrial infrastructure, land uses and value chains, but also energy system transformation strategies towards WB2. Countries differ concerning biophysical conditions for bioenergy and other energy sources, geological CO_2 storage capacity, gas and electricity grids, public transport infrastructure, etc. The attractiveness of different bioenergy options therefore differs between countries and bioenergy strategies should not be prescribed at global/continental level, but rather developed within each country, reflecting the local context.

Integrated Assessment Models (IAMs) are used to analyse and assess complex interactions between human and natural systems. They can provide important insights about the role of biomass and bioenergy within the broader energy, economy, and land use systems, including the role of BECCS vis-à-vis other CDR options. They support exploration and learning about our "solution space" assessing the effects and uncertainties of several technical, socio-economic and policy developments. IAMs make significant simplifications concerning the systems they represent. This simplification causes certain ambiguities concerning input parameters, elasticities, and system boundaries, which can make interpretation and communication of results, and development of insights difficult. Moreover, sustainability criteria are applied in different ways, between the various IAMs, and the broader SDG trade-offs are not yet explored at depth in IAM modelling.

Looking forward, several steps are foreseen that will help inform deployment of bioenergy and BECCS to support energy system transitions towards a WB2 world.

1. Decisions concerning development of biomass resources and bioenergy systems are determined by the global as well as national and regional context. Therefore, analyses using models with different geographic scope and spatial resolution, ranging from global IAMs to more fine grained models (covering individual countries/regions and/or individual sectors or technologies), are needed. Non-OECD countries need to be better represented in national and regional models.
2. As BECCS and other CDR options commonly play important roles in WB2 pathways, it is warranted to intensify investigation and implementation of CDR in the near term. Early action also helps to identify potential barriers that prevent or slow down implementation of different CDR options. While there will be competition for funding between CDR options, based on respective cost of removing CO_2 from the atmosphere, some CDR options also interact in synergistic ways. For example, land may be used to produce biomass for BECCS or for in-forest carbon storage, or both.
3. Integrated land use planning, applied at the landscape scale, can identify options for deployment of bioenergy and BECCS in ways that support achievement of multiple SDGs. For example, rehabilitation of degraded through establishment of energy crops can contribute to land degradation neutrality goals (SDG15.3). Strategic integration of short-rotation woody crops can enhance agricultural production by providing windbreaks, hosting beneficial insects and lowering saline watertables. Realisation of these opportunities requires cooperative planning involving a broad range of stakeholders, including landholders, agribusiness and technical experts. It relies on recognition of the potential for integrated policies to deliver multiple benefits through well-designed interventions on the land, supported by effective coordination between local and national governments, and across ministries.
4. Finally, governance is critical to avoid or mitigate adverse side-effects and to promote synergies among important objectives, not the least associated with biomass supply systems. The scope and quality of governance influences biomass availability as well as demand for bioenergy. Policies can also (e.g., through sustainability requirements) influence how the bioenergy systems that satisfy the demand affect other land uses and the environment.

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We gratefully acknowledge the contributions of all workshop participants who provided valuable inputs in the workshop sessions and participated collegially in the group discussions.

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List of Abbreviations

AFOLU	Agriculture, Forestry and Other Land Use
BECCS	Bioenergy with Carbon Capture and Storage
BEV	Battery Electric Vehicles
CCU	Carbon Capture and Utilization
CDR	Carbon Dioxide Removal
CHP	Combined Heat and Power
CSP	Concentrated Solar Power
DAC	Direct Air Capture
EoL	End of Life
FJF	Fossil Jet Fuels
GBEP	Global Bioenergy Partnership
GHG	Greenhouse Gas
GIS	Geographical Information System
GTP	Global Temperature Change Potential
GWP	Global Warming Potential
IAM	Integrated Assessment Model
IGCC	Integrated Gasification Combined Cycle
IPCC	Intergovernmental Panel on Climate Change
IVEV	Internal Combustion Engine Vehicles
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
MCA	Multi Criteria Analysis
MEA	Monoethanolamine
NDC	Nationally Determined Contributions
NTCF	Near-term Climate Forcers
RJF	Renewable Jet Fuels
SDG	Sustainable Development Goal
VRE	Variable Renewable Energy Resources
WB2	Well Below 2°C

1 Background

Helen Kollai, Uwe Fritsche, Daniela Thrän

The Paris Agreement central aim is to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius (WB2) above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5°C (UNFCCC 2015). This is related to limited carbon budgets and strong reduction needs of in the energy system (Friedlingstein et al. 2019). Many scenarios that meet the target of limiting global warming to WB2 include a significant – and increasing – contribution of biomass-based energy supply (bioenergy). At the same time, there is disagreement about the role of bioenergy for reaching the WB2 target and studies differ significantly concerning the potential and usage of biomass at global as well as regional levels. On the one hand, bioenergy implementation is associated with trade-offs and challenges. On the other hand, bioenergy has advantages in terms of technological readiness (esp. in the transport sector), storability and flexibility[1]. Bioenergy may in the future be combined with carbon capture and storage (CCS) to remove CO_2 from the atmosphere and store it underground in depleted oil and gas fields or deep saline aquifer formations (see, e.g., Creutzig et al. 2019, Noothout et al. 2019, POST 2020 and for bioenergy with biochar: Schmidt et al. 2019).

Furthermore, bioenergy can support progress on several of the Sustainable Development Goals (SDGs) (Fritsche 2018, Iriarte & Fritsche 2019, Fritsche & Rösch 2020, Junginger et al. 2019), and bioenergy implementation strategies differ depending on context conditions and prioritization among SDGs. It is clear that climate and energy policies incentivizing bioenergy should not be developed in "sectoral silos", but must seek synergies with other societal goals. The ramping-up of bioenergy supply capacities needs to be based on a holistic perspective that recognizes a multitude of societal objectives, including climate change mitigation and environmental protection, energy security and human wellbeing for which the SDGs are an appropriate framing (Pelkmans et al. 2019).

An Inter-task project involving IEA Bioenergy Tasks 40, 43, 44 and 45[2] is assessing the role of bioenergy in WB2/SDG scenarios, with the objective to identify and disseminate strategies for bioenergy implementation that contribute positively to societal transition towards the WB2 target, while simultaneously contributing to other SDG objectives. This also requires methods to address trade-offs and concerns about possible negative impacts of bioenergy expansion, with a focus on mitigating these challenges and identifying opportunities for synergies between bioenergy deployment and SDG implementation.

As part of the Inter-task project, IEA Bioenergy launched an initiative to engage experts in the assessment of bioenergy's possible roles in WB2/SDG scenarios. A workshop held in Berlin, Germany on 25th November 2019 aimed to examine, synthesize and distribute information from recent studies that investigate how bioenergy and associated technologies may contribute to achieving the reductions in greenhouse gas (GHG) emissions that are needed to meet the WB2 target. A broad range of studies were presented and discussed at the workshop (see program in Figure 1). Some studies were specific to a region or nation, and others of global scope; some focused on one individual sector while others covered several energy sectors. They are summarised in Chapter 7.

1 See IEA Bioenergy Task 44 "Flexible bioenergy and system integration": https://www.task44.ieabioenergy.com

2 These IEA Bioenergy tasks gather experts on topics surrounding bioenergy regarding deployment (Task 40), resource potential and supply chains (43), flexibility and systems integration (44) as well as bioenergy sustainability (45).

IEA Bioenergy

IEA Bioenergy Workshop 25 Nov 2019, Berlin (GER)

ROLES OF BIOENERGY TECHNOLOGIES IN ENERGY SYSTEM PATHWAYS TOWARDS A WB2/SDG WORLD

Final workshop program

8:15 - 9:00	Registration	
Introduction	**Inputs**	
9:00 - 9:15	Volker Niendieker (BMEL)	Welcome from the German Federal Ministry of Food and Agriculture
9:15 - 9:30	Norbert Gorißen (BMU)	German Federal Ministry for Environment views on climate change mitigation & the role of bioenergy
9:30 - 9:45	Cowie, Thrän, Berndes	Scope of the workshop
9:45 - 10:15	Vassilis Daioglou	Sensitivities and uncertainties of bioenergy strategies in a WB2 world: Integrated Assessment Models perspective
10:15 - 10:45	Felix Creutzig & Filip Johnsson	Can we stay well below 2 degree warming without relying on biomass based options? A Dialogue
10:45 - 11:00	*Tea/coffee break*	
Megaregions	**Inputs**	
11:00 - 11:15	Joana Portugal	Bioenergy in pathways towards a WB2 future in Latin America
11:15 - 11:30	Matthew Langholtz	Economic accessibility of bioenergy with carbon capture and sequestration (BECCS) in the US
11:30 - 11:45	Fabian Schipfer	Sustainable and optimal use of biomass for energy in the EU beyond 2020
11:45 - 12:00	Sylvain Leduc	Optimal biomass use for energy and transport in Europe
12:00 - 12:30	Uwe Fritsche (moderator)	Plenary discussion with previous speakers
12:30 - 13:30	*Lunch break*	
Country level	**Inputs**	**National Bioenergy Plans and Studies**
13:30 - 13:45	Mariliis Lehtveer	Regions in Europe
13:45 - 14:00	Adam Brown	United Kingdom
14:00 - 14:15	Tomi Lindroos	Finland
14:15 - 14:30	Markus Millinger	Germany
14:30 - 14:45	Bintang Yuwono	Indonesia
14:45 - 15:00	Daniela Thrän (moderator)	Plenary discussion with previous speakers
15:00–15:30	*Tea/coffee break*	
Synthesis	**Workshop session**	**Group discussions on synthesis report & dissemination activities**
15:30 - 16:45	all	Discussion in four parallel groups
16:45 - 17:00	Cowie, Thrän, Berndes	Summary and conclusions
17:00		Farewell

Figure 1: Program of the workshop on 25th November 2019 in Berlin.

The aim of this report is to analyse the studies' common and contrasting features (Chapter 2) and embed the synthesized findings in the larger framework of implementation strategies of different bioenergy pathways in future scenarios (Chapter 3). Furthermore, potentials and challenges of integrated assessment models (IAM) are discussed (Chapter 4) and key qualities for a successful translation of modelling results into practice are determined (Chapter 5). Conclusions are drawn regarding the potential and limitations of bioenergy in a WB2 world within the context of SDGs and with respect to the needs for further development of assessment methods and measures (Chapter 6).

This report **summarizes the status** of the role of bioenergy in WB2 strategies, identifies a current knowledge base and recognizes, where gaps in knowledge and in the strategies may lead to delays in implementation. The report informs stakeholders – including governments, scientific community, industry, land owners and other decision-makers engaging in relevant areas – about the scientific basis for the discussions but also barriers which need to be reduced, to unlock the potential of bioenergy to contribute to fulfilment of the Paris Agreement goal.

Within the WB2/SDG Inter-task project, the status of SDG implementation and respective links to sustainability governance of bioenergy (and the broader bioeconomy) is researched, and IEA Bioenergy Task 45 collaborates with GBEP[3] and the Biofuture Platform[4] to identify prospects of sustainability governance on national and international levels. This will help to shape future activities as indicated in Chapter 6.

2 Summary of the workshop

Malgorzata Borchers, Francesco Cherubini, Annette Cowie, Gustaf Egnell, Lorie Hamelin, Zoe Harris, Helen Kollai, Concetta Lodato, Mirjam Röder, Daniela Thrän

On 25th November 2019 an audience of 44 experts and stakeholders met at the German Federal Ministry of Food and Agriculture (BMEL) in Berlin to contextualize recent bioenergy studies and identify different bioenergy strategies with regard to the WB2 target. The workshop was opened with welcome talks from Volker Niendieker (BMEL) and Norbert Gorißen from German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) with remarks on the role of bioenergy for climate mitigation in Germany.

Twelve of the studies submitted to the workshop were presented in one of three input sessions. The presentations can be found in the supplement of this report. Other studies that were submitted to the workshop but were not selected for presentation are also part of the study descriptions in Chapter 7. Table 1 gives a comparison of some main characteristics. The analysis combines medium- and long-term perspectives, considering diverse technical, economic, regulatory and policy aspects that influence the transition process of energy systems.

The various contributions were discussed in plenary then in four parallel discussion groups, in a synthesis session. The central topics of discussion were:

- common and contrasting features of the different development pathways;
- possible reasons behind differences between countries and regions;
- points of alignment and divergence among the participants, and
- issues for further investigation.

The summarized results of the four discussions groups are presented in the following subsections.

3 Global Bioenergy Partnership: http://www.globalbioenergy.org

4 http://www.biofutureplatform.org/

Table 1: Overview of study characteristics

Study	Geographical scope			GHG target addressed			Spatially explicit information (Y/N)	Consideration of LUC (Y/N)	Costs assessed (Y/N)	Social aspects included (Y/N)
	global	megaregion	national	WB2	95-100% RE supply	GHG gernerally addressed				
Brown (2019)			✗ UK			✗	Y	Y	Y	Y
Cavalett (2018)	✗		(✗) Norway			✗	Y	Y	N	Y
Collet (2019)			✗ France	✗			N	N		N
Diaoglou (2019)	✗	✗		✗			Y	Y	Y	Y
George (2012)			✗ NSW Australia			✗	Y	Y	N	N
Hoefnagels (2018)		✗ EU		✗			Y	Y	N	N
Kang (2019)		✗ Southern Africa				✗	Y	Y	Y	N
Langholtz (2019)			✗ US	✗			Y	Y	Y	N
Leduc (2018)		✗ EU				✗	Y	N	Y	N
Lehtveer (2020)		✗ EU27		✗			Y	N	Y	
Lindroos (2020)		(✗)	✗ Finland					N	Y	N
Millinger (2019)			✗ Germany			✗	N	Y	Y	N
Portugal-Peireira (2019)			✗ Brazil	✗			Y	Y		N
Röder (2018)		(✗)	✗ UK	✗			N	Y	N	Y
Schipfer (2017)		✗ EU28	(✗)		✗	✗	N	Y	Y	Y
Souza (2019)		✗ Latin Am. + Africa				✗	N	Y	Y	N
Yuwono (2019)			✗ Indonesia	✗			N	Y	N	N

Table 1: Overview of study characteristics (continued)

Study	Biomass potential in 2050	Bioenergy potential in 2050 (Biomass conversion)		Bioenergy supply in 2050 (% of overall energy supply) - if not applicable, sectors assessed	BECCS addressed
	Absolute value from study (EJ/yr)	Absolute value from study (EJ/yr)	Per capita value derived by calculation* (GJ/cap*yr)		(Y/N)
Brown (2019)	2032: 1.1	2032: 0.9	2032: 12	2032: 16%	Y
Cavalett (2018)				aviation	N
Collet (2019)				heat & power	Y
Diaoglou (2019)	(primary biomass potential) Baseline scenarios: 132 - 140 Mitigation scenario: 128 - 193	(primary biomass production) Baseline: 64 - 74 Mitigation: 114 - 174	Baseline: 6.6 - 7.6[1] Mitigation: 11.7 - 17.9[1]	Baseline: 8-9% Mitigation: 26-35%	Y
George (2012)				heat & power	N
Hoefnagels (2018)	EU domestic biomass supply potential: 8.2 - 25 (195 - 597 Mtoe)			heat, power & transport	N
Kang (2019)		potential 2030: 0.21 – 0.57 (el), 0.01-2.7 (ethanol)	potential 2030: 0.8 – 2.2[2] (el), 0.04-10.6 (ethanol)	power & transport	N
Langholtz (2019)				power	Y
Leduc (2018)				heat, power & transport	N
Lehtveer (2020)				power	Y
Lindroos (2020)				heat & power	N
Millinger (2019)		domestic bioenergy potential: 1.2 - 1.9	domestic bioenergy potential: 15.7 - 25.5[3]	heat, power & transport	N
Portugal-Peireira (2019)				transport	Y
Röder (2018)				heat, power & transport	Y
Schipfer (2017)	EU domestic biomass supply potential 2030: 14.2 - 16,4 (338 - 391 Mtoe)	EU domestic bioenergy potential 2030: 5.1 - 6.6 (123 - 159 Mtoe)	EU domestic biomass supply potential 2030: 9.9 - 12.8[4]	baseline 2030: 11 - 14,8%	N
Souza (2019)				transport	N
Yuwono (2019)				heat, power & transport	Y

*Estimated population in 2030/2050 (World Bank 2019): [1] 9.7 billion (World) [2] 2030: 254.3 million (SZ, MW, MZ, ZA, TZ, ZM, ZW) [3] 76.5 million (DE) [4] 2030: 513.8 million (EU)

2.1 DISCUSSION GROUP 1

The scientific community departs from polarized opinions and a "one size fits all" rhetoric but agrees that the framing of society, climate and land needs a holistic view on bioenergy pathways. The group noted that sustainability is still considered to be underrepresented in bioenergy reflections.

It is common sense that the different bioenergy development pathways are important for multiple sectors. But views on whether it serves for a transitional phase or is a key long-term solution differ considerably between the sectors, and also regions. Inherent differences in society and local context, e.g. climate and land availability, lead to site specific relevance of the various bioenergy implementations. This was also shown in the presented studies. It is of particular relevance to be clear in communication of these boundary conditions when assessing different bioenergy strategies.

The inputs indicate that advanced bioenergy technologies have not found their way into the majority of studies and should thus be subject of further work.

2.2 DISCUSSION GROUP 2

As overall biomass consumption rises, the focus in bioenergy implementations has shifted from first generation biomass (edible biomass) to transformations of cellulose-based, nonedible biomass and residues. Attention is placed on new technologies. Flexibility and integration into broader technology suits sets bioenergy as a feasible solution to handle intermittency of other renewables.

The potential to decarbonize the sectors is diverse. Sectors like shipping are comparatively harder to decarbonize. From the presentations we learned that a lack of models and assessments covering the whole bioenergy life cycle is apparent. In national-level studies imported biomass is not explored much. The studies are based on diverse local conditions (e.g. energy demand, land use restrictions, feedstocks) and different questions that drive the models. The experts point out that a holistic understanding of cultural differences, political desires and the various underlying sustainability criteria is important for the interpretation and comparison of bioenergy strategies.

The group emphasised that despite different scales and aggregation of data the presented studies indicated the necessity for further collaboration to fill knowledge gaps. The potential of connecting high resolution approaches (e.g. LCA) and integrated assessment models (IAM) is mentioned and identified as a field for further work, as well as combining these approaches with empirical data collection, and ground-truthing to further root modelled approaches within 'reality'. Furthermore, biocascading and design of end of life (EoL) use are highlighted as subjects for deeper investigation.

2.3 DISCUSSION GROUP 3

The Paris Agreement aim of keeping the global temperature below 2°C above pre-industrial level with an effort of further limit to 1.5°C has been considered and investigated in many studies. Academics understand that results differ when the target is 2°C compared to 1.5°C (e.g. the presentation by Bintang Budi Yuwono). Non-academics are not aware of these relevant differences in results. Thus, the scientific community need different approaches to communicate the consequences for example in terms of emissions.

An aspect to be considered, which drives an energy system pathway is the availability of resources and their nature. This is country and region specific. Relevant is the availability of resources in the countries and a sustainable research of the potential to meet energy demand from renewable energy resources. There are many different biomass feedstocks, with high but also individual potential. There is also the need for investigation of economic feasibility of different pathways.

Research on bioenergy technologies is encouraged. Assumptions behind technologies impact scientific results. The latter are sensitive to assumptions, such as techno-economic parameters. Many questions concern the scientific community such as: What are the next steps the scientific community as well as the policy makers should take to enable the leap towards successful implementation of strategies? One central point mentioned is the great importance of communication, particularly across different stakeholder groups.

2.4 DISCUSSION GROUP 4

As in the other discussions the group took note of a variety of distinct features of the different bioenergy pathway modelling approaches. Even though the supply side seems to be less uncertain than the demand side, the resource estimates vary a lot. The question what a robust estimate actually is was raised.

The group found the explicit linkages between the SDGs and modelling approaches unclear and identified a lack of reflection of large regional differences in the global models. Current trends in energy markets are often not integrated. The different framing conditions (e.g. development stage of a country, lobbying of large businesses, variances of supply and demand and infrastructures) are reflected in distinct modelling approaches and outcomes. Yet, the studies make only few statements about how exactly the objectives are to be achieved.

In accordance with the remarks of the other discussion groups the significance of science to policy bridging was underlined. A resource base review focusing on identifying reasons behind the large differences between resource estimates was proposed. As an underrepresentation of bodies outside the OECD was perceived by the experts, intensified outreach activity was suggested.

2.5 CONCLUSION

Drawing on the results of the group discussion 1-4 the workshop highlighted that within the scientific community different understandings of bioenergy pathways are apparent and in particular the diversity of national and local boundary conditions is integrated into the models in different ways. The scientists' views are influenced by different experiences and the use of different methods. As can be seen from the various studies, there are many facets to the role of bioenergy technologies in energy pathways. Immediate actions to long-term solutions are investigated, to strive for the WB2 target. For a consistent interpretation of the study results and their transfer into conclusive strategies and policies a harmonized language is important. There was a clear statement from the audience that to implement the potential of bioenergy technologies will require also drafting simple messages and recommendations that can easily be formulated into policies.

The contributions showed that especially the estimations of resource potentials are based on a variety of concepts and drivers. Moreover, different sustainability criteria are applied, and the broader SDG tradeoffs are yet missing in most of the modelling. Data availability on influencing variables is heterogeneous. The potential of advanced technologies and BECCS is observed by several studies, but is still identified as a field needing further research. These key perceptions brought up by the workshop participants in the discussion rounds set the foundation for the contextualization of the various inputs in the following chapters.

3 Role of bioenergy in global and national studies

Daniela Thrän, Göran Berndes, Malgorzata Borchers, Alena Hahn, Markus Millinger

Bioenergy is commonly an important leverage factor in scenarios consistent with long-term climate goals. All scenarios that were included in the IPCC 1.5 report (IPCC SR1.5 2018) and that limited equilibrium warming to 1.5°C (with no or limited overshoot), were found to use carbon dioxide removal (CDR) from the atmosphere. These scenarios commonly rely on BECCS, and/or afforestation/reforestation (A/R), which were the two CDR methods most often included in the Integrated Assessment Models (IAMs) used for the scenario modelling. BECCS often occurs after 2050 for mitigating earlier emissions, whereas A/R occurs also pre-2050 for concurrent mitigation (IPCC SR1.5 2018). Biomass use for energy use was substantial, ranging from 40 to 312 EJ in 2050 (IPCC SR1.5 2018). The IPCC Special Report on climate change and land (IPCC 2019) found that far-reaching land use changes were common in scenarios limiting warming to 1.5 or 2°C. Changes of global forest area ranged from about –0.2 to +7.2 Mkm^2 between 2010 and 2100, and land demand for bioenergy crops ranged from about 3.2 to 6.6 Mkm^2 in 2100 (Shukla et.al. 2019).

Thanks to its versatility as an energy carrier, biomass can cater to different needs in terms of sectoral allocation and GHG emission abatement. In scenarios with strongly limited biomass resources, IAMs direct biomass towards BECCS technologies with high capture rates such as bioelectricity combined with CCS. In contrast, with greater levels of biomass availability, bioenergy is to a large extent used instead of fossil fuels in the transport sector. If BECCS is assumed to not be available, more biomass may be required since more fossil fuels need to be replaced in order to limit warming to 1.5°C. While CDR appears to be necessary for staying well below 2°C – and even more so for staying below 1.5°C – it should not be used as an argument for postponing near-term mitigation actions.

3.1 ESTIMATES OF BIOMASS SUPPLY POTENTIALS

A central question is how much biomass can be made available for bioenergy and BECCS. This question can be answered in different ways and as shown in Table 2 estimates of biomass supply potentials vary widely. One reason is that studies refer to different types of potentials. Some studies estimate biomass supply as limited only by biophysical conditions, often referred to as a *theoretical potential*. Such potentials represent ultimate limits rather than achievable levels of biomass supply. Estimates of *technical potentials* consider different types of limitations such as agronomic and other factors limiting yield levels, competing biomass demand for food and other biobased products, and area requirements for human infrastructure. The term *sustainable potential* is sometimes used when additional constraints are considered, e.g. in relation to nature conservation and biodiversity preservation, and soil and water protection. Different definitions of the technical potential and the sustainable potential are used and overlaps in their restrictions can be observed. A *market potential* corresponds to the amount of biomass that can be produced for energy under certain requirements for economic profits in the production. This depends on the supply cost and the price of the biomass, which in turn depends on many factors, including characteristics of biomass conversion technologies and the price of competing energy technologies.

– Besides that studies refer to different types of potentials, there are many reasons why biomass potential estimates vary widely: The number of considered biomass resources differ from one study to another. It is relatively common that three principal resource categories are covered: (i) plants produced specifically for bioenergy, including conventional agriculture crops, trees and other woody plants, and lignocellulosic grasses; (ii) residues from conventional food and fiber production in agriculture and forestry; (iii) organic food/forest industry by-products and retail/post-consumer waste. (Slade et al 2014). At the same time, there are studies that do not cover all these three resource categories and there is in addition a wide variation in how comprehensive studies are in assessing these resources. For example, having compiled a detailed list of 93 biomass resource types, Brosowski et al. (2016) found that even the most comprehensive potential estimates for Germany only cover up to 16 different waste and residue streams.

– Different approaches are used to consider how the availability of a specific resource for bioenergy use is influenced by different factors, such as the availability of arable land, yield developments, food demand, as well as biomass use to produce various biomaterials and how such are reused in cascading chains. The influencing factors are manifold, but can be described with standardised documentation lists to enhance transparency when determining biomass potentials and their most salient influencing variables (Brosowski 2015). At least a coherent documentation of the assumptions should be provided (Thrän & Pfeiffer 2015). For assumption of biomass potentials in 2050, the dynamics of the driving factors are also a matter of different consideration. Especially, availability of arable land, yield development, and population development (including related diets and consumption patterns) are well known dynamic factors, while effects of climate change and adaptation on biomass potentials remain uncertain (Haberl et al. 2011, IPCC SRREN 2011).

– With respect to biomass cultivation, the use of degraded and marginal lands are commonly considered, a land category suitable for producing biomass for bioenergy and also for carbon sequestration and storage (Lemus & Lal 2007, Edrisi & Abhilash 2016). For instance, paludicultures, i.e. the wet cultivation of peatlands, can produce biomass for either material or energetic use while actively providing ecosystem services in terms of improved soil carbon sequestration, water purification and biodiversity (Searle et al. 2016, Guerts et al. 2019). However, the challenge for this and other biomass cultivation measures is to quantify their availability and productivity (Dauber et al. 2012).

– Another factor for differences in biomass potentials is a lack of common ground when it comes to sustainability criteria. In 2011, the Global Bioenergy Partnership (GBEP) set up a list of 24 sustainability indicators and suggested approaches for their measurement (GBEP 2011). However, while these indicators have served for 14 countries to monitor the impact of bioenergy-related developments and policies (GBEP 2020), they have not yet been used in academic assessments of bioenergy potentials. Alternatively, the Sustainable Development Goals (SDGs) provide a framework against which bioenergy can be assessed. To this end, a recent assessment of linkages between GBEP indicators and SDGs highlights how both sets of sustainability criteria might be mutually reinforcing, amongst others with respect to data sharing as well as the joint development of new data mining approaches (Fritsche et al. 2018). However, neither GBEP nor SDG indicators are yet a common tool for sustainability assessments in the bioenergy modelling community. In comparison, the SDGs are more widely recognized in the sustainability discussion of the bioeconomy (see e.g. BBIC 2018, Bracco et al. 2019, Egenolf & Bringezu 2019, FAO 2019, Fritsche & Rösch 2020, Ronzon & Sanjuán 2020, Zeug et al 2019).

As can be seen in Table 2, the upper limit in the ranges are lower in the more recent studies, especially for energy crops. One explanation is that more recent studies have increasingly focused on how biomass supply potentials are affected when restrictions are introduced to reflect various sustainability concerns. Large variations in future supply potentials can also be explained by diverging assumptions about future crop yields and land requirements for food. For example, two older studies reporting very high potentials for energy crops include (Hoogwijk et al. 2003) (up to 988 EJ) and (Smeets et al. 2007) (1272 EJ). These studies relied only on surplus agricultural land but with assumptions of high levels of advancement of agricultural technology. The biomass requirement in IPCC scenarios is significantly lower in the 2014 AR5 than in the 2007 AR4. But the high level of mitigation required to limit warming to 1.5°C shifts the range upwards again in IPCC's 1.5 report. This illustrates another aspect that contributes to uncertainty concerning limits on the future biomass supply; it can be assessed based on inventories of biomass resources (resource focus) or in relation to the necessary bioenergy supply in scenarios (demand driven). Thus, the higher range in the 1.5 report can be said to reflect a larger bioenergy demand rather than an upward revision of the estimated future availability of biomass resources.

Table 2: Biomass potentials in different studies and intended biomass use in IPCC scenarios

	Energy crops	**Other** (forest biomass, waste, residues)	**Total**
Global biomass potentials (in EJ)			
Studies until 2007[1]	8-1272	70-451	47-1548
Studies 2008-2012[1]	16-330	30-270	58-530
Studies after 2012[2]	n/a		50-244
IEA bioenergy roadmap (2017b)	60-100	71-140	131-240
IPCC scenario results for bioenergy deployment in 2050 (in EJ)			
IPCC AR4 (2007)	n/a		22-400
IPCC SRREN (2011)			25-300
IPCC AR5 (2014)			10-245
IPCC SR1.5 (2018)			40-312

[1]Based on compilation by Pfeiffer & Thrän (2018); [2]Based on review by Rogelj et al. (2018)

In conclusion, a sustainability framework for the mobilization of the biomass is more relevant than the detailed biomass potentials. Nevertheless, we propose that 100-250 EJ/a can be used as a first approximation concerning the global bioenergy potential in the 2050-2100 time frame, while acknowledging that studies also report smaller and larger supply potentials. Considering the expected population growth towards 9.7 billion by 2050 (World Bank 2019), this translates to 10-25 GJ/capita as a global average annual supply. As a comparison, the TatBio project presented at the WB2 workshop included a biomass potential for energy in Germany at 11.8-22.6 GJ/cap*yr, which is a similar range as the global average.

Biomass supply potentials vary also in national or regional studies due to different biomass resource types, different assumptions for availability and driving forces. Additionally, national and regional studies address the import/export relations of biomass in different ways: All kinds of resource supply strategies can be found, ranging from (1) taking a national available potential as a starting point (i.e., United Stated of America, Finland), via (2) a mix of domestic and imported biomass (i.e., Germany), to (3) the assumption of intensified international trade (i.e., the Netherlands, United Kingdom).

The amount of biomass that can be used for energy obviously has a large influence on bioenergy's possible contribution to climate change mitigation. However, the fossil fuel substitution patterns and the influence of biomass use on land-atmosphere carbon exchanges are also critically important. The substitution pattern depends on the allocation to and relevance for different branches of the energy system, which in turn depend on national and regional energy and climate policies – as described in the following chapters.

3.2 FUTURE ROLES OF BIOENERGY IN RENEWABLE ENERGY SYSTEMS

Biomass is a limited resource and is expected to adapt to the developments of other renewable options (IEA 2017b), especially the variable renewable energy resources (VRE) wind (on and offshore) and photovoltaic power. VRE is the most important element in a renewable future (IEA 2014) and are, through sector coupling, expected to provide all sectors with renewable energy and resources.

In the power sector, VRE is supply-dependent and does not always match the electricity demand, which is a challenge for maintaining a stable power grid. In order to meet the demand at times when VRE cannot, flexibly dispatchable options are necessary. The extent of the availability of different such options is geographically heterogeneous. In some regions, large quantities of hydro power can be used as a flexible option (IEA Hydropower 2019), whereas other regions may have potential for concentrated solar power (CSP) to fulfil this role (Trieb et al. 2014). High-capacity transmission grids may alleviate geographical weather and insolation differences instantaneously (Schaber et al. 2012, Goop 2017) and thereby reduce the need for other (temporal) balancing measures, including electricity storage. The potential for off-shore wind power with higher capacity factors and thus a smoother generation are advantageous if available regionally. As an important back-up capacity, natural gas or renewable gas power plants will likely play a role, also depending on regional gas grids and storage options (Child et al. 2019, IEA 2014, Thrän 2015).

Heat provision is currently a large share of the energy demand in industrialised countries. Some of this demand can be substantially reduced through refurbishment of buildings, and a large part of the remaining room-heating demand can be provided through heat pumps driven by electricity (IEA 2017a). For industrial heat applications, hydrogen and bioenergy are expected to be the main renewable options, but a clear prioritisation cannot be seen in literature, and renewable hydrogen potentials depend on the deployment of VRE capacities. Also, large geographical differences regarding heating grids (Connolly et al. 2014) and thus e.g. the potential economic viability of (industrial) CHP plants necessitate geographically specific analyses.

Mobility can to a large extent be electrified by the use of battery electric vehicles (BEV) (IEA 2017a). Thus, the road passenger vehicle sector can reduce its energy demand substantially owing to a superior energy economy of BEVs compared to internal combustion engine vehicles (ICEV). In freight (IEA 2017c) and marine transport (UNCTAD 2017), electrification is not expected to be as dominant, but renewable gaseous fuels may become important. The most efficient fuel pathways based on biomass or renewable power produce gaseous fuels rather than liquid ones, but demand for such fuels is currently limited (Millinger, 2018). However, Liquefied natural gas (LNG) is already increasing in the maritime sector (Naya Olmer et al. 2017, Cames et al. 2015), and thus may pave the way for renewable gaseous fuels. Drop-in renewable kerosene may play an important role in aviation even in the longer term (IATA 2015).

3.3 TAILORING ENERGY AND CLIMATE STRATEGIES

While global studies show a clear ambition and pathway on how to bridge the gap to a WB2 world, national or regional perspectives need to be strengthened. As highlighted by the latest UNEP Emission Gap Report, there still is a significant ambition gap between countries' current pledges and a pathway consistent with WB2 temperature rise (UNEP 2019). To bridge this gap, appropriate strategies in the different countries are necessary, which strongly embed the energy sector into net-zero climate strategies.

Considering the energy sector, the demand side is still the driving force for the development of bioenergy strategies. Until now, bioenergy is mainly considered as a flexible supply option for power, heat and transport in energy systems with high shares of fluctuating renewables such as wind and solar. This can include (1) flexible dispatchable biopower, (2) high temperature process heat for industry, (3) biofuels for transport modes difficult to electrify such as aviation or shipping, and (4) combined decentralised/ district heating systems with heat pumps or solar heating systems. To describe renewable energy systems towards 2050, the open question from energy system perspective is how much of flexible energy carriers are necessary for the different applications and what are the alternatives to bioenergy? Those framework conditions decide which of the four options are to be preferred in a given setting. Different answers to this question can be found between countries and regions, but also for different studies within those countries and regions (Szarka et al. 2017).

For example, the anticipated future demand for bioenergy differs in energy scenarios due to (1) different modelling approaches (either limited by available biomass or driven by targets from energy system side), (2) sectoral scopes and level of techno-economic details, as well as (3) biomass availability assumptions. Therefore, bioenergy technologies develop with different dynamics in those models, have different underlying learning curves, are shaped by different drivers, and hence play different roles in the energy market.

This being said, despite the very individual framework conditions, a number of key issues are relevant for assessing the role of bioenergy in future scenarios:

1. **Infrastructure for energy supply**: While power transmission grids receive a lot of attention due to the above-mentioned transformation of the energy system, bioenergy can play a crucial role in district heating and gas grids. They offer a valuable balancing option by providing bioenergy for a flexible generation of electricity and heat generation. This system flexibility can be achieved both in small, more decentralised plants, as well as on a larger, centralised scale. Gas infrastructure can be versatile to distribute gaseous biofuels and can bridge decentralised sources with decentralised demand.
2. **Capacity of advanced biofuels to complement electric mobility and electrofuels (power-to-liquid)**: Biorefineries for lignocellulosic material are assessed with high economic potential, but are still in the phase of market introduction (Lask et al. 2019, Clariant International 2019). While the lignocellulose processing consists of many technological steps that are at different phases of development, modular biorefinery concepts can accelerate and facilitate their deployment (Dahmen et al. 2019). With the need of raw materials, but also the chance for additional revenues from co-products (Rosales-Calderon & Arantes 2019), the realisation depends very much on the site-specific frame conditions, and will lead to different success stories in different countries. Electric mobility and electrofuels (power-to-liquid) are additional renewable transport fuels, which are applicable for certain transport modes. While electric mobility is expected to increase in the rail and road sector soon, the potential in marine transport and aviation is currently seen as limited. Electrofuels are limited by the availability of renewable power as well as in the long term maybe also by carbon availability (Millinger et.al. 2020). As long as biorefineries for advanced fuels and refineries for electrofuels are still in an early stage of market introduction their complementation and capacities are difficult to foresee in long-term strategies.
3. **Integration of CCS into climate policy**: CCS is more often integrated in global energy system analyses (e.g. IPCC SR1.5; Global CCS Institute 2018) than in national studies, although the number of the latter ones have increased over the recent years (e.g. UK: UK Government 2017, Sweden: SOU 2020). As CCS technologies may be crucial for decarbonisation of industry and are commonly found to be

essential for meeting the Paris Agreement goal, their implementation needs regulatory support and policy intervention (Olsson et al. 2020). CCS is a proven technology that has been in operation since 1972 (started as Enhanced Oil Recovery project in the USA). However, the public is ambivalent, mainly due to the concern about CO_2 leakage (Alcade et al. 2018, Thomas et al. 2018), and lock-in effects. If CCS is rejected by society, it will not be possible to use BECCS. It must be noted that not all "BECCS" options are equal: Firstly, it is increasingly recognized that bioenergy + biochar ("pyCCS") offers an alternative to CO_2 sequestration in large-scale reservoirs or other underground repositories, and second, there are very different options for geologic sequestration (e.g. deep aquifers, depleted offshore gas and oil reservoirs).

Furthermore, in the scientific literature and among the presentations given at the WB2 workshop, country-level BECCS assessments are mostly confined to developed countries. The perspectives from non-OECD countries are underrepresented; only studies for China, Brazil, Indonesia and Tanzania are known to the authors (Pan et al. 2018, Moreira et al. 2016, Kraxner et al. 2015, Hansson et al. 2019). However, this is not an isolated phenomenon when it comes to BECCS or bioenergy but a more general problem in climate and environmental sciences (Pasgaard et al. 2015, Karlsson et al. 2007). This is insofar problematic as certain climatic zones and their respective local specificities are not adequately considered. In addition, when studies do exist for developing countries, they have often been led by researchers from the northern hemisphere. Considering expectations that large quantities of CO_2 will be captured and stored in non-OECD countries by 2050 (IEA 2017a), tailored capacity-building measures to build up and strengthen local BECCS expertise are warranted.

These three key issues outlined above can fundamentally transform the bioenergy sector and, depending on policy decisions for each of them, some bioenergy application might be more suited than others in the future. This is illustrated for Germany in Figure 2, under the assumption that mainly biomass residues and wastes will be used as feedstock for bioenergy plants. It shows that a fundamental transition of bioenergy provision can be expected if (BE)CCS becomes an integral part of the German climate policy framework. To launch and implement such a transformation, a broader dialogue on environmental impacts and societal acceptance will be key. However, in case of a deliberate and explicit exclusion of (BE)CCS from the portfolio of climate actions, the question arises of how to achieve far-reaching emission cuts without it, and what the opportunity costs for dismissing (BE)CCS might be.

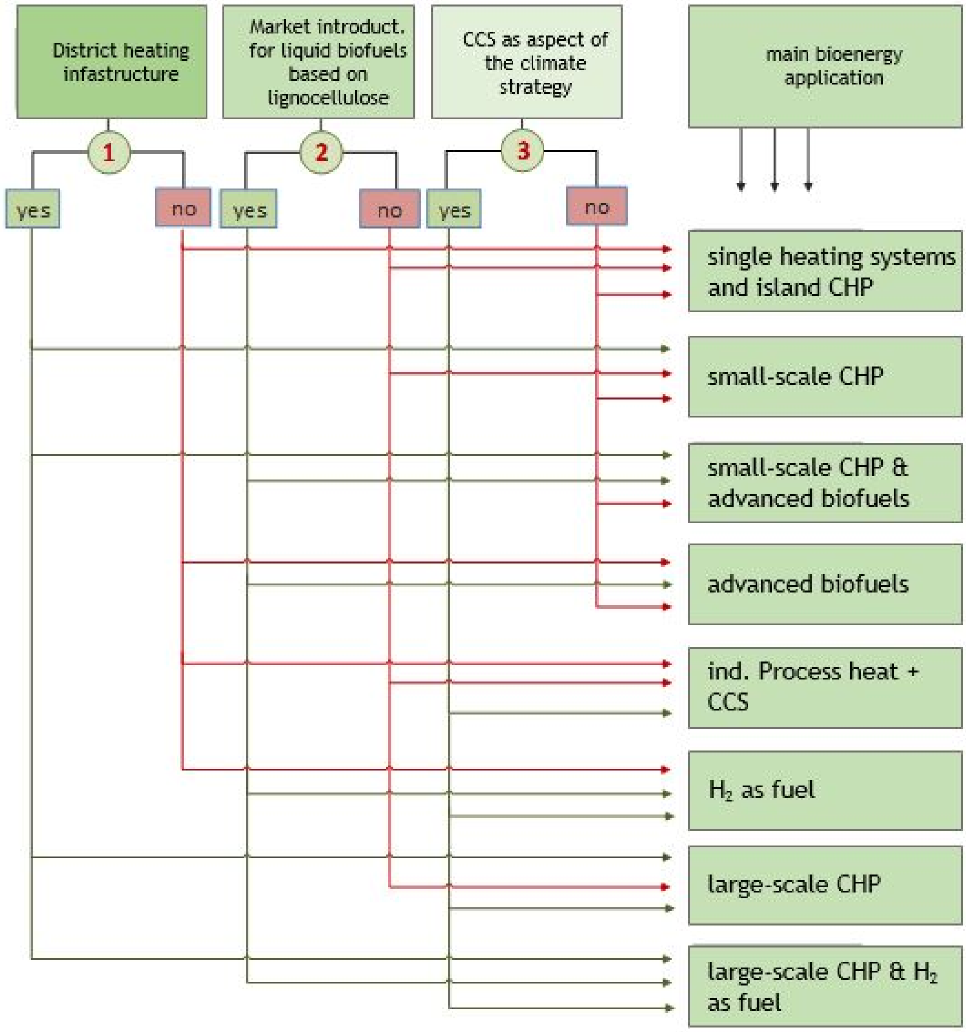


Figure 2: Key issues and resulting preferences for future bioenergy application in Germany (adapted from acatech 2019a)

While the afore-mentioned key issues steer tailor-made bioenergy solutions in the different energy systems, there are also “no regret” options for biomass cultivation and utilization, i.e. cost-effective measures that generate net social, environmental and/or economic benefits without causing lock-in effects in the long term (see chapter 5.4).

3.4 STUDY APPROACHES TO MATCH BIOENERGY AND BECCS

Finally, to bring the role of bioenergy in a WB2 world into full play, site-specific dimensions need to be taken into account for bioenergy deployment. For 2050, we cannot expect a clear picture today, but – as the transformation has to take place as soon as possible – we need at least a rough understanding where biomass production and provision, bioenergy conversion plants, and BECCS could be located. Whereas studies with a global scope cannot go into high spatial resolution and detail, national and/or regional studies can provide more spatially explicit information.

3.4.1 Spatial modelling of biomass potentials

In Chapter 3.1, recurrent differences in studies on biomass potentials were highlighted. In addition, while some studies refer exclusively to statistical biomass data on an aggregated national, regional or global level, many analyses also consider the spatial distribution and availability of biomass (Long et al. 2013). These are most notably available for dedicated energy crops (e.g. Fiorese and Guariso 2010, Zhuang et al. 2011, Perpiña Castillo et al. 2016), followed by forest biomass (e.g. Blackard et al. 2008, Flores Hernández et al. 2017, Verkerk et al. 2019). In contrast, spatially explicit data for waste and residues is only emerging more recently (e.g. Singlitito et al. 2018, Pfeiffer et al. 2019, Lozano-García et al. 2020). Due to different methodological approaches for spatially assessing these different biomass types, studies that cover the geospatial dimension of all feedstock categories in an integrated manner are even less abundant (e.g. Wit and Faaij 2010, Dees et al. 2017a).

In addition to locating resource potentials, it is also necessary to monitor and regularly update the resource development both in terms of supply of specific biomass types and demand over time as a means of evaluating future raw material use (Brosowski et al. 2019). To this end and with a view to harmonizing data collection efforts, the European S2Biom project proposes a "Roadmap for regional end-users on how to collect, process, store and maintain biomass supply data" (Dees et al. 2017b).

3.4.2 Optimizing bioenergy conversion plant locations

Spatially explicit configuration of bioenergy systems goes beyond climate policy. In many nations and regions, this comes along with a fundamental transformation of bioenergy use: from distributed to centralised, from heat to biofuels, from base load to flexible systems etc. This shift is a response to a need of decarbonisation of energy systems, and is largely driven by innovation in technologies. Deciding on an optimal location for a bioenergy plant related to spatial distribution of available feedstock, organisation of logistics (transport & storage on supply and demand sides) and location of final bioenergy recipients (e.g. industry) is complex (Schmidt et al. 2010).

The need for conversion plants to be located in proximity to the biomass resource depends on the biomass type and bioenergy product. For wet feedstocks with a low energy density, bioenergy plants are planned and built according to the location of the raw materials (e.g. manure or maize silage for biogas systems, O'Keeffe & Thrän 2020), while dry feedstocks with a high energy density are also traded and transported internationally (e.g. compressed wood pellets). Because the biomass distribution (whether residues from forestry and agriculture, short-rotation coppice or bio-waste) is usually scattered and regionally differentiated, it influences not only the number of bioenergy plants to be built, but also their type (bio-based fuels, power and/or heat generation). Apart from that, decentralised systems may require extension of existing transmission grids, and, in the case of biogas, adaptation of grids for feed-in options.

In conclusion, optimal allocation is a multi-criteria decision depending on (1) biomass availability, (2) preferred bioenergy product, (3) biomass and energy infrastructure and (4) bioenergy related policies. Allocation approaches in scientific literature (i.e. Delivand et al. 2015, Woo et al. 2018, Budzinski et al. 2019) give guidance for those decision processes but cannot replace the priority setting of investors.

3.4.3 Source-sink matching to identify suitable BECCS locations

When optimizing conversion plant size and locations, the integration of a CO_2 capture unit for BECCS purposes should be investigated in order to transform global BECCS potential into domestic realities (Fridahl 2018). To this end, a number of studies use geospatial data to perform source-sink matching, i.e. comparing the capacity of underground storage reservoirs for CO_2 injection with locally available biomass potentials and hence the potential amount of CO_2 captured from bioenergy plants. Such studies have among others been performed on national or sub-national level for the U.S., U.K., Sweden, Japan, South Korea, Indonesia, and Brazil (Kraxner et al. 2014a,b, 2015, Baik et al. 2018, Sanchez et al. 2018, Johnson et al. 2014, Karlsson et al. 2017, Zhang et al. 2020, da Silva et al. 2018). While their overall approach is similar, these studies vary with respect to:

- variety and scale of biomass feedstock and conversion plants;
- greenfield plant approaches vs. brownfield studies that take into consideration existing plant locations and pipelines;
- in-situ CO_2 storage vs. CO_2 transportation to suitable geological formations, notably offshore;
- use of simple overlay maps vs. spatial optimization models, and
- different time horizons of BECCS deployment in the near- or long-term.

While spatially explicit modelling exercises help to single out suitable BECCS locations, the local deployment potential of BECCS is – especially if on-shore storage locations are selected – contingent upon the acceptance by local communities. Gough and Mander (2019) therefore suggest applying lessons learned from fossil CCS deployment to future BECCS projects, notably but not exclusively regarding the influence of geographical contexts on social dynamics.

3.4.4 Integration of BECCU

In contrast, technologies that utilize captured CO_2 (CCU) tend to have a more positive public perception (Arning et al. 2017, van Heek et al. 2017), but are not so advanced in maturity and in deployment levels as CCS (IOGP 2019). In comparison to total global CO_2 emissions (36.8 ± 1.8 Gt CO_2 in 2019), and despite the technical feasibility, only a fraction of available CO_2 is currently being converted into other goods (Billig et al. 2019). From around 120 Mt CO_2 that are globally utilized per year, almost 96% goes into synthesis of urea, followed by methanol synthesis (2-3 Mt CO_2), and production of cyclic carbonates (acatech 2019b).

The selection of (bio)energy plants suitable for CO_2 capture and ultimately provision of CO_2 for CCU processes and products depends on several factors, namely (1) the composition of the CO_2-rich gas mixture, (2) the CO_2 concentration in the gas stream, (3) the volumetric flow rate, and (4) the availability of H_2 for subsequent conversion into platform chemicals or hydrocarbon energy carriers (e.g. methanol, methane, Fischer-Tropsch fuels). For those reasons, the most commonly chosen types of point sources are power plants (fossil- and bio-based), industry facilities (cement, steel, and chemical) and bio-ethanol plants. Fossil-based CCU options are still more common than their bio-based alternatives. Currently six facilities in full operational/commercial scale (in Europe, North America and Japan) are capturing biogenic CO_2 for utilization, five of which are bio-ethanol plants and one waste incineration plant (Consoli 2019). But as CO_2 is a possible raw material (especially in chemical industry), more and more CCU projects and installations (laboratory to demonstration scale) are emerging.

CCU applications fix carbon typically only a limited time before the CO_2 is released back to the atmosphere. For instance, when CO_2 is used to produce synthetic transport fuels, the carbon retention time is almost negligible as the CO_2 is emitted again when combusting these fuels. However, net emissions may ultimately be reduced when processes or products that currently rely on fossil fuel inputs are substituted with carbon neutral ones (e.g. electrofuels instead of fossil-based transportation fuels). In addition, there are also CCU pathways with longer retention times, for example plastics and building materials can store the fixed carbon for several decades.

3.5 CONCLUSION

- Bioenergy plays a crucial role in the IPCC scenarios to stay in a WB2 world. This is assumed in combination with CCS, but even more bioenergy is necessary if BECCS is not available.
- Most BECCS studies focus on its long-term carbon dioxide removal potential. However, to achieve the required level of BECCS capacity in 2050, the first BECCS plants would have to be built in the near future. In order to use the existing bioenergy plants, both technical and systemic retrofitting criteria for CO_2 capture need to be developed. Furthermore, CO_2 pooling options, such as the Northern Lights flagship project (equinor 2019), should be intensified. Such clusters, or hub-and-spoke arrangements, might even enable small to medium-sized point sources to be connected to a joint CCS infrastructure.
- However, there is a contrast between top-down and bottom-up approaches. While global assessments quantify the 1.5 - 2°C scenarios, most of the countries and regions are behind in the formulation of mitigation targets and strategies and – in conclusion – have not investigated BECCS pathways in detail. Reasons for this delay can be seen in ambition gaps of national and regional policies, but also in the high complexity when transposing global agreements into national or regional strategies, policies and regulations.
- Therefore, it is necessary to have fundamental and site-specific discussions on (a) the resource potential, (b) suitable transformation pathways from today’s bioenergy use into future systems, and

(c) spatially specific risks and opportunities for implementation.

(a) There are still uncertainties in finding a common ground for the resource base due to different approaches in estimating the biomass potential, lack of data for different biomass streams, and disagreements between researchers on biomass availability for energetic use. However, during the last years the wide range of estimations have converged to not more than 240 to 300 EJ/a, equal to 24.8 -30 GJ per capita in 2050. National strategies can use this as an orientation point, when developing their biomass mobilisation strategies. While the biomass potential influences the quantity of bioenergy in a WB2 world, the selection and use of bioenergy products is much more induced by the national and regional energy and climate policies.

(b) The pathway for bioenergy to contribute to WB2 should not be prescribed, but rather developed within each country, reflecting the local context. Different nations and regions have already very different bioenergy supply chains in place, and have varying potentials for other renewables and different technology expectations (for electrification, power-to-X, hydrogen etc.). In conclusion, a "one-fits-all-solution" cannot be expected. Countries need to analyse the relevant decision factors and develop stepwise decision processes.

(c) Biomass production and provision is embedded in landscapes, infrastructure and value chains. Utilization for BECCS prioritizes central locations with storage options. However, there are many other spatial aspects to consider (i.e. soil carbon, land use, forest management). Biomass for energy needs to be embedded in a wider risk assessment to avoid leakage effects.

4 Biomass and bioenergy in Integrated Assessment Models (IAMs)

Vassilis Daioglou

4.1 BACKGROUND

IAMs are stylized numerical approaches which aim to represent the complex interactions between human and natural systems (Clark et al. 2014). Unlike biophysical process models, there is no single unifying theory of integrated assessment; rather than applying a specific IAM methodology, IAMs borrow from multiple intellectual traditions including energy systems modelling, macroeconomic forecasting and systems dynamics (Cointe et al. 2019). Since IAMs aim to incorporate a holistic view of human and natural systems, they do not focus on biomass and bioenergy, but rather investigate their role within the broader energy, economy, and land use systems. Thus, typical insights IAMs aim to gain, amongst others, include (i) the role of bioenergy in decarbonizing the energy system, (ii) how it competes with other renewable energy forms, (iii) how bioenergy demand may affect food markets and/or land-use change, (iv) the carbon consequences of biomass induced land use change, and (v) the role of BECCS in WB2 scenarios vis-à-vis other negative emission technologies.

While the exact representation of biomass and bioenergy differs across different models, IAMs broadly aim to investigate both the supply and demand in a consistent method. IAMs determine the supply of biomass endogenously by calculating potential biomass production from dedicated crops, forestry, and residues (with the level of detail and aggregation varying across IAMs). Supply curves are then generated by combining biomass supply with costs (which are also determined endogenously). These in turn, are used to determine the use of bioenergy in the energy/materials system in competition with other resources (fossil and renewable). The energy system representation usually covers multiple bioenergy technology options including pelletisation, liquid fuels (1st and 2nd generation), electricity, hydrogen, and heat. These provide energy for the demand – endogenously calculated – of multiple end-uses in industry, transport, residential, services, agriculture, and feedstocks.

4.2 PURPOSE: SCENARIO ANALYSIS

As IAMs aim to provide strategies for tackling temporally and spatially complex problems such as climate change, their projections are long term (typically till 2100) and global (with regional and in some cases grid-scale disaggregation). This implies that IAM projections operate within a space of insurmountable uncertainties concerning the multiple drivers and constraints of biomass supply and demand.

Concerning biomass supply, uncertainties include the future demand for food and feed, the level of societal environmental consciousness (and how that affects behaviour), as well as technological developments in agricultural production. Similarly, the role of bioenergy in the energy system depends on technological development (of bioenergy as well as other energy technologies), behavioural choices, capital stocks, international trade of energy carriers, and the effectiveness of climate policy. IAMs explore these uncertainties and how they may affect the future of biomass and bioenergy through scenarios spanning several socio-economic and policy dimensions. The SSP-RCP framework, which combines different socioeconomic development pathways and climate change levels, was developed by the climate change research community (including IAM developers) for this purpose (Moss et al. 2014, O'Neil et al. 2017). These scenarios represent the "solution space" of possible futures that may arise depending on how uncertain elements evolve. Importantly, this means that these scenarios are not predictions, and probabilities of likelihood cannot be attached to them.

Besides the uncertainty with regard to socioeconomic developments, there is significant uncertainty concerning technology availability (or desirability). Thus, IAMs are also used to explore the sensitivity of energy and land-use projections, as well as the costs of WB2 scenarios, across the availability of specific technologies. These sensitivity analyses have also been undertaken specifically for advanced bioenergy technologies such as 2nd generation fuels, bio-hydrogen, or BECCS (Bauer et al. 2018). By comparing the results of the socioeconomic and sensitivity analyses, it is possible to better understand the uncertainties, synergies and trade-offs of different bioenergy supply and demand possibilities. These include the option of limiting biomass supply, which allows the production of significant volumes of biomass without extreme land-use change emissions (Figure 3).

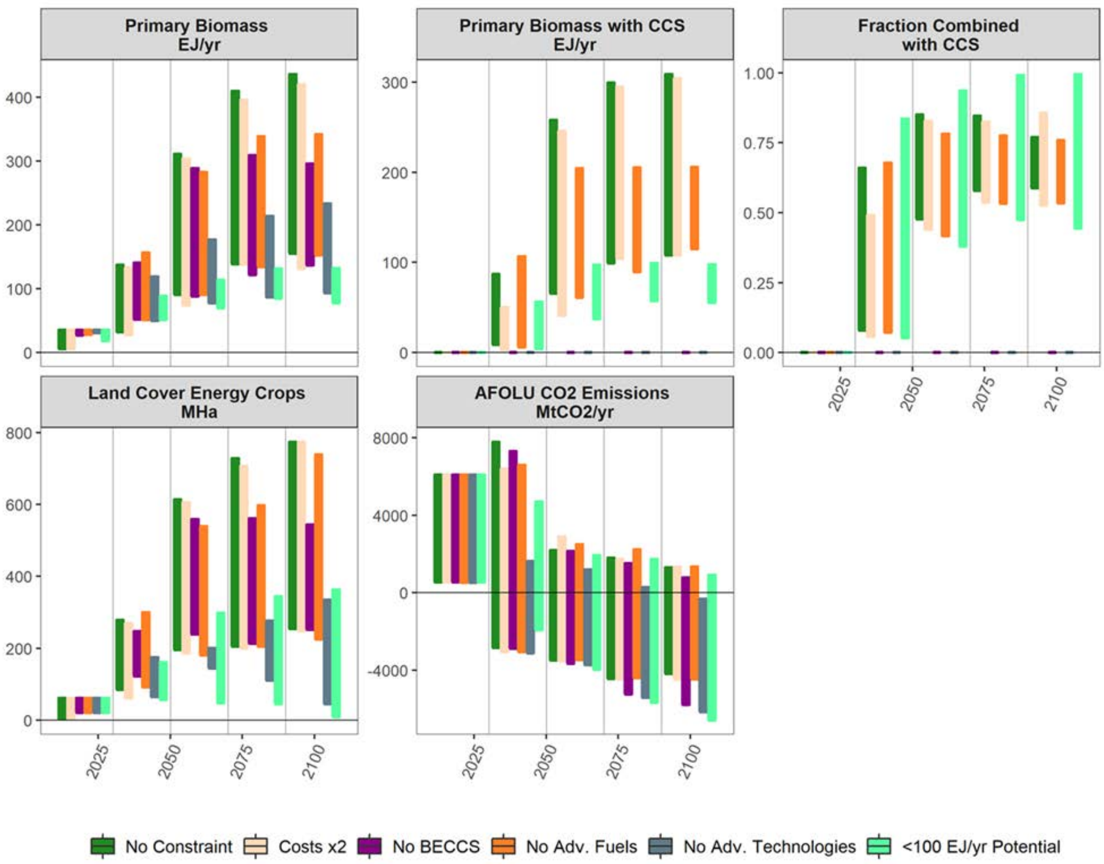


Figure 3: Biomass and bioenergy indicators across scenarios consistent with the Paris Agreement 1.5 and 2°C targets. For each indicator the results of specific sensitivity analyses are shown: (a) no constraint (base assumptions), (b) double the costs of bioenergy technologies, (c) avoid the use of BECCS, (d) no 2nd generation fuels or bio-hydrogen, (e) no advanced technologies (c+d), and (f) limit primary biomass potential to 100 EJ/yr. Ranges show results across different IAMs. Results taken from (Huppmann et al. 2019, Bauer et al. 2018)

4.3 LIMITATIONS AND OUTLOOK

IAMs make significant simplifications concerning the systems they represent. This is largely due to lack of data, gaps in knowledge of system behaviour, limited computing power, and expert judgment concerning importance of the “model detail vs. uncertainty” balance. The latter is particularly important but also very subjective. For instance, adding technical detail in IAMs may make some calculations more exact, but also compound uncertainty over the long-term and at the global level. Thus, IAMs tend to “stylize” many system components through simplified relationships which aim to represent broad dynamics and feedbacks. These include learning-by-doing, cost-supply curves, price-induced efficiency improvements (including crop yields), and the assumption of completely substitutable and fungible goods. This may lead to several issues concerning the supply of biomass since important logistical challenges such as feedstock-technology specificity or seasonality and storage are typically ignored. Furthermore, this simplification raises certain ambiguities concerning input parameters, elasticities, and system boundaries which are not easily communicated.

IAMs have historically focused on climate change mitigation scenarios. However, with the growing importance of the UN Agenda 2030, there is a coordinated effort within the IAM community to make their tools more relevant for assessing pathways aimed at meeting the Sustainable Development Goals. This includes developing scenarios beyond the SSP-RCP framework (which is, by definition, climate-focused) through a deliberative process, as well as linking IAMs with more detailed process-level tools such as Multi-Region Input Output, and Life Cycle Assessment.

5 Translating research into practice

Annette Cowie, Göran Berndes, Daniela Thrän

For a successful translation of the modelling results into practice, common understanding of the bioenergy system and the associated energy, industry and land use systems, and a common terminology are key.

5.1 COMMON UNDERSTANDING OF SUSTAINABLE BIOENERGY SYSTEMS

Bioenergy pathways need to be defined to specify the roles of bioenergy in energy system pathways towards a WB2 world. Those bioenergy pathways need to reflect national and regional context, and should address the following system elements, which are also shown in Figure 4:

1. **Sustainability governance**: sustainability governance is a precondition to prevent adverse side-effects and promote co-benefits, especially from biomass provision. There are several guidelines, standards, certification schemes and other initiatives at government level and led by industry, to support sustainability governance of bioenergy (Florin & Bunting 2009; GBEP 2011, 2020; Junginger et al. 2019). Examples include the ISO standard for sustainability criteria for bioenergy (ISO 13065); the Global Bioenergy Partnership (GBEP); the Roundtable on Sustainable Biomaterials (RSB); the Roundtable on Sustainable Palm Oil (RSPO) and the Sustainable Biomass Partnership (SBP). These initiatives have developed indicators for the three dimensions of sustainability, to support risk assessment during project development, and monitoring of bioenergy supply chains. Enabling policies that facilitate common approaches to sustainability governance across all land uses should be implemented. Sustainability governance for bioenergy should be integrated with existing national governance systems, to complement and strengthen existing governance, and avoid overlaps, inconsistences and deliver multiple benefits.
2. **Biomass resources**: Assessments of biomass supply potentials need to specify the **biomass sources assessed**, as well as **technical and sustainability restrictions applied**. Marginal and degraded land could be utilised for biomass production, with potential social and environmental benefits, if appropriate safeguards are in place to protect livelihoods of communities that use such land informally. Accurate assessment of available marginal and degraded land is needed, as well as realistic estimation of biomass growth rates on this land. Assessments should consider the potential for biomass production to be integrated with existing agriculture and forestry activities. For national and regional studies, imports and exports need to be included. Estimates of bioenergy supply potential vary widely between studies, due to differences in methods and data used. It is not possible to specify precisely the future bioenergy supply potential due to inherent uncertainties concerning critical factors, including priorities among a multitude of societal objectives. Nevertheless, studies employing improved databases and modelling capacity have over time improved the understanding of how various factors influence the supply potential, e.g., future diets, crop yields, cropping intensity and land use efficiency in meat and dairy production, and land reservation for nature conservation. These studies have also shown that both positive and negative effects may follow from increased biomass use for energy. In this report, 100-250 EJ/a is proposed as a first approximation of the global bioenergy potential in the 2050-2100 time frame. This may appear a broad range, but uncertainty in potentials should not become a barrier to deployment of bioenergy systems; sufficient knowledge is available to support implementation of best bet options and can provide the opportunity to enhance knowledge if deployed within an adaptive management context.
3. **Energy system transformation strategy**: Bioenergy provision is embedded in national and regional energy systems, industrial infrastructure, land uses and value chains. Countries differ concerning biophysical conditions for bioenergy and other energy sources, geological CO_2 storage capacity, gas and electricity grids, public transport infrastructure, etc. A country specific energy system transformation strategy for WB2 needs to **frame the role of bioenergy**. The attractiveness of different bioenergy options differs between countries. Bioenergy plants applying CCS will likely be

located where logistics are favourable concerning both biomass supply and transport of CO_2 to storage locations. They will likely be relatively large and designed for continuous and uninterrupted operation to maximize the production of energy carriers and CO_2 removal from the atmosphere. On the other hand, the value of dispatchable balancing power based on biomass may be high in energy systems with high shares of wind and solar power. Other options for managing the variability of wind and solar power, such as demand-side management, storage systems, and reservoir hydropower, represent alternative solutions. The roles of these different options will depend on regional conditions, such as the transmission capacity and the availability of biomass and reservoir hydropower. Thus bioenergy strategies cannot be developed in isolation from interacting systems like the actual provision and use, including the related investments, infrastructure and stakeholders. The current local context needs to be explicitly described as a **starting point**. This is especially important because the actual biomass and bioenergy use is very different between different global regions and there is a lack of studies from key world regions, such as the BRIC countries as well as from the global South.

4. Spatially and temporally explicit information: Spatially explicit assessments of biomass resources and suitable locations for CCS can be overlaid, to enable planning for logistics infrastructure to facilitate inclusion of BECCS in transformation pathways. Temporally explicit milestones are an additional necessity to translate the pathways into strategies. Differentiation between BECCU and BECCS is necessary, because their permanence differs significantly. All this information is necessary to develop dedicated strategies but also to monitor the progress in the contribution of bioenergy in a WB2 world. The additional energy demand to run BECCS and other CDR options needs to be considered.

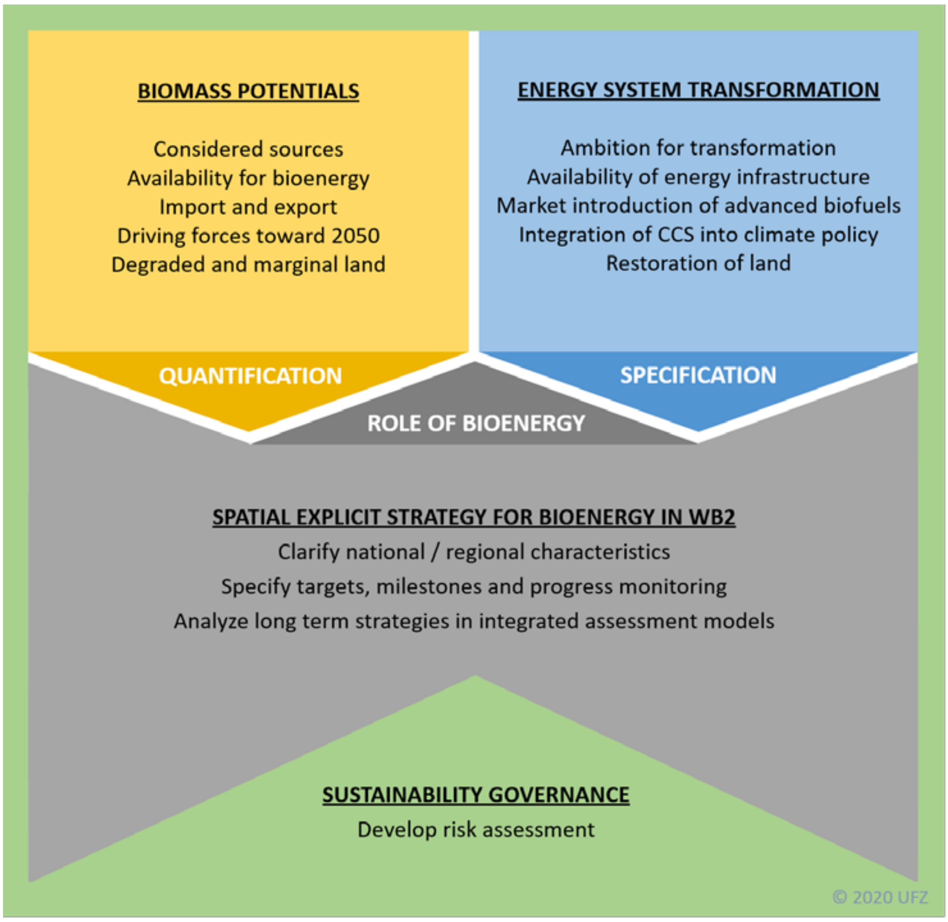


Figure 4: Assessing and translating bioenergy technology research into practice in a WB2 world

IAMs are suitable assessment tools, because they are built for coherent system analysis and modelling, and (BE)CCS requires integration across sectors. But strategy and pathway development can also be realized with more simplified approaches if all relevant elements are included. It should be noted, models are always imperfect depictions of reality and never cover all relevant aspects, and thus need to be complemented with monitoring systems.

Many modelling studies are deterministic in nature. In several key areas, behaviour is an important element which is seldom addressed explicitly. Especially investment behaviour regarding, for example, heating applications and refurbishment, personal vehicle investment and mobility behaviour, as well as dietary choices affect the availability of biomass. Such aspects are seldom depicted in detail, if at all in modelling studies.

Details regarding potentials, cost and price developments for biomass need to be explicitly stated. Ideally, all relevant societal sectors should be covered, in order to analyse competition for the resource. Furthermore, inclusion of electricity-based options is important, in order to cover a wider scope regarding other renewable options in the different sectors.

5.2 CONSIDERATION OF TIMELINES FOR DECARBONISATION

Describing **the dynamics of** atmospheric GHG concentrations, and radiative forcing under modelled scenarios offers a better understanding and communication on the time-relevant aspects of climate change mitigation and the possible role of bioenergy and BECCS. In the IPCC's SR1.5 report, all analysed pathways limiting warming to 1.5°C with no or limited overshoot included CO_2 removal (CDR) through A/R and BECCS to balance residual emissions. Most pathways that involved overshoot relied on BECCS to provide net negative emissions, to return global warming to 1.5°C (IPCC SR1.5, 2018).

Concerns have been raised that illustrating such overshoot pathways could encourage over-confidence in BECCS to achieve climate stabilisation, and diminish efforts to reduce emissions in the short term. Some have suggested that such pathways imply inter-generational inequity, increasing the mitigation challenge for future generations.

On the other hand, exclusive focus on achieving short term emission reductions could exclude bioenergy options that would deliver longer term mitigation benefits. Strategic deployment of bioenergy (with or without BECCS/BECCU) could play a key role in achieving energy system transformation.

Achieving the goal in the Paris agreement (UNFCCC 2015) will require contributions from all nations. Each country has declared its target, through the nationally determined contributions (NDC), which are to be reported as agreed within the Paris agreement. While some countries indicate the intention to include bioenergy measures, the NDCs do not specify implementation plans at country level, and thus there are no concrete targets for the role of bioenergy for achieving the NDCs. Keeping in mind that with current policies the transformation pathways to achieve the Paris Agreement goal cannot be reached, we propose to use the NDCs as a **reference point** for modelling. In the workshop it also was mentioned clearly, that the term "Business as usual" (BAU) is not appropriate as a reference point in transformation scenarios, as long as business as usual does not lead to the necessary transformation.

5.3 IMPLEMENTATION OF NO-REGRET OPTIONS

No-regret options provide the chance to begin taking relevant steps towards a WB2 world, in parallel to the long term pathway development. No-regret options are described for several sectors relevant for bioenergy, such as:

1. With respect to land management, many studies have investigated opportunities for strategic integration of perennial plants (short rotation woody crops and lignocellulosic grasses) into agricultural landscapes to enhance, e.g. landscape diversity, pollination, pest and disease control, retention of nutrients and sediment, erosion control, and flood regulation (Asbjornsen et al. 2014,

Berndes et al. 2008, Christen & Dalgaard 2013, Dauber & Miyake 2016, Holland et al. 2015, Milner et al. 2016, Styles et al. 2016, Ssegane et al. 2015, Ssegane & Negri 2016, Zumpf et al. 2017, Cacho et al. 2017). Such solutions can help mitigate negative impacts of agriculture, while providing biomass for energy. Furthermore, using degraded land for bioenergy would not only avoid competition with other land uses, but could well sequester carbon and contribute to land rehabilitation, supporting achievement of land degradation neutrality goals (Fritsche et al. 2017). Beyond the land use dimension, no regret approaches further extend to resource efficiency improvements, such as the reduction of food waste and losses, as well as improved cooking stoves to decrease fuelwood harvesting (IEA 2017b). Thanks to these improved land management and resource efficiency practices, the required biomass supply for food and material might be easier to achieve, therefore potentially releasing land for bioenergy purposes (IRENA 2016). Implementation of no-regret options will be facilitated by land governance approaches that encourage integrated land use planning, and landscape-scale approaches to land management, in which land users participate in planning decisions, and use of land according to its potential is encouraged (Cowie et al., 2018).

2. No-regret options are also considered to include deployment and/or investment decisions that do not cause stranded assets. From this viewpoint, an assessment of optimal biomass allocation in the UK finds that biomass for industrial heat applications is a no-regret option as it is both required in the near term to fulfil requirements of the EU Renewable Energy Directive and in the long-term as a cost-effective decarbonisation option for the industry sector (Redpoint Energy 2012). Similarly, bioenergy production from biomass waste and residues can qualify as a no-regret option as long as such resources are extracted responsibly to avoid negative impact such as soil degradation (McCarl & Plieninger 2008, Gabrielle et al. 2016).

6 Recommendation and next steps

Göran Berndes, Annette Cowie, Daniela Thrän

Several steps are foreseen that will help inform deployment of bioenergy and BECCS to support energy system transitions towards a WB2 world.

1. Decisions concerning development of biomass resources and bioenergy systems are determined by the global as well as national and regional context. Therefore, analyses using models with different geographic scope and spatial resolution, ranging from global IAMs to more fine grained models (covering individual countries/regions and/or individual sectors or technologies), are needed. Non-OECD countries need to be better represented in national and regional models.
2. As BECCS and other CDR options commonly play important roles in WB2 pathways, it is warranted to intensify investigation and implementation of CDR in the near term. Early action also helps to identify potential barriers that prevent or slow down implementation of different CDR options. While there will be competition for funding between CDR options, based on respective cost of removing CO_2 from the atmosphere, some CDR options also interact in synergistic ways. For example, land may be used to produce biomass for BECCS or for in-forest carbon storage, or both.
3. Integrated land use planning, applied at the landscape scale, can identify options for deployment of bioenergy and BECCS in ways that support achievement of multiple SDGs. For example, rehabilitation of degraded through establishment of energy crops can contribute to land degradation neutrality goals (SDG15.3). Strategic integration of short-rotation woody crops can enhance agricultural production by providing windbreaks, hosting beneficial insects and lowering saline watertables. Realisation of these opportunities requires cooperative planning involving a broad range of stakeholders, including landholders, agribusiness and technical experts. It relies on recognition of the potential for integrated policies to deliver multiple benefits through well-

designed interventions on the land, supported by effective coordination between local and national governments, and across ministries. Finally, governance is critical to avoid or mitigate adverse side-effects and to promote synergies among important objectives, not the least associated with biomass supply systems. The scope and quality of governance influences biomass availability as well as demand for bioenergy. Policies can also (e.g., through sustainability requirements) influence how the bioenergy systems that satisfy the demand affect other land uses and the environment.

4. The integration of smart bioenergy concepts in future energy systems, in particular but not limited to the implementation of BECCS und BECCU, needs dedicated policies, laws and implementation strategies. IEA Bioenergy has published numerous reports that provide different elements on how to shape such support schemes and instruments (IEA 2017b; Pelkmans et al. 2019; Olsson et al. 2020; IEA Bioenergy 2020). Additional information and country-specific policy suggestions can be found for the German context (acatech 2019a), as part of a bioenergy strategy proposal for UK (Brown 2020; see chapter 7.1), and within the Swedish draft negative emissions strategy (Swedish Government 2020).

7 Studies submitted to the workshop

Adam Brown, Francielle Carvalho, Otavio Cavalett, Francesco Cherubini, Pierre Colett, Vassilis Daioglou, Brendan George, Lorie Hamelin, Seungwoo Kang, Matthew Langholtz, Sylvain Leduc, Mariliis Lehtveer, Tomi J. Lindroos, Markus Millinger, Joana Portugal-Pereira, Mirjam Röder, Fabian Schipfer, Glaucia Souza, Ivan Vera, Bintang Yuwono

The selection of the presented studies was based on the following information gathered in structured study fact sheets (see Table 3) with the aim to cover a broad variety of frame conditions and scales. The contributors were asked to illustrate the following issues and questions in their presentations: (i) the climate change mitigation contribution of bioenergy; (ii) the usage of biomass in power, heat and/or transportation in the medium to long term; (iii) which factors have strong influences on the outcomes; and (iv) important uncertainties and limitations of the study, e.g. methodological limitations and potentially important factors that are not addressed. In addition, we asked for background information on (v) assumptions about critical factors such as biomass supply potentials and costs, technological characteristics and greenhouse gas calculation methods; (vi) how studies have considered social and environmental aspects, land use and land use change, and (vii) enabling policies and other governance required to support implementation of the pathways (if possible).

In the following all studies that have been submitted to the workshop are described with regard to their key messages, facts and figures, key recommendations and references. Studies that were presented to the workshop audience and whose slides are included in the supplement are marked with an asterisk.

Table 3: Study fact sheet template summarizing information on study design.

Study fact sheet	
General	
Title of the study	Provide the title of the study.
Contact name	Specify whether you are submitting as an individual or on behalf of an organization.
Initiator of the study	Please indicate if the study was commissioned or initiated the study.
Year of the study	Specify the year the study has been conducted or started.
Publication	Provide a list of publications (if any) on the specific project/policy/practice described.
Links	Provide the link to the project web-site (if any).
Details of the study	
Geographical system boundaries	Please indicate the geographical scope of the study and whether analyses are made and results reported for sub-regions.
Temporal boundaries	Please specify the temporal extent observed in the study.
Sectors system boundaries	Please name the sectors included in the study (heat, power, transportation).
Land use system boundaries	Please indicate whether specific land related mitigation options are considered (e.g., forest management, diet shifts, afforestation, reforestation, biochar production and use, etc.).
Ambition in GHG reduction	Please describe the framing of the study with regard to the CO_2 emissions.
Ambition in SDG improvement	Which SDGs are addressed (explicitly and implicitly)?
Framing of the study	Describe the assumed framing conditions for a WB2 world, such as main environmental, social, economic and/or policy-related factors (e.g., strong forest protection, diet changes) as well as technological characteristics and calculation methods, which build the background of the study.
Assessment approach	Which approach is applied to assess the role of bioenergy and associated technologies to meet the WB2 target? (e.g. IAM...)

7.1 BROWN (2019): *BIOENERGY STRATEGY FOR THE UK* *

7.1.1 Study Design

Study fact sheet	
General	
Title of the study	UK Renewable Energy Association – Bioenergy Strategy
Contact name	Adam Brown
Initiator of the study	Renewable Energy Association
Year of the study	2019
Publication	Renewable Energy Association, Bioenergy Strategy, Delivering the UK's Bioenergy Potential
Links	https://www.bioenergy-strategy.com/publications
Details of the study	
Geographical system boundaries	The United Kingdom
Temporal boundaries	The study looks at potential for bioenergy to contribute to UK's climate change reduction ambitions to 2032.
Sectors system boundaries	Looks at the potential for use of bioenergy in the UK based on indigenous resources and imports.
Land use system boundaries	The study focusses on the use of wastes and residues and also on the thus of limited amounts of energy crops produced in the UK.
Ambition in GHG reduction	The study examines role of bioenergy in the UK to contribute to GHG reductions to 2032 in the heating, transport and power generation sectors, with potential savings estimated at 65 $MtCO_2e/y$. It also identifies potential for a further 23 $MtCO_2e/y$ from CCUS.
Ambition in SDG improvement	The study identifies benefits in terms jobs associated with bioenergy, which could rise from 43,000 in 2017 to 120,000 by 2032, and also assesses qualitatively other environmental and economic benefits.
Framing of the study	The study was carried out by industry in the absence of a government led integrated approach to bioenergy in the UK
Assessment approach	The study was based on a bottom-up assessment by industry of the potential to scale up bioenergy production and use given a helpful enabling policy and regulatory environment.

The study was initiated by the UK Renewable Energy Association in the absence of an up-to-date national government strategy for the sector, and a perception that the potential for bioenergy was underestimated in UK Government plans for reducing GHG emissions. The objectives of the study were:

- To spell out why Government and stakeholders need to care about bioenergy, building on current progress to realise short term GHG savings and other benefits and its potential role in achieving decarbonisation targets by 2032 and in a Net Zero scenario.

- To identify the contributions that bioenergy can make in a number of policy areas while recognising and addressing concerns that have been raised around sustainability and air quality associated with bioenergy.
- To set out a route and policy recommendations for delivering bioenergy potential in the medium and longer term.

The study was carried out with in close cooperation with industry and academic players in the UK, and also involved a public call for evidence. The study was carried out in three phases:

- A review of the current contribution of bioenergy to the UK energy economy and of the policy and regulatory framework.
- The development of a bottom up vision of the contribution that bioenergy could make in the UK by 2032 (the end of the UK's 5th carbon accounting period) and of the associated benefits.
- The identification of the policy and regulatory changes needed to be able to deliver this vision.

7.1.2 Key messages

The key messages identified by the study included:

- Bioenergy has grown rapidly in the UK in recent years, stimulated by enabling policy measures, but further progress is at risk as these measures come to an end.
- Bioenergy can play an essential role in the future low carbon economy, based on established technologies and some new options including BECCS.
- This increased bioenergy contribution could lead to GHG savings which would be enough to offset the currently projected overshoot in UK emissions by 2032, and would also help avoid a shortage of "clean electricity" by providing low carbon heating and transport options without increasing electricity demand
- A wide range of policy and other actions are needed to enable this growth of sustainable bioenergy including specific sectoral support measures in the heat, transport and the electricity sectors and supporting the development of BECCUS
- These measures should be complemented by a progressive increase in carbon prices across the energy economy.

7.1.3 Facts and figures

- Bioenergy's contribution to UK energy need has grown by a factor of more than 2.5 in ten years, from 250 to 673 PJ/year providing around 8% of UK total primary energy supply compared to 2.6% in 2008. The growth in the use of bioenergy has so far been concentrated in the electricity sector.
- Bioenergy could provide 16% of UK energy needs by 2032.
- This increased bioenergy contribution could lead to GHG savings of over 80 $MtCO_2e$/year by 2032.

7.1.4 Key recommendations

The ambitious vision for bioenergy can only be realised with an appropriate enabling policy and regulatory framework. Previous policies have successfully stimulated bioenergy deployment, helped to reduce costs and built up expertise, as well as establish the necessary feedstock supply chains. Yet many of the measures that have helped develop the market have lapsed, been cut or lack the ambition necessary to realise the sectors full potential. The report includes detailed recommendations for policy and regulatory changes. These include

- Introducing a replacement to the Renewable Heat Incentive (RHI), currently funded only until 2021. A replacement scheme is required to secure a market for renewable heat technologies including biomass boilers, anaerobic digestion and biofuels. A heat premium feed-in scheme could ensure continued growth in these markets

- Growing biomethane production as a way of greening the gas grid via the introduction of a “Green Gas Obligation”
- Introducing the much delayed 10% ethanol blend for petrol (E10) in the transport sector, and raising ambitions within the Renewable Transport Fuel Obligation (RTFO)
- Supporting the development of bioenergy with carbon capture use and storage (BECCUS)
- Introduce strong carbon price signals in all sectors of the energy economy reaching carbon prices of £70-80/t CO_2 by 2026, and over £120 by 2032.
- Continue evolve the comprehensive sustainability governance system developed by Government and industry.
- Develop the necessary infrastructure including expanding the availability of heat networks transport and storage systems for captured CO_2.
- Develop a coordinated approach to innovation related to the bioeconomy, with better integration of early-stage university research with industry-focused development and demonstration.

7.1.5 References

REA Bioenergy strategy reports:

- Bioenergy Strategy Phase 1: Bioenergy in the UK - The State of Play
- Bioenergy Strategy Phase 2: A Vision to 2032 and Beyond
- Bioenergy Strategy Phase 3: Delivering the UK's Bioenergy
- Bioenergy Strategy: Summary of recommended actions

https://www.bioenergy-strategy.com/publications

7.2 CAVALETT (2018): *RELEVANCE OF LACAF BIOFUELS FOR GLOBAL SUSTAINABILITY*

7.2.1 Study Design

Study fact sheet	
General	
Title of the study	Contribution of jet fuel from forest residues to multiple Sustainable Development Goals
Contact name	Otavio Cavalett and Francesco Cherubini
Initiator of the study	Norwegian Centre for Sustainable Bio-based Fuels (Bio4Fuels, FME)
Year of the study	2018
Publication	Cavalett, O. & Cherubini, F. (2018). Contribution of jet fuel from forest residues to multiple Sustainable Development Goals. *Nature Sustainability, 1*(12), 799-807.
Links	https://www.nmbu.no/en/services/centers/bio4fuels
Details of the study	
Geographical system boundaries	We consider our analysis generally representative of an average global level, but there are some regional peculiarities specific to the Norwegian context.
Temporal boundaries	The study reflects modern technologies for jet fuel production systems. Climate impacts are calculated using different metrics, including time horizons up to 100 years in the future.
Sectors system boundaries	The main sectors involved are aviation, biofuels and forestry. Our study focuses on the renewable jet fuel (RJF) production for the aviation sector. Biomass availability is modeled based on forest residues from annual forest wood removals in Norway.
Land use system boundaries	The main land mitigation options in our study are related to land management and bioenergy production. Biomass availability is modeled using a spatially explicit analysis covering species-specific annual forest wood removals in Norway to quantify the volume of forest residues from existing harvest operations. We limit biomass resources for production of RJF to the residues currently available in Norway. Despite capped RJF production volumes, this minimizes the additional pressure on terrestrial ecosystems and land competition and stimulates a circular economy perspective.

Ambition in GHG reduction	The climate impact analysis of jet fuel pathways included emissions from both near term climate forcers (NOx, CO, SOx, volatile organic compounds, organic carbon, black carbon and contrail cirrus) and GHGs (most notably, CO_2, CH4 and N2O, but also other climate-active species like fluorinated gases). It is recognized that no single metric can adequately and simultaneously assess the impact of different climate forcers on different aspects of climate change, such as the rate of change or long-term temperature increase. Following recent guidelines from the United Nations Environment Programme - Society of Environmental Toxicology and Chemistry Life-Cycle Initiative (Levasseur et al., 2017), we applied the complementary climate metrics global warming potential (GWP) and global temperature change potential (GTP) with different time horizons. GWP20 and GWP100 were used to address the short- and medium-term climate change impacts, respectively, targeting the effects of the rate of climate change. GTP100 is used as a proxy for long-term impacts.
Ambition in SDG improvement	We introduced a traceable quantitative approach to link indicators from environmental impact assessment methods with the SDGs. It departed from the original definitions of the official United Nations SDGs, targets and indicators, and links nine (2, 3, 6, 7, 11, 12, 13, 14 and 15) environmentally orientated SDGs to a specific set of complementary metrics derived from several updated life-cycle impact assessment models based on complex stressors–response mechanisms.
Framing of the study	We perform a detailed, spatially explicit, bottom-up analysis to quantitatively assess the environmental sustainability profile of two major representative RJF technologies (a thermochemical process considering gasification followed by Fischer–Tropsch synthesis (RJF FT)) and a biochemical process considering alcohol-to-jet (RJF ATJ)) relative to nine environmentally orientated SDGs that are closely connected to biofuels deployment. Our analysis focuses on large-scale production of RJF from forest residues available in Norway - a pioneering country when it comes to the commercial use of RJF, with ambitious deployment targets (up to 30% by 2030). We quantify climate impacts with multiple metrics addressing different spatial and temporal perspectives, including contributions from near-term climate forcers (NTCFs). Effects on the different SDGs are addressed using a specific set of indicators derived from life-cycle impact assessment models.
Assessment approach	With limited decarbonization options in the aviation sector, renewable jet fuels produced from biomass resources represent a promising opportunity. We quantified life-cycle climate impacts of jet fuel pathways including emissions from both NTCFs and GHGs. In addition to the potential implications of their deployment on the Sustainable Development Goals (SDGs), we show that climate benefits of renewable jet fuels produced from forest residues are larger in the medium/longer term than the shorter term.

7.2.2 Key messages

With limited decarbonisation options in the aviation sector, renewable jet fuels produced from biomass resources represent a promising opportunity. However, potential implications of their deployment on the Sustainable Development Goals (SDGs) remain largely unexplored.

We introduce an approach for SDG analysis based on life-cycle impact assessment methods. Climate action benefits of renewable jet fuels produced from forest residues available in Norway are larger in the medium/longer term than the shorter term, but they increase pressure on other SDGs – mainly SDGs 2, 3, 6, 11, 12 and 14 – especially for alcohol-to-jet fuel technology. Most of these adverse side-effects are alleviated with technological and supply-chain improvements.

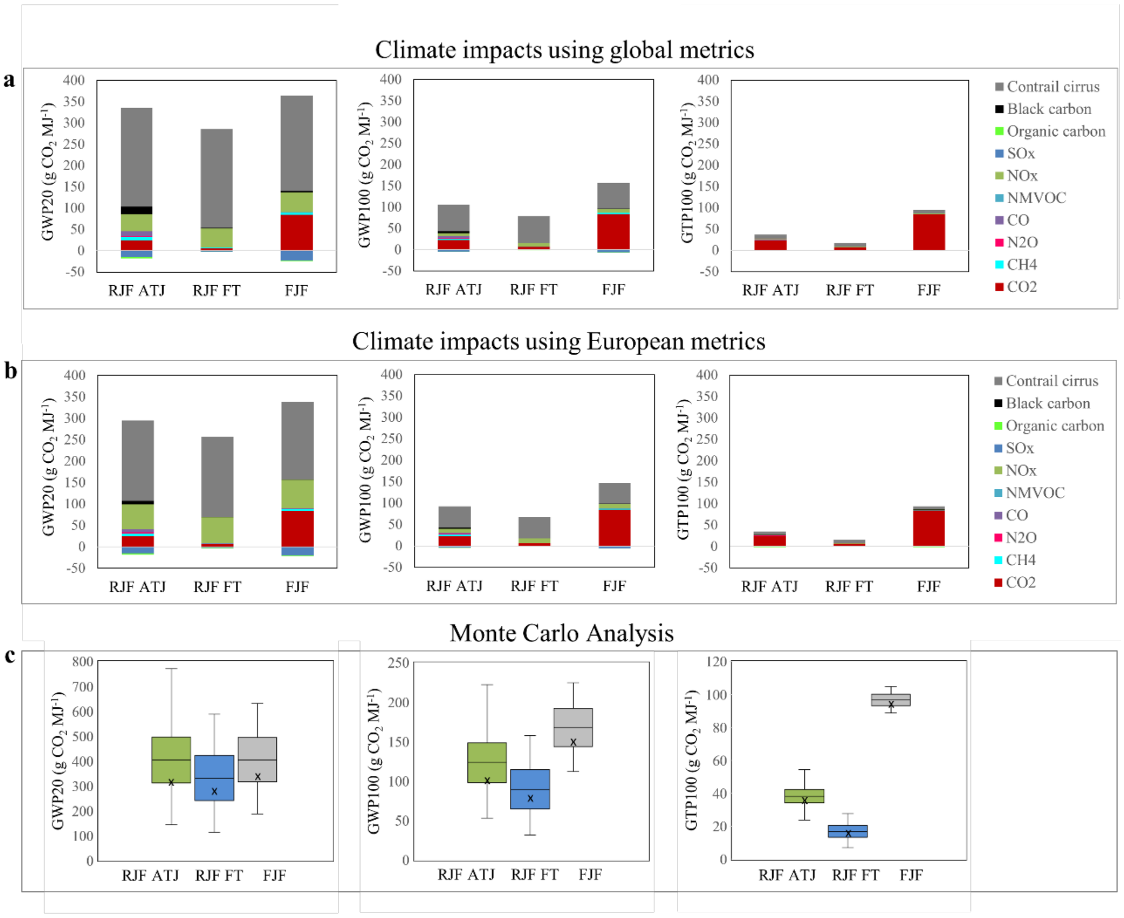
Environmental sustainability analysis can identify both synergies (mitigation options that co-deliver across SDGs) and trade-offs between climate change mitigation and the SDGs, thereby supporting their early management and mitigation.

7.2.3 Facts and figures

Both RJF pathways presented relatively lower climate impacts than conventional fossil jet fuels (FJF) across three complementary climate metrics representing short (20-year global warming potential; GWP20), medium (100-year global warming potential; GWP100) and long (100-year global temperature potential; GTP100) temporal perspectives (Figure 5). However, differences in the short term are reduced due to the relatively higher contributions of some NTCFs from RJF than FJF – especially contrail cirrus formation. The relative contribution of NTCFs decreases under a long-term perspective.

Environmental impacts of jet fuel pathways are normalized and aggregated for each SDG, producing a score to enable better visualization of the trade-offs at play. These scores are used to monitor the effects of specific improvements in technology (for example, higher conversion efficiency) and the supply chain (for example, cleaner raw materials or electricity mix) aimed at mitigating the major adverse side-effects. shows the co-benefits and adverse side-effects for aviation fuel alternatives across the different environmental impact indicators connected to the SDGs. FJF presents higher scores than RJF pathways not only in SDG 13 ‘Climate Action’ (as discussed above), but also in SDG 7 ‘Affordable and Clean Energy’ (namely, for non-renewable energy use and depletion of fossil resources), SDG 12 ‘Responsible Consumption and Production’ (ecological footprint only), and SDG 15 ‘Life on Land’ (natural land transformation and ecosystems). In the other SDGs, one or both RJF pathways show larger impacts than FJF. Major trade-offs are identified for RJF ATJ, and some of them are inherent to most biofuels.

When the technology improvement options are considered simultaneously with those in the supply chain (Figure 6d), the impact profile of the two RJF pathways significantly improves. However, trade-offs are still found for RJF ATJ in SDGs 11 and 14, while the results are similar to FJF in SDGs 3 and 6. RJF FT has comparable impacts to FJF in SDG 11 only. Innovative process design and materials that can abate specific environmental stressors, or management strategies of the associated impacts, are needed to mitigate adverse side-effects for these SDGs.



Climate impacts using global metrics
a
GWP20 (g CO2 MJ-1)
GWP100 (g CO2 MJ-1)
GTP100 (g CO2 MJ-1)
RJF ATJ
RJF FT
FJF
Contrail cirrus
Black carbon
Organic carbon
SOx
NOx
NMVOC
CO
N2O
CH4
CO2
Climate impacts using European metrics
b
Monte Carlo Analysis
c

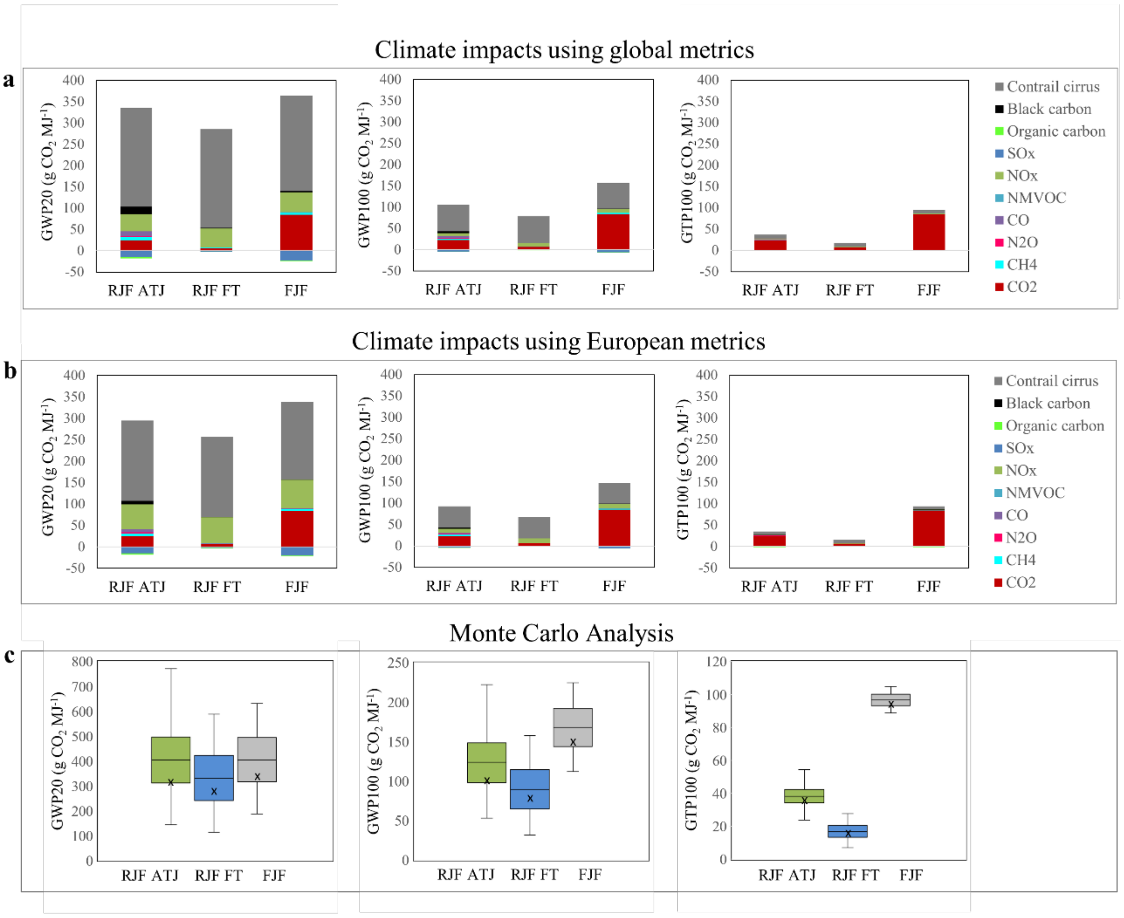


Figure 5: Climate impacts of jet fuel pathways under multiple global and regional metrics. The RJF from alcohol-to-jet pathway (RJF ATJ) and Fischer-Tropsch pathway (RJF FT) are benchmarked against fossil jet fuel (FJF). Results for 20- and 100-year GWP and 100-year GTP are presented considering global (a) and European (i.e., explicitly considering Europe as emission region) (b) metrics for NTCFs. Uncertainty results using a Monte Carlo analysis are shown in (c). The box, whiskers, and line show the interquartile range, minimum and maximum, and median from all simulation data considering global metrics from NTCFs, respectively. Symbol "x" in (c) indicates results from (a). Note the variation of the vertical scale in the different panels.

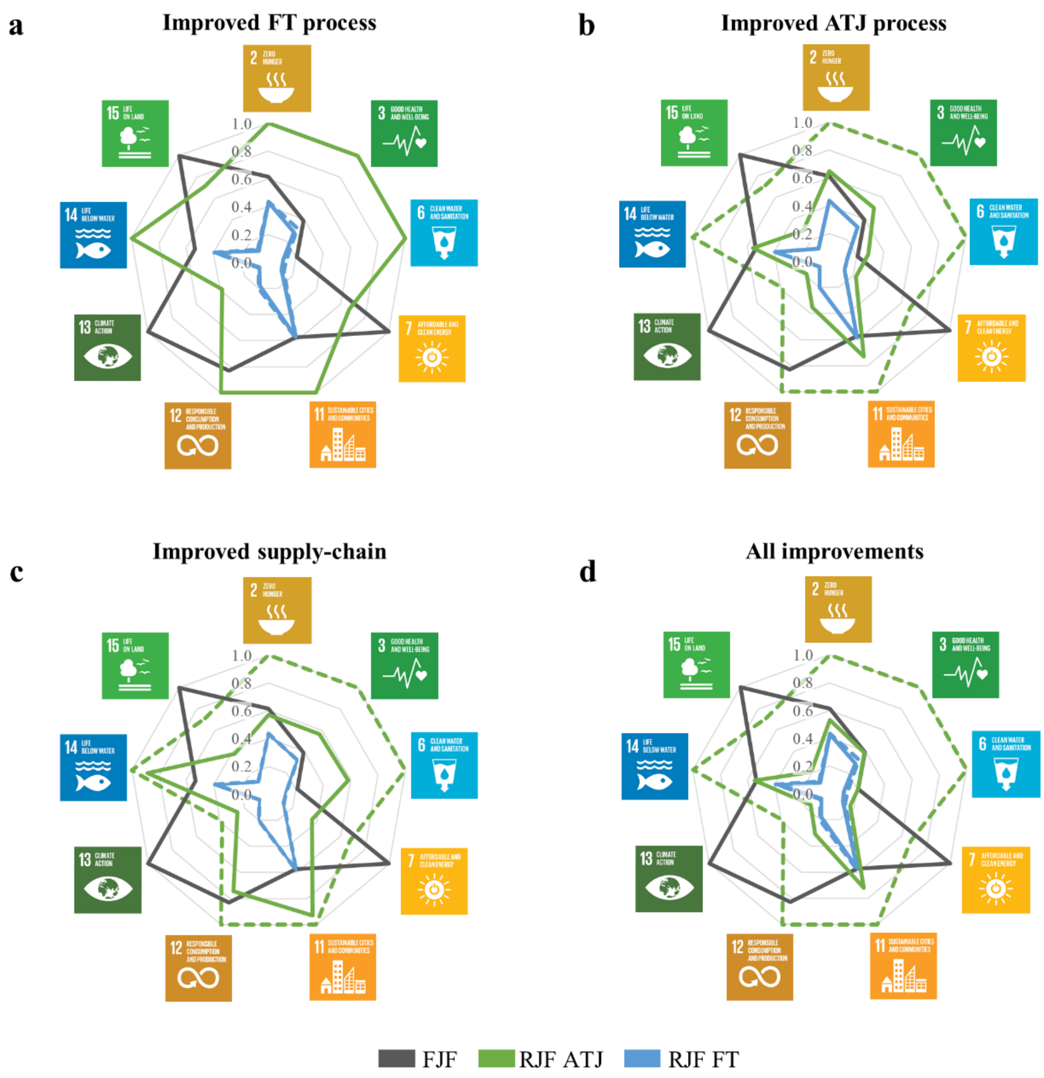


Figure 6: Contribution of technology advances and improvements in the supply-chain in the RJF pathways across the SDGs using score indicators. Improvement options are applied to the FT process only (a), to the ATJ process only (b), to the processes in supply-chain (c) and all combined (d). Solid lines show the scores after the implementation of improvement options and dashed lines show the original scores. Within each SDG, results for each one of the three indicators are normalized relative to the highest impact in the full set of simulations, and then averaged to derive a score for each SDG. Normalized scores ranges between 0 and 1, where 1 indicates the worst relative performance.

7.2.4 Key recommendations

Our analysis identified sizeable differences in climate impacts between RJF pathways, especially across temporal (from short to long term) and spatial (European versus global average values) dimensions. The inclusion of NTCFs and contrail cirrus formation in the climate assessment of RJF yields impacts up to one order of magnitude higher than those considering GHGs only. In addition to the 'climate action' SDG, RJF presents better scores than FJF in SDGs 7 and 15. However, our analysis unravelled quantitative trade-offs connected to SDGs 2, 3, 6, 11, 12 and 14, which require a range of specific technological and supply-chain improvements to be mitigated. To this end, an early environmental sustainability analysis before large-scale deployment of novel technologies is key to identify potential side-effects and quantify achievable benefits of improvement options.

A comprehensive understanding of the environmental sustainability profile along the entire life cycle of biofuel pathways is vital if we are to realize the transition to a cleaner society and their implementation at scale. Large-scale implementation would benefit from policy mechanisms that help to overcome the economic barriers of the integrated mitigation response options that can co-deliver across a range of SDGs, thus creating synergies in addressing the multiple challenges our society is facing. Future refining and developments of indicators more specifically tailored for the SDGs, ideally established through international multidisciplinary efforts, will be instrumental to identify, manage and prevent potential conflicting implications of biofuel systems for the SDG agenda.

7.2.5 References

Levasseur, A. et al. (2017). In Frischknecht, R. & Jolliet, O. (eds.), Global Guidance for Life Cycle Assessment Indicators, 58–75.

Cavalett, O. & Cherubini, F. (2018). Contribution of jet fuel from forest residues to multiple Sustainable Development Goals. *Nature Sustainability, 1*(12), 799-807.

7.3 COLLET (2019): INTRODUCTION OF DYNAMIC IN (BIO)CCS

7.3.1 Study Design

Study fact sheet	
General	
Title of the study	Introduction of dynamic in (bio)CCS
Contact name	Pierre Collet
Initiator of the study	Pierre Collet
Year of the study	2019
Publication	Albers, A., Collet, P., Benoist, A. & Hélias, A. (2019). Data and non-linear models for the estimation of biomass growth and carbon fixation in managed forests. *Data in brief*, *23*, 103841. Albers, A., Collet, P., Lorne, D., Benoist, A. & Hélias, A. (2019). Coupling partial-equilibrium and dynamic biogenic carbon models to assess future transport scenarios in France. *Applied energy*, *239*, 316-330. Albers, A., Avadí, A., Benoist, A., Collet, P. & Hélias, A. (2019). Modelling dynamic soil organic carbon flows of annual and perennial energy crops to inform energy-transport policy scenarios in France. *Science of The Total Environment*, 135278. Albers, A., Collet, P., Benoist, A. & Hélias, A. (2019). Back to the future: dynamic full carbon accounting applied to prospective bioenergy scenarios. *The International Journal of Life Cycle Assessment*, 1-17.
Links	n/a
Details of the study	
Geographical system boundaries	Scope of the study is France but can be extended to other temperate regions with similar forests composition.
Temporal boundaries	2020-2050
Sectors system boundaries	Sectors included in the study are heat and power production. CCS mitigation option is considered for both fossil and biomass resources.
Land use system boundaries	Forest management
Ambition in GHG reduction	Negative emissions (positive climate solutions) via BECCS development.
Ambition in SDG improvement	Goal 13: Take urgent action to combat climate change and its impacts by regulating emissions and promoting developments in renewable energy
Framing of the study	Dynamic models are used to include the time dimension into dynamic LCA (inventories and impact assessment) of carbon flows from the carbon sequestration and storage in the vegetation to permanent sequestration.

Assessment approach	Life Cycle Assessment, Biomass modelling

7.3.2 Key messages

Including sequestration dynamics increases climate change impact. Forest ecosystems are dynamic and mitigation targets require dynamic approaches. The dynamic LCA method is a constructive approach for timing fossil and biogenic carbon flows both upstream and downstream the supply chain/life cycle of bio-based products. Rotation length has also a strong effect on climate change results.

7.3.3 Facts and figures

Life Cycle Assessment (LCA) is a standardized method to assess multiple environmental impact categories of a system from extraction of raw materials to its final decommissioning. However, current methods used in LCA are limited for carbon accounting through linear simplifications and aggregation of carbon flows without accounting the timing of the emissions. Thus, under this study dynamic models are used to include the time dimension into dynamic LCA (inventories and impact assessment) of carbon flows from the carbon sequestration and storage in the vegetation to permanent sequestration. Climate change impact of electricity generation is assessed, from fossil (coal) and renewable (biomass) resources, with and without Carbon Capture and Storage (CCS) technologies.

The main purpose of this study is to find out if dynamic models significantly influence the environmental profiles of (bio)CCS technologies compared with static approaches. Residues from short rotation coppice such as poplar or willow (rotation length r = 15 years) are compared to biomass for bioenergy with higher rotation periods (residues from oak with r = 200 years). The dynamic biogenic carbon is assessed through a biogenic carbon modelling tool of French forest developed at IFPEN (Albers et al. 2019a). The model generates dynamic inventories of the biogenic carbon embedded in the biomass. It applies dynamic growth models from forestry science, elaborated for the French forest wood industry.

Figure 7 presents the different temporal boundaries associated with static and dynamic approaches. In static approach, all emissions / sequestration are aggregated at t=0 (year 2019 in this study). The use of the GWP100 metric for climate change assessment leads to an integration over 100 years of all the emissions / sequestration. Therefore, impacts are assessed between 2019 and 2119. In dynamic approaches, there is no consensus on when impacts should be assessed. We choose to stay in the same vein than the IPCC metric. Consequently impacts are assessed 100 years after the last emissions / sequestration, resulting in different duration over climate change assessment depending on the rotation lengths (between 2019 and 2319 for r = 200 years, and between 2019 and 2134 for r = 15 years).

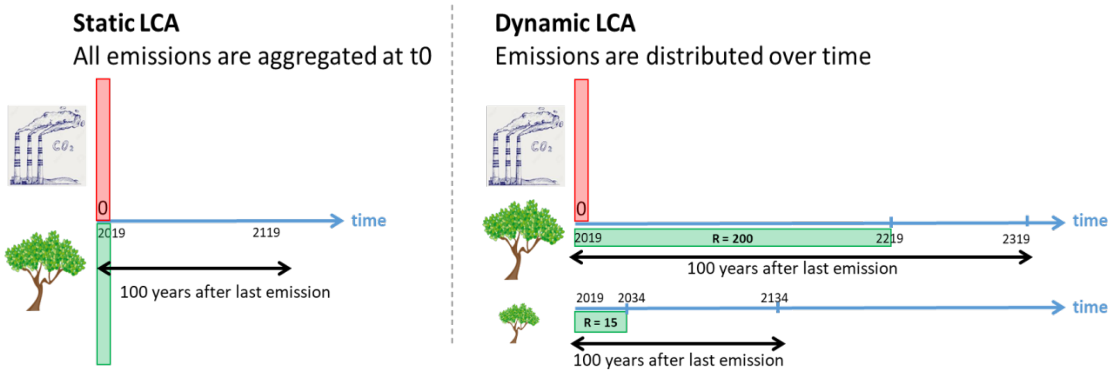


Figure 7: Different temporal boundaries in Static and dynamic LCA

Figure 8 presents the climate change impact for both static and dynamic approaches, and for the two different rotation lengths. Coal emissions are derived from the ecoinvent database, and CCS based on Monoethanolamine (MEA) capture from Pour el al. (2018). Including biogenic carbon dynamics increases climate change of electricity production from biomass. When CCS is implemented after biomass combustion, taking into account these dynamics leads to a reduction of climate change mitigation. In both cases, the increase of the rotation length has a negative effect on climate change (whether intensification of climate change in the case of direct biomass combustion, or diminution of climate change mitigation in the case of BECCS).

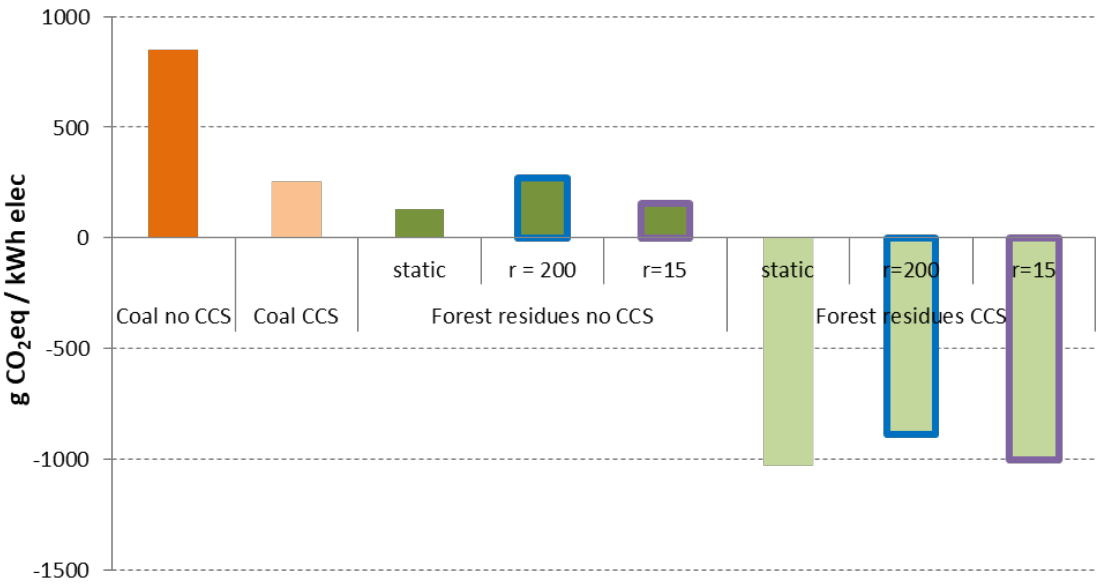


Figure 8: Climate change impact of coal / biomass electricity generation with and without CCS, and under different LCA approaches.

7.3.4 Key recommendations

The setting of the temporal boundaries and assessment approaches need to be defined with precaution, particularly in the context of biogenic carbon accounting, as different assessment approaches are possible when taking into account different temporal boundaries considered for accounting the life cycle inventory (LCI) balance. We choose to keep a time integration of 100 years after last emissions / sequestration, but fixed time horizon for climate change integration could also be an option. Furthermore, we consider that sequestration happens after emissions in this study, but different approach for carbon sequestration are possible: before or after emission. Both approaches have been applied in published studies, but few justifications have been proposed on the use of one modelling approach over the other. Proposition for forestry biomass harvest (without land use change) has recently been done in Albers et al. (2019b). At last, alternative scenario in which residues from logging operations are left on the ground (Albers et al. 2019c) instead of being used for electricity production could also be considered.

7.3.5 References

Albers, A., Collet, P., Benoist, A. & Hélias, A. (2019a). Data and non-linear models for the estimation of biomass growth and carbon fixation in managed forests. *Data in brief*, *23*, 103841. DOI: 10.1016/j.dib.2019.103841

Albers, A., Collet, P., Benoist, A. & Hélias, A. (2019b). Back to the future: dynamic full carbon accounting applied to prospective bioenergy scenarios. *The International Journal of Life Cycle Assessment*, 1-17. DOI: 10.1007/s11367-019-01695-7

Albers, A., Collet, P., Lorne, D., Benoist, A. & Hélias, A. (2019c). Coupling partial-equilibrium and dynamic biogenic carbon models to assess future transport scenarios in France. *Applied energy*, *239*, 316-330. DOI: 10.1016/j.apenergy.2019.01.186

Levasseur, A., Lesage, P., Margni, M., Deschenes, L. & Samson, R. (2010). Considering time in LCA:

dynamic LCA and its application to global warming impact assessments. *Environmental science & technology*, *44*(8), 3169-3174. DOI: 10.1021/es9030003

Pour, N., Webley, P. A. & Cook, P. J. (2018). Opportunities for application of BECCS in the Australian power sector. *Applied Energy*, *224*, 615-635. DOI: 10.1016/j.apenergy.2018.04.117

7.4 DAIOGLOU (2019): *BIOENERGY STRATEGIES IN A WELL BELOW 2˚C WORLD: INTEGRATED ASSESSMENT MODELS' PERSPECTIVE* *

7.4.1 Study Design

Study fact sheet	
General	
Title of the study	Bioenergy strategies in a Well below 2°C world: Integrated Assessment Models' perspective
Contact name	Vassilis Daioglou
Initiator of the study	Vassilis Daioglou
Year of the study	2019
Publication	The study summarizes results from the following publications, together with insights/analysis of the presenter. Huppmann, D., Rogelj, J., Kriegler, E., Krey, V. & Riahi, K. (2018). A new scenario resource for integrated 1.5° C research. *Nature climate change, 8*(12), 1027-1030. Bauer, N., Rose, S. K., Fujimori, S., van Vuuren, D. P., Weyant, J., Wise, M. et al. (2018). Global energy sector emission reductions and bioenergy use: overview of the bioenergy demand phase of the EMF-33 model comparison. *Climatic Change*, 1-16. Daioglou, V., Doelman, J. C., Wicke, B., Faaij, A. & van Vuuren, D. P. (2019). Integrated assessment of biomass supply and demand in climate change mitigation scenarios. *Global environmental change, 54*, 88-101.
Links	https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/
Details of the study	
Geographical system boundaries	Global. Results available for 6 world mega-regions (Latin America, Reforming Economies, Asia, OECD+EU, Middle East & Africa, Other)
Temporal boundaries	2000-2100
Sectors system boundaries	Complete coverage of Energy and Land systems as defined by the IPCC
Land use system boundaries	Depends on scenario and model (study presents the results of multiple), but typically the following are included: - Afforestation - Reforestation - Diet shifts - BECCS - Intensification - Forest management Level of detail of the above depend on the model used and scenarios
Ambition in GHG reduction	1.5 and 2°C

Ambition in SDG improvement	SDG 13 is addressed explicitly. Depending on the scenario context other SDG (primarily SDG 1,2,7,10,12 and 15) may be addressed implicitly to varying extents
Framing of the study	This study shows aggregate results concerning bioenergy supply and demand for all the scenarios which meet "well below 2°C" climate targets on the IPCC database created for the Special Report on 1.5°C scenarios. Some of the main IAM assumptions are highlighted in order to put these results into context by elaborating how the IMAGE model works. Sensitivity of the role of biomass across different techno-economic and technology availability (for bioenergy technologies) are also discussed. Finally, some of the future research avenues are presented
Assessment approach	Integrated Assessment Model

7.4.2 Key messages

- Biomass plays an important and active role in mitigation scenarios with up to 400 EJ/yr being deployed by 2100 (most scenarios at 100-250 EJ/yr).
- Scenarios meeting the 1.5˚C use more and sooner than those meeting the 2˚C target.
- The biomass is expected to be predominantly supplied by lignocellulosic crops and residues.
- Advanced conversion technologies such as 2nd generation fuels and BECCS options are preferred.
- It has also been shown that the deployment of biomass and bioenergy is not sensitive to techno-economic parameterization or technology availability. Even if technologies have double the price or if advanced technologies are not available, high levels of biomass are still expected in order to meet climate targets.
- Scenarios which do not have BECCS options depend on other CO_2 removal options (e.g., afforestation) at very high levels, or extreme changes in lifestyle & efficiency.

7.4.3 Facts and figures

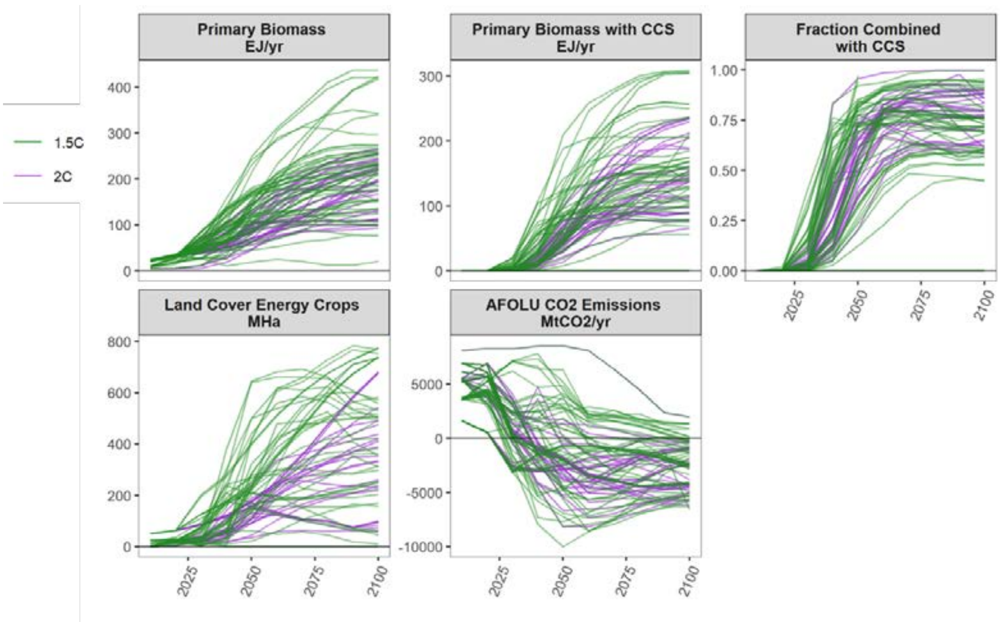


Figure 9: Projections of bioenergy, land use, and AFOLU emissions in scenarios consistent with the Paris targets.

7.4.4 Key recommendations

Climate change mitigation strategies projected by IAMs imply strong land governance. That is how they are able to provide vast quantities of biomass while keeping land use change emissions manageable. This include zoning off land with high carbon stocks and also investing in significant improvement in yields (i.e. closing yield gaps).

This is necessary because land plays a crucial role in mitigation scenarios. This is because is it an important source of negative emissions, either via BECCS or afforestation. Thus, mitigation strategies have profound implications for land management.

However IAMs suffer from a number of uncertainties, sensitivities, and areas of concern:

- IAMs adopt a plethora of methods…each with its own energy and land-use strategies. IAMs disagree on many of the specifics of bioenergy and land-use strategies.
- IAMs lack details on deployment logistics (seasonality, infrastructure, international trade, etc.)
- There is increasing interest in understanding the broader ‘sustainability’ implications of these biomass strategies such as impacts on nutrients, water use and quality, livelihoods, etc.

7.4.5 References

Bauer, N., Rose, S. K., Fujimori, S., van Vuuren, D. P., Weyant, J., Wise, M. et al. (2018). Global energy sector emission reduction and bioenergy use: overview of the bioenergy demand phase of the EMF-33 model comparison. *Climatic Change*, pp. 16.

Daioglou, V., Doelman, J. C., Wicke, B., Faaij, A. & van Vuuren, D. P. (2019). Integrated assessment of biomass supply and demand in climate change mitigation scenarios, *Global Environmental Change* (52), 88-101

Daioglou, V. et al (2017). Greenhouse gas emission curves for advanced biofuel supply chains, *Nature Climate Change* (12), 920-926

Huppmann, D., Rogelj, J., Kriegler, E., Krey, V. & Riahi, K. (2018). A new scenario resource for integrated 1.5° C research. *Nature climate change, 8*(12), 1027-1030.

7.5 GEORGE (2012): CONSIDERING POLICY OPTIONS FOR THE GREENHOUSE GAS BALANCE OF NATIVE FORESTS IN NEW SOUTH WALES, AUSTRALIA

7.5.1 Study Design

Study fact sheet	
General	
Title of the study	Considering policy options for the greenhouse gas balance of native forests in New South Wales, Australia.
Contact name	Brendan George
Initiators of the study	Brendan George, Fabiano Ximenes & Annette Cowie
Year of the study	2012
Publication	Ximenes, F. A., B. H. George, A. L. Cowie, J. Williams and G. Kelly (2012). "Greenhouse gas balance of native forests in New South Wales, Australia." Forests **3**: 653-683.
Links	https://www.mdpi.com/1999-4907/3/3/653
Details of the study	
Geographical system boundaries	Forestry regions in coastal NSW Australia.
Temporal boundaries	200 years of alternative forest management
Sectors system boundaries	The study considers native forest areas managed for wood production, and substitution value in the building and energy sectors.
Land use system boundaries	The carbon dynamics of the forest, the life cycle of harvested wood products, and the substitution benefit of using biomass and wood products (compared to more greenhouse gas intensive options) are estimated in the model.
Ambition in GHG reduction	We demonstrate the capacity of actively managed native forests to produce multiple products and GHG reduction across the lifecycle of 200 years.
Ambition in SDG improvement	The study addresses SDG 13
Framing of the study	Biophysical estimation of forest production in coastal NSW The study quantified the climate change impacts of forestry and forest management options across the entire forestry system including: the carbon dynamics of the forest, the life cycle of harvested wood products, and the substitution benefit of using biomass and wood products compared to more greenhouse gas intensive options. This included bioenergy products. The paper presents modelled estimates of the greenhouse gas balance of two key coastal native forest areas managed for production in New South Wales for a period of 200 years, and compares it to the option of managing for conservation only.

Assessment approach	We assessed 'production' and' conservation' forest management systems, reporting the carbon values in two coastal forests in northern and southern NSW. The empirically based model, Forest Resource and Management Evaluation System (FRAMES), was employed to estimate growth from Year 0 – 80. The FRAMES model is based on in-field inventory collected from fixed area plots and is used operationally to inform decision making processes in native forests. Extrapolation beyond year 80 was based on a constrained growth model set by an imposed basal area limit for the relevant forest types, as inventory data was not available beyond age 80. The forest "production" scenario considered: • Above-ground forest C — C removed from or added to the atmosphere by the growing forest (expressed as the change in long term average C stock); • C storage in harvest residues (above and below-ground); this is included in the "above-ground forest C" component above; • C storage in HWPs in use and in landfill; • GHG emissions due to the establishment and management of forests, harvesting and log transport; • GHG emissions due to manufacture of products and transport to customer; • GHG emissions due to disposal of products; • GHG emissions due to transport of harvest residues to the power station. The forest "*conservation*" scenario considers: • Above-ground forest C—C removed from or added to the atmosphere by the growing forest (expressed as the change in long term average C stock); • GHG emissions for non-wood products manufacture and use; • GHG emissions from fossil energy (GHG emissions due to the use of coal for electricity generation if harvest residues were not used for energy). Substitution benefits were quantified as follows: • SubstitutionHWP: The difference between GHG emissions to make and use HWPs and GHG emissions to make and use equivalent non-wood products; • SubstitutionRES: fossil-fuel GHG emissions avoided by using a proportion of harvest residues for bioenergy generation (assumed to displace NSW grid electricity); • SubstitutionEOL: fossil-fuel GHG emissions avoided by combusting HWPs for energy at the end of their service life (This is an alternative option to landfill; more C was stored when the woody material was returned to landfill compared to use for energy, substituting for fossil fuels).

7.5.2 Key messages

To quantify the climate change impacts of forestry and forest management options, we must consider the entire forestry system: the carbon dynamics of the forest, the life cycle of harvested wood products, and the substitution benefit of using biomass and wood products compared to more greenhouse gas intensive options.

Two case studies, NSW North Coast and NSW South Coast, show that forests managed for production deliver greater climate change mitigation than provided by conservation forests, particularly as the simulation progresses in time. Long-term carbon storage in products, and product substitution benefits, are critical to this outcome. At year 200, the net GHG mitigation benefit for production forests on the north coast is up to 195 t C ha^{-1} greater than that of "*conservation*" forests; where above-ground forest C for the corresponding NC area is estimated at 77.4 t C ha^{-1}.

The product mix for the two forest areas is significantly different as shown Figures X1 (NC) and X2 (SC). The resulting long-term C storage in wood products from the NC was much greater than that of the South Coast. The main reason for the difference was the fact that the SC forests yielded a much higher proportion of short-lived products (pulp and paper), which were not assumed to provide long-term C storage. This also explains the differences in the product substitution effect between the North Coast and SC (195.5 and 49.7 t C ha^{-1} respectively).

The GHG abatement of the 'harvest' scenario option after 200 years, excluding use of harvest residues for bioenergy, is 2-2.7 Mt C (65-92%) and 0.8-2.0 Mt C (7-15%) greater than the conservation option for the North Coast and South Coast areas, respectively.

Low level extraction of 30% of available residues for bioenergy generation results in an additional greenhouse benefit in the order of 1-2.5 Mt C for the North Coast and 4-9 Mt C for the South Coast forests in the scenarios we present.

Accounting for C in products and emissions saved by product substitution makes a large difference to the GHG outcome of the 'harvest' scenario. For the North Coast forests, C in products contributes 28% and product substitution 69% of the mitigation value.

Native forests could play a significant part in climate change mitigation, particularly when sustainably managed for production of wood and non-wood products including biomass for bioenergy.

The potential role of production forestry in mitigating climate change, though substantial, has been largely overlooked in Australian climate change policy.

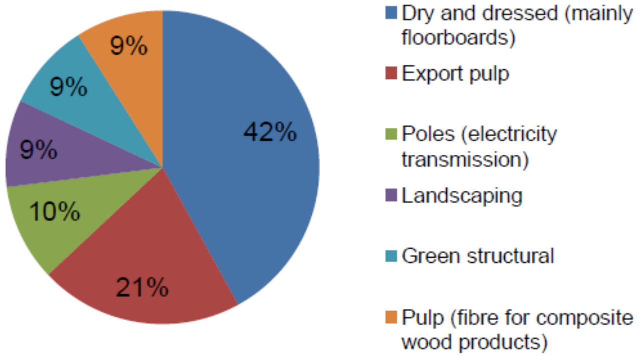


Figure 10: The product mix emanating from NC forests.

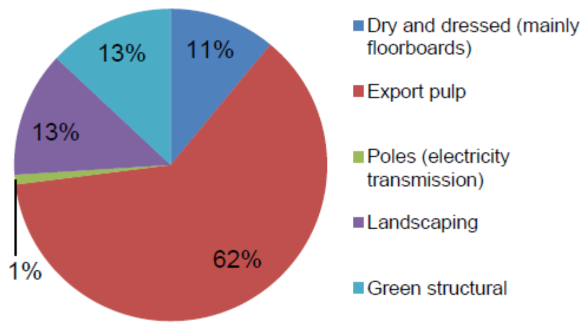


Figure 11: The product mix emanating from SC production forests. A larger portion of the wood products is used for paper manufacture (export pulp) and will release C into the atmosphere in a shorter time compared to the larger proportion of dry and dressed timber

7.5.3 Facts and figures

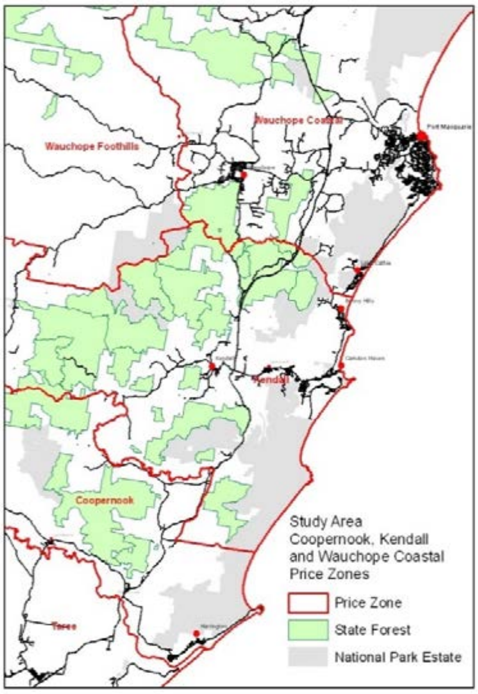


Figure 12: The study area for the north coast of New South Wales (Australia). Forests in these areas represent approximately 50% of native forest logs harvested in NSW.

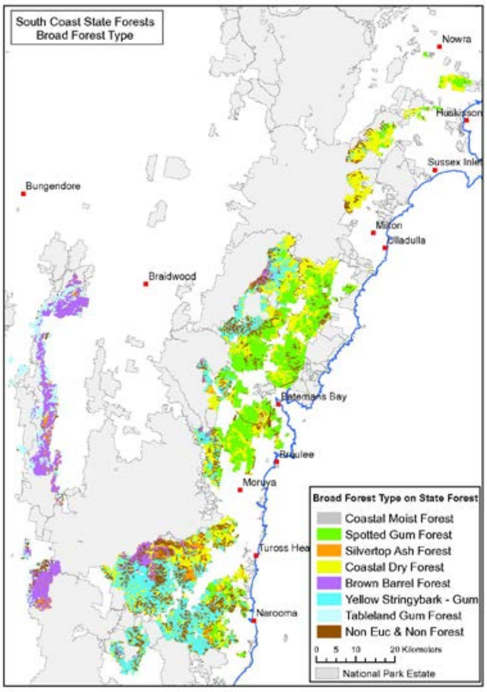


Figure 13: The study area for the south coast of NSW. Forests in these areas represent approximately 50% of native forest logs harvested in NSW.

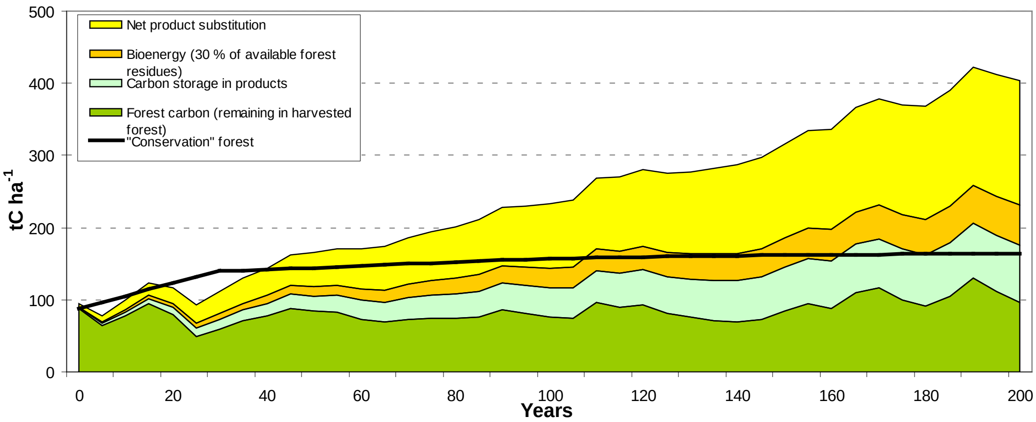


Figure 14: GHG implications of the 'conservation' and 'harvest' scenarios (t C ha^{-1} sequestered or displaced) for North Coast forests modelled over a 200 year period.

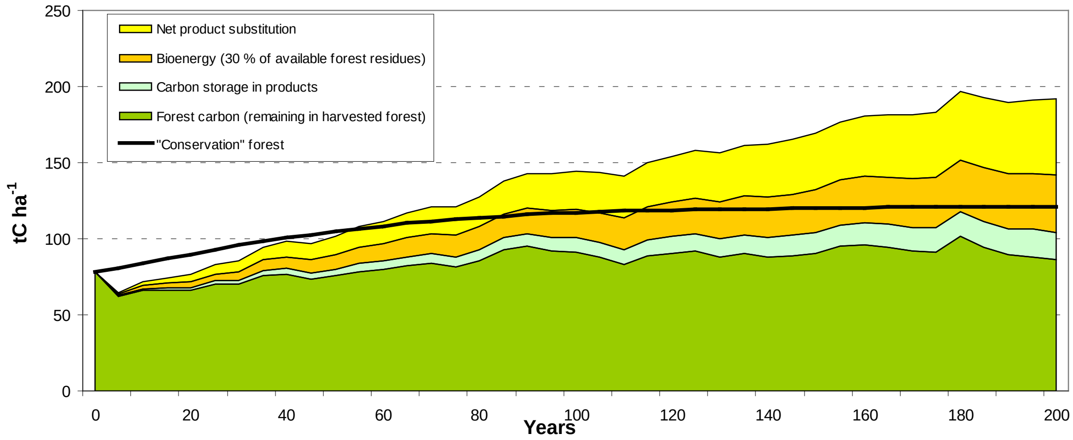


Figure 15: GHG implications (t C ha^{-1} sequestered or displaced) of the 'conservation' and 'harvest' scenarios for South Coast forests

7.5.4 Key recommendations

The following key conclusions are drawn from the case studies:

(1) Whilst in the short term, the C stored in a forest reserved for conservation may be greater than in a harvested forest, in the long term, when the full GHG balance is considered, multiple-use production forests have significantly larger GHG abatement potential than conservation forests. Proper consideration of substitution benefits and leakage potential is critical in this assessment.

(2) There is a need to explore opportunities associated with limited extraction of harvest slash (residues) for bioenergy (taking into account biodiversity and forest nutrition needs). This limited extraction has potentially large GHG mitigation benefits associated with replacing coal-based emissions from electricity generation.

(3) Irrespective of the end of life path for harvested wood products (HWPs) the GHG outcome from harvested forests will be positive compared with conservation forests.

(4) Managing the forests so they grow productively is important for sustained mitigation benefit, as is ensuring timber is processed to long-life products and can be utilised to offset fossil-fuel emissions at the end of their lifespan.

(5) Current policy directions in Australia towards returning more of the "*production*" forest estate into "*conservation*" areas, on the basis of perceived GHG benefits, will have perverse outcomes in the long-term, resulting in increased GHG emissions.

7.5.5 References

Forestry Corporation of NSW. Forest Resource and Management Evaluation System (FRAMES). A Report on its Development and Implementation to 30 June 2016. Report. Forestry Corporation of NSW. Sydney, Australia.

Lippke, B.; Oneil, E.; Harrison, R.; Skog, K.; Gustavsson, L.; Sathre, R. Life cycle impacts of forest management and wood utilisation on carbon mitigation: knowns and unknowns. *Carbon Manag.* 2011, *2*, 303–333.

May, A.; England, J.R.; Raison, J.R.; Paul, K.I. Cradle-to-gate inventory of wood production from Australian softwood plantations and native hardwood forests: Embodied energy, water use and other inputs. *For. Ecol. Manag.* 2011, *264*, 37–50.

Sathre, R.J.; O'Connor, J. Meta-analysis of greenhouse gas displacement factors of wood product substitution. Environ. Sci. Pol. 2010, 13, 104–114.

Ximenes, F. A., B. H. George, A. L. Cowie, G. Kelly, J. Williams, G. Levitt and K. Boer (2012). Harvested forests provide the greatest ongoing greenhouse gas benefits. Does current Australian policy support optimal greenhouse gas mitigation outcomes? Sydney, Australia, NSW Department of Primary Industries: 61.

Ximenes, F. A., B. H. George, A. L. Cowie, J. Williams and G. Kelly (2012). "Greenhouse gas balance of native forests in New South Wales, Australia." Forests 3: 653-683.

7.6 HOEFNAGELS (2018): *REGIONAL SPECIFIC IMPACTS OF BIOMASS FEED-STOCK SUSTAINABILITY*

7.6.1 Study Design

Study fact sheet	
General	
Title of the study	Regional specific impacts of biomass production on marginal lands
Contact name	Ivan Vera, Ric Hoefnagels, Floor van der Hilst
Initiator of the study	EADVANCEFUEL, funded by EU H2020 under grant agreement N.º764799
Year of the study	Started in 2018
Publication	The present study is submitted as D4.3 of the ADVANCEFUEL project: http://www.advancefuel.eu/en/publications
Links	http://www.advancefuel.eu/
Details of the study	
Geographical system boundaries	The geographic scope of the study is the European Union with 1 km^2 grid cell a spatial resolution. The assessment was limited to 26 EU countries: France, Lithuania, Czech Republic, Germany, Estonia, Latvia, Sweden, Finland, Luxembourg, Belgium, Spain, Denmark, Romania, Hungary, Slovakia, Poland, Ireland, United Kingdom, Greece, Austria, Italy, Netherlands, Slovenia, Croatia, Bulgaria and Portugal
Temporal boundaries	2020, 2030, 2040 and 2050
Sectors system boundaries	The focus of this study is on lignocellulosic energy crops grown on marginal land in the EU.The demand sectors included are electricity, heat, and transport, but the main focus is on advanced biofuels (road, marine aviation).
Land use system boundaries	Land related mitigation options that are assessed include the possible benefits or negative consequences of changes in above and below ground biomass and soil organic carbon from change of marginal lands to lignocellulosic energy crops; As well as impacts on water and soil erosion are included
Ambition in GHG reduction	We determine spatially explicit what the areas are that result in net GHG savings from the production of 8 different lignocellulosic crops in the European union in 2020, 2030, 2040 and 2050. The scope is limited to land use change related impacts
Ambition in SDG improvement	The SDG 13 Climate action is assed explicitly and SDG 15 is considered implicitly

Framing of the study	To meet the European Union (EU) climate objectives, the contribution of bioenergy needs to grow substantially post 2030. Especially in sectors that have few renewable alternatives to biomass such as heavy road transport, aviation and shipping, chemicals and materials. However, there are many concerns related to the availability and sustainability of biomass for these biobased applications. Furthermore, part of the sustainable biomass potential remains currently unexploited due to major barriers, lack of infrastructure, farmers experience, regulatory compliance, high uncertainty regarding the sustainability aspects and lack of markets. This is the case for lignocellulosic energy of which experience is limited to small test fields (0.05% of utilized agricultural area in the EU). Lignocellulosic energy crops are unlikely to be cultivated on productive lands due to the poor cashflow for farmers compared to food and feed crops. However, they could have a comparative advantage if grown on low productive land due to the relatively high yields and potential co-benefits that could be achieved (e.g carbon stock increase, socio-economic benefits). Potential yields and environmental impacts of energy crop cultivation depend on the biophysical conditions (e.g agro-ecological suitability, former land use) and are therefore spatially heterogenous. The objective of this study is to assess the current and future potential and environmental impacts of lignocellulosic energy crop production on marginal land in the European union under RED II criteria.
Assessment approach	We assessed the potential and LUC-related environmental impacts of 8 lignocellulosic energy crops spatially explicitly (1km2) in EU up to 2050. The considered indicators are: GHG emissions determined by the IPCC guidelines, water scarcity determined by a water balance approach and risk of soil erosion determined by the universal soil loss equation.

7.6.2 Key messages

- The use of marginal lands for lignocellulosic energy crops production is a valuable strategy to increase sustainable biomass supply in the future. However, there is currently little experience with these types of crops. Although potentially available, it will require substantial efforts before they are readily available to produce bioenergy at commercial scale. This includes the development of infrastructure, farmers experience, regulatory compliance and support, as well as enabling sustainable biomass production in the EU under RED II sustainability criteria and incorporate innovative cropping schemes.
- It is projected that the potential production of lignocellulosic energy crops in EU can contribute to mitigate from 20 to 26 million t CO_2/year by carbon sequestration in biomass and soils under the right conditions. The GHG savings from the replacement of fossil fuels with advanced biofuels will increase the net GHG saving potential substantially.
- This study shows that smart choices on location and crop type for lignocellulosic energy crop production can enable sustainable biomass production in Europe under RED II sustainability criteria whilst leading to increased GHG savings from carbon sequestration in biomass and soils.

7.6.3 Facts and figures

The lignocellulosic energy crops potentials on marginal lands in the EU is estimated to be the highest for grassy lignocellulosic energy crops such as Miscanthus, Switchgrass and Reed canary grass. By 2050, their potential is estimated at 1050 PJ for Miscanthus, 880 PJ for Switchgrass, and 881 PJ for Reed canary grass. Grassy crops have a relatively high yield compared to woody crops as well as relative high suitability under various biophysical conditions. When considering for each potential production site the most suitable crop (highest attainable yield) under local conditions, the biomass potential (referred as yield efficient in Figure 16) increases up to 1610 PJ by 2050. To provide some context, current (2017) gross inland consumption of bioenergy stands at 6033 PJ, from which 1089 PJ were supplied from agriculture (Bioenergy Europe 2018).

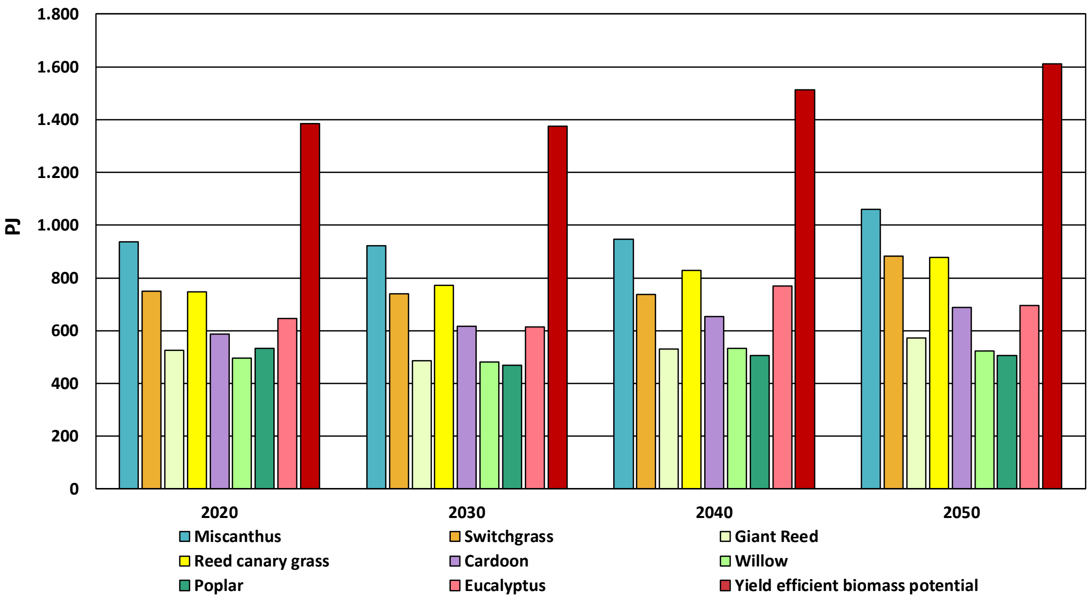


Figure 16: Biomass potentials for each lignocellulosic energy crop (i.e. all available land is allocated to one crop) and yield efficient biomass potential (for each location the crop with highest potential biomass yield is selected) in Europe for 2020, 2030, 2040 and 2050.

On spatial basis (Figure 17), the lowest biomass yields (GJ/ha year) are obtained in areas that are characterized by extreme local biophysical conditions that limit the potential biomass production. For example, the most northern parts of Europe (Sweden and Finland) and areas located in the vicinity of the Alps. On average, these locations can only potentially deliver 0 - 100 GJ/ha year. On the contrary, the areas with the highest biomass potentials are in some areas of Spain, Greece and Hungary. These areas feature favourable biophysical conditions which result in potential biomass yields of 350-450 GJ/ha year (depending on crop type).

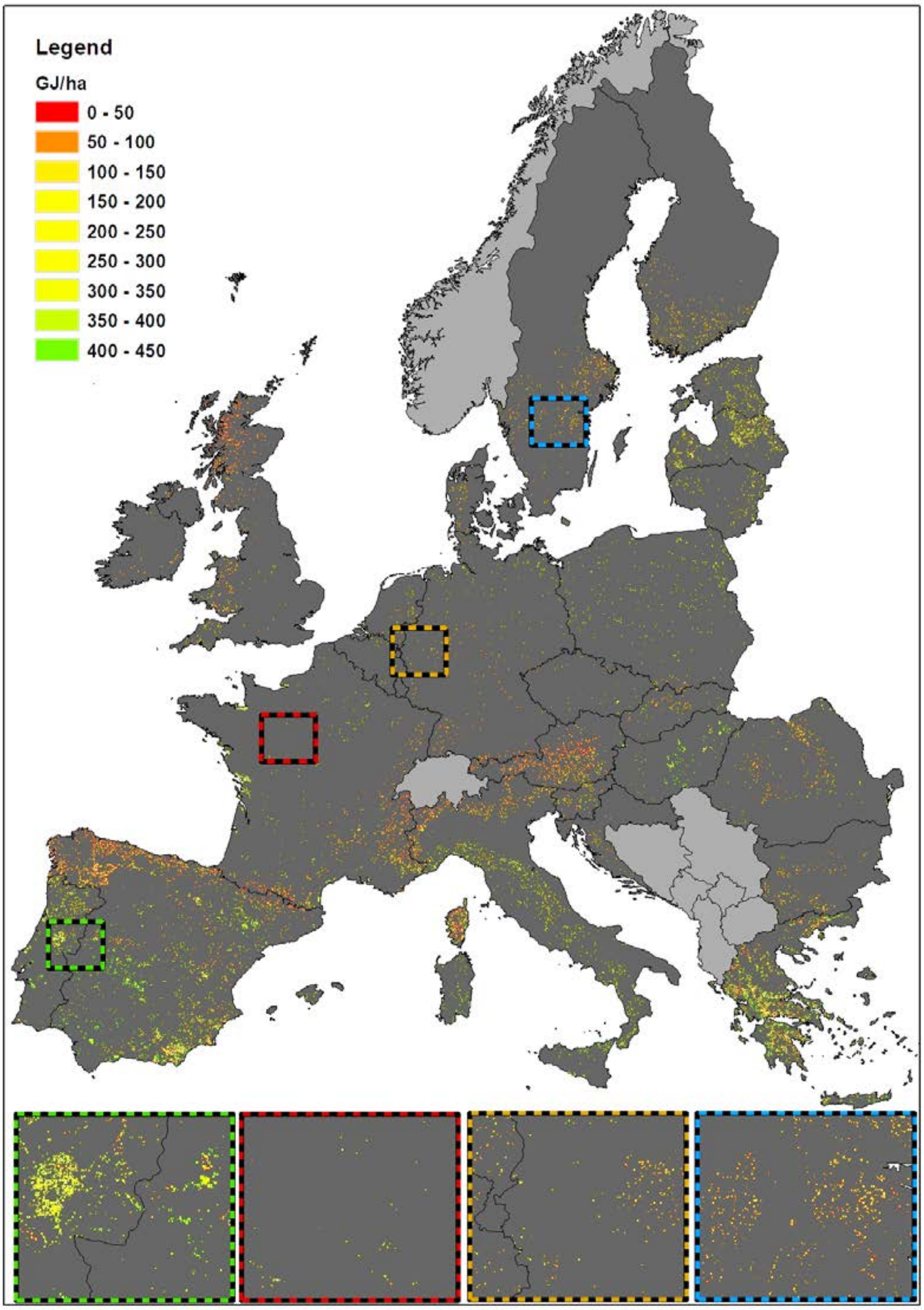


Figure 17: Yield efficient biomass potential (at each location of available land, the crop with the highest attainable biomass yield is selected) in Europe for 2050.

On average, the cultivation of all feedstock types results in carbon sequestration for different points in time. Net CO_2 emissions from LUC vary on average between -0.23 t CO_2/ha year and – 7.1 t CO_2/ha year depending on crop type and point in time. However, the difference in location specific biophysical conditions determines that for several areas in Europe, the production of lignocellulosic energy crops results in LUC-related CO_2 emissions (as seen in Figure 18, in the Scandinavian countries). The changes in carbon stocks are mostly the result of changes in biomass carbon and to a lesser extent of changes in the SOC. Generally, the conversion of land to grassy lignocellulosic energy crops results in the loss of soil organic carbon. Conversely, the change of land towards woody lignocellulosic energy crops results in carbon accumulation in the soil. For all the feedstock types, most of the carbon accumulation occurs in the above ground biomass. Still, a large share of this carbon is contained in the harvestable section of the plant.

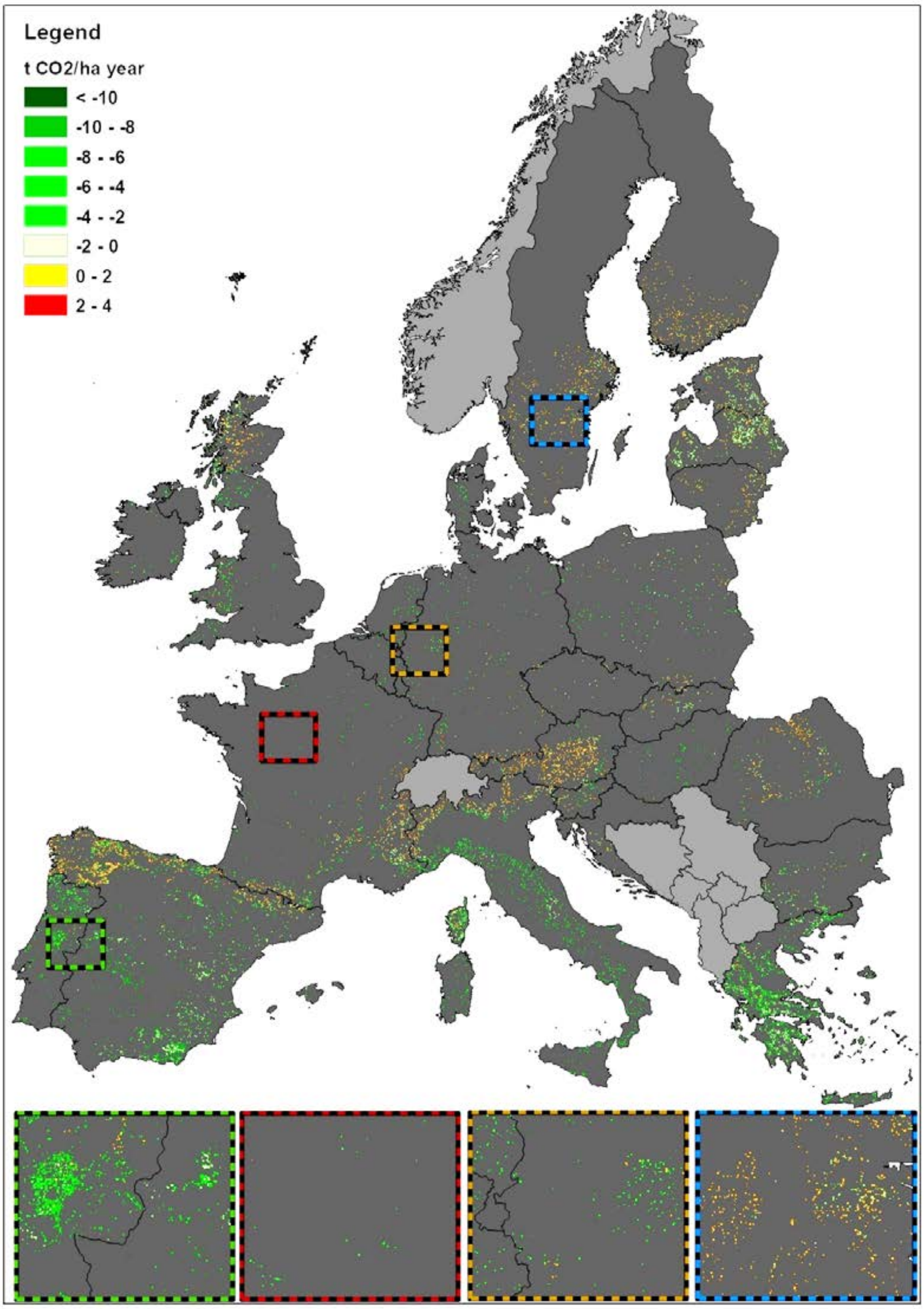


Figure 18: Spatial variation of max carbon sequestration potential (for each available location, the crop with highest carbon sequestration potential is selected)) in Europe for 2050.

7.6.4 Key recommendations

The potential production of lignocellulosic energy crops on marginal lands can cover to some extent future bioenergy demand. However, the deployment of such production should be done with care. Despite that it can contribute towards EU GHG emissions reduction targets it can also generate considerable impacts in other areas. The implementation of lignocellulosic energy crops production in marginal land will require demanding location specific measures that promote an efficient use of water and include support practices targeted to reduce soil loss. In addition, considerable support from the government would be required to support farmers and implement location specific measures to reduce potential environmental impacts.

7.6.5 References

Bioenergy Europe (2018). Bioenergy Europe statistical report.

7.7 KANG (2019): *SUGARCANE BIOENERGY IN SOUTHERN AFRICA: ECONOMIC POTENTIAL FOR SUSTAINABLE SCALE-UP*

7.7.1 Study Design

Study fact sheet	
General	
Title of the study	Sugarcane bioenergy in Southern Africa: Economic potential for sustainable scale-up
Contact name	Seungwoo Kang
Initiator of the study	IRENA (International Renewable Energy Agency)
Year of the study	2019
Publication	IRENA (2019). *Sugarcane bioenergy in southern Africa: Economic potential for sustainable scale-up.* Abu Dhabi: IRENA.
Links	https://www.irena.org/publications/2019/Mar/Sugarcane-bioenergy-in-Southern-Africa-Economic-potential-for-sustainable-scale-up
Details of the study	
Geographical system boundaries	Southern Africa : Eswatini (formerly Swaziland), Malawi, Mozambique, South Africa, Tanzania, Zambia and Zimbabwe
Temporal boundaries	Time horizon to 2030
Sectors system boundaries	Bioethanol and electricity from sugarcane
Land use system boundaries	Farmland and grassland suitable and available for sugarcane cultivation excluding protected areas, forests and other land use under environmental criteria as well as terrain slope over 16% for soil protection
Ambition in GHG reduction	Sugarcane ethanol can reduce greenhouse gas (GHG) emissions by up to 80% compared to gasoline
Ambition in SDG improvement	Bioethanol and electricity are related to SDG 7. Improved productivity and technologies would enhance energy access and affordability. As sugar industry is an important part of economy in the region, bioenergy from sugarcane would contribute to economic growth as well.
Framing of the study	Substantial potential exists to scale up sustainable production of bioenergy from sugarcane cultivation in southern Africa. This study evaluates the potential for seven sugar-producing countries in the Southern Africa Development Community (SADC): The potential for both liquid biofuel and electricity production is evaluated, as surplus to current and projected sugar demand for domestic consumption and export.
Assessment approach	GIS-based economic potential assessment

7.7.2 Key messages

Sugarcane has been produced in Africa for centuries, but little has been used for biofuel. Southern African countries possess substantial sugarcane industries that could also be a significant source of sustainable heat, power and biofuels. Sugarcane is a highly productive feedstock for bioenergy due to its semi-perennial production cycle, which allows annual harvests and replanting at intervals of five years or more, and its high energy content. Sugarcane ethanol can be cost-competitive and reduce greenhouse gas (GHG) emissions by up to 80 % compared to gasoline.

Sugarcane is currently grown on some 554 000 hectares of land in the seven countries studied. If yields were improved to the extent that the maximum potential can be reached on all the existing sugarcane farms and all the sugarcane surplus to sugar requirements produced therefrom were converted to bioenergy, some 1.4 billion litres of ethanol could be produced at an average cost of USD 0.71 (71 USD cents) per litre of gasoline equivalent. But only a very small portion of this, about 70 million litres of low-cost ethanol from molasses would compete with gasoline at a world crude oil price of USD 50 per barrel (gasoline price of USD 0.43 USD/L), close to prices in recent years. Depending upon whether sugarcane feedstock is directed primarily to sugar production or ethanol production, different amounts of bagasse and straw are available for electricity generation.

Prospectively, sugarcane cultivation could expand as much as nine-fold, to some 5.1 million hectares (Mha) of rainfed land without irrigation, or 99-fold, to some 54.9 Mha of land if irrigation were introduced. If irrigation were introduced to only the 3.7 Mha of the most suitable land, implying overall expansion to 8.8 Mha of rainfed and irrigated land, bioenergy output could expand to some 72 billion litres of ethanol and 156 terawatt-hours (TWh) of electricity per annum. New technologies for sugarcane growth and conversion could further expand the bioenergy potential. Energy cane, with yields up to twice those of conventional sugarcane, offers one key technology vector. Second-generation conversion plants, which can produce ethanol not only from the sugar portion of the cane but also the straw, offer a second key technology vector. These twin technology vectors, applied to all land suited to sugarcane cultivation, could further expand energy production to some 129 billion litres of ethanol production and 159 TWh of electricity generation per annum. With crude oil prices towards the middle of a prospective range of USD 50 to USD 100 per barrel, most of the ethanol thus produced would be cost-competitive on an energy-equivalent basis. The electricity could be generated for as little as USD 0.054 per kWh.

7.7.3 Facts and figures

The land potentially suitable for sugarcane production was estimated at 54.9 Mha with good soil in the seven selected countries of southern Africa. The potential from direct sugarcane conversion could reach 40.2 billion litres with sugarcane cultivation expanding to 5.1 million hectares of land only suitable for rainfed farming, or 71.7 billion litres and 156 terawatt-hours (TWh) of electricity per annum with further expansion to 54.9 Mha of land suitable for irrigated farming at an average cost of USD 0.69 per litres of gasoline equivalent. About another 0.5 billion litres could be converted from molasses, by-products of sugar production. With crude oil prices of USD 100 per barrel, the total amount would be cost-competitive for transport fuel.

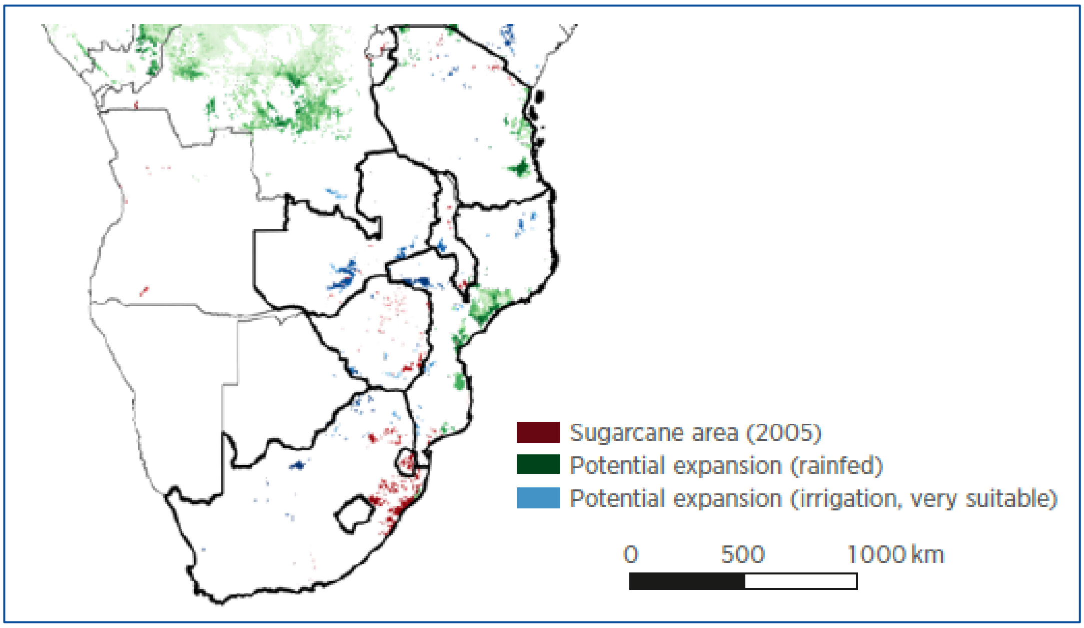


Figure 19: Areas of potential sugarcane expansion.

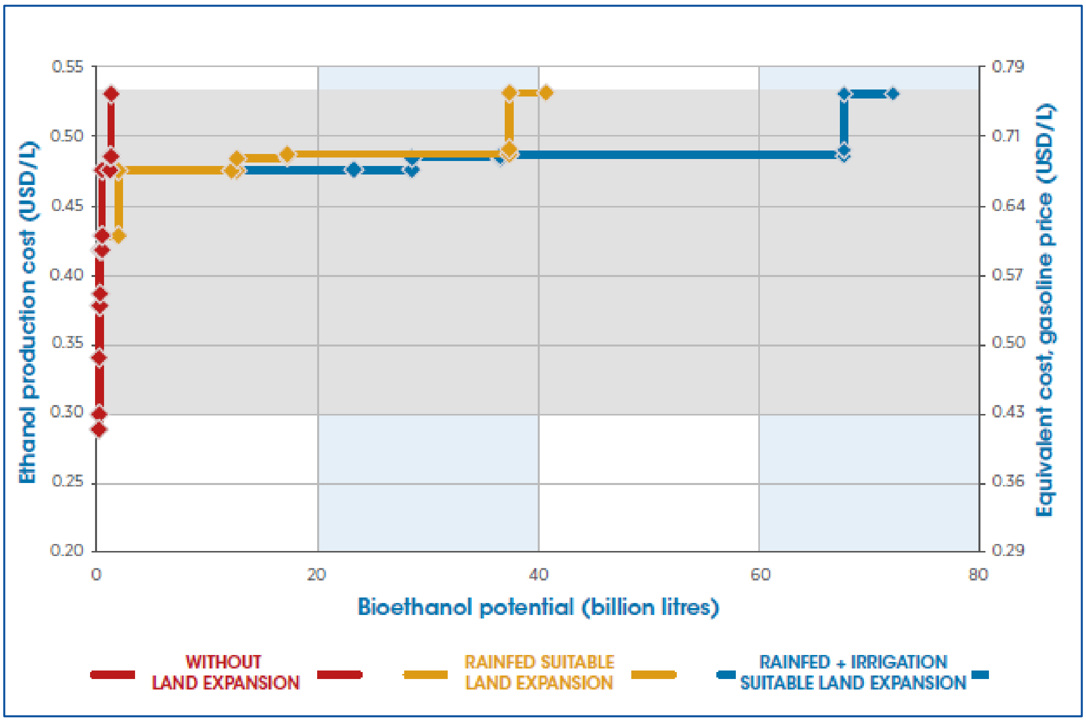


Figure 20: Supply curves for ethanol with improved yield and land expansion by 2030.

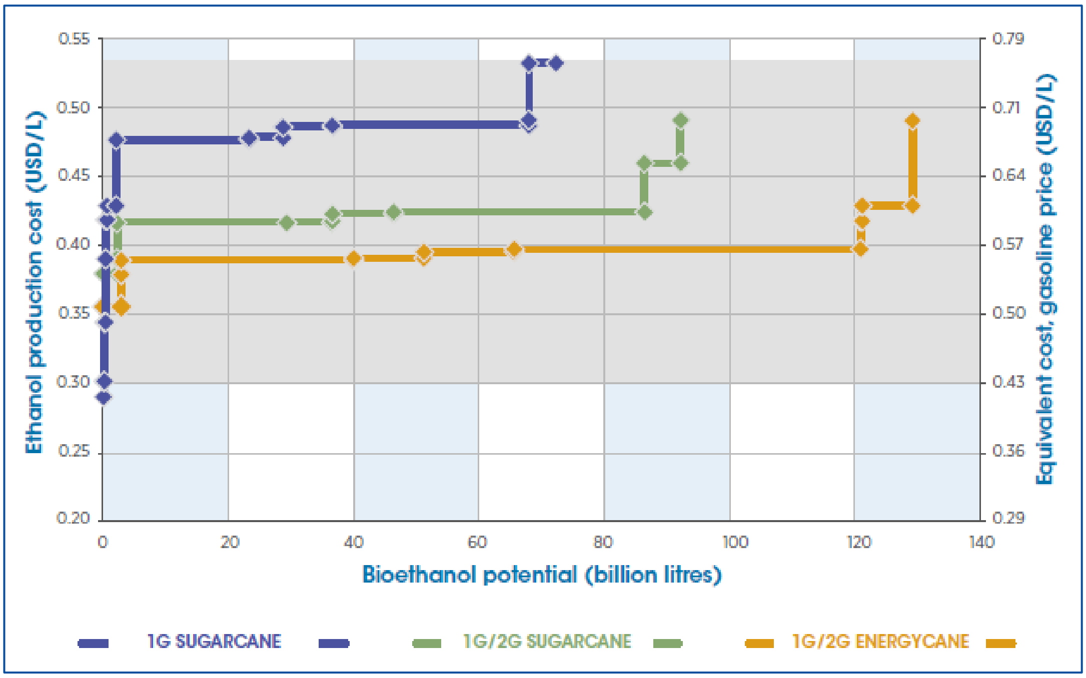


Figure 21: Supply curves for ethanol with integrated 1G and 2G processes.

With the future application of advanced technology for cultivation and conversion, the ethanol potential would be further enhanced. Most of the potential, in either case, would be cost-competitive with gasoline in the middle of the postulated crude oil price range of USD 50 to USD 100 per barrel. Ethanol is even more cost-competitive with current gasoline market prices in the region, which range from USD 0.92 to USD 3.34 per litre. This is especially true in those countries with the highest gasoline prices, namely Zambia (USD 1.71/L) and Zimbabwe (USD 3.34/L).

7.7.4 Key recommendations

This study reviews the theoretical bioenergy potential from sugarcane and associated development costs in seven sugar-producing countries in the Southern African Development Community (SADC), with the aim to provide a foundation for more detailed country-level studies exploring practical potential. With support from development agencies and engagement by both government and business sectors, the seven sugar-producing countries could tap the huge potential of sustainable bioenergy production from this high-yielding energy crop. Further research could focus on how much of this potential should be developed in which time frame and in what way, with due consideration of prevailing and anticipated land-use patterns. Best crop mix within arable land should be explored to feed ever-increasing population in the region and therefore the land on which energy crops and other non-staple cash crops are planted or expected to be planted should be planned with due consideration of trade-offs and synergies. The geo-spatial methodologies employed in this study could be a useful tool to pave the way for expanding sugarcane cultivation as a possible alternative. This would also raise awareness about added value of sugarcane cultivation and thereby improve the livelihood of rural communities.

7.7.5 References

IRENA (2019). Sugarcane bioenergy in southern Africa: Economic potential for sustainable scale-up. Abu Dhabi: International Renewable Energy Agency.

7.8 LANGHOLTZ (2019): *ECONOMIC ACCESSIBILITY OF BIOENERGY WITH CARBON CAPTURE AND SEQUESTRATION (BECCS) IN THE US* *

7.8.1 Study Design

Study fact sheet	
General	
Title of the study	Economic accessibility of bioenergy with carbon capture and sequestration (BECCS) in the US
Contact name	Matthew Langholtz
Initiator of the study	U.S. Department of Energy
Year of the study	2019
Publication	Langholtz et al., submitted to journal *Land*
Links	www.bioenergykdf.net
Details of the study	
Geographical system boundaries	Contiguous US States
Temporal boundaries	2020 and 2040
Sectors system boundaries	Biomass production through biopower production
Land use system boundaries	Agricultural lands and forestlands
Ambition in GHG reduction	Agnostic (reporting CO_2 supply potential and supply cost)
Ambition in SDG improvement	Policy agnostic
Framing of the study	Given potential future demand for C sequestration, report potential near-term and long-term C sequestration in the US from BECCS using agricultural residues, biomass energy crops, forest residues, and forest thinnings
Assessment approach	Quantify potential C sequestration as a function of price with 1) OR-SAGE, a facility citing model, 2) potential biomass feedstock supplies from

7.8.2 Key messages

Initial results suggest that BECCS in the US has a technical potential to sequester nearly 200 million tonnes of CO_2 with currently available feedstocks, and over 700 million tonnes per year of CO_2 if energy crops are brought into production, while meeting projected demands for food, feed, fibre, and exports. These results are not unlike the 100 million to 630 million tonnes CO_2 per year reported by Baik et al. (2019). Cost of sequestration varies with scenario, logistics assumptions, accounting equation, and marginal unit of CO_2 sequestered. CO_2 sequestration costs vary within each simulation, but average costs are generally within or below the $100 to $200 per tonne CO_2 reported by IPPC (2018: Fig. 4.2). For example, average costs of BECCS are estimated to start at about $125 per tonne CO_2, but accounting for electricity revenues reduces cost about 25%, and additionally accounting for avoided CO_2 emissions from conventional generation reduces costs about 60%. Final results are expected to be forthcoming in Langholtz et al. (in preparation). Preliminary results are shown in Figure 22.

IPCC (2018) includes three of four pathways to less than 1.5 degrees warming that include BECCS, but raises concerns of negative side effects of BECCS including biodiversity and food security. Concerns have been raised that bioenergy in general can have unintended environmental effects (e.g. Norton et al. 2019) or can cause land competition with food production (Searchinger et al. 2015). As with many types of agricultural or forestry land uses, cellulosic biomass feedstocks can be produced in ways that are environmentally and socially detrimental or beneficial depending on practices in the field and system-specific contexts (e.g. Brandes et al. 2016, Brandes et al. 2018a, Brandes et al. 2018b, Chaplin-Kramer et al. 2016, Dale et al. 2016, Efroymson et al 2013, Englund et al. 2020, Tilman et al 2009). From an economic supply perspective, inflation-adjusted commodity crop prices in the US are near historic lows (USDA ERS 2019), US farm bankruptcies are rising, and billions of dollars are spent annually on US farm subsidies, suggesting there are opportunities for perennial cellulosic biomass feedstocks as an alternative revenue stream for US farmers. Perennial biomass feedstocks offer strategies for farmers to adapt to climate change (Jager et al. 2020, Langholtz et al. 2014). Forest management can benefit from price supports for harvesting small-diameter trees to reduce threats of forest fires, mitigate pine beetle infestations, and realize desired future stand conditions. The feedstocks in this study are limited to those that can have neutral or beneficial environmental and socioeconomic effects if applied with strategies such as best management practices, landscape design, precision agriculture, multipurpose biomass production, and providing economic incentives for environmental services (USDOE 2017). If executed deliberately, bioenergy in general and BECCS in particular has the potential to contribute to United Nations Sustainable Development Goals such as life on land, life below water, affordable and clean energy, decent work and economic growth, sustainable cities and communities, no poverty, and climate action without compromising the other Sustainable Development Goals (Kline et al 2017).

The future role of BECCS in the US as a component of strategies toward a WB2 world while addressing UN SDGs will be driven by yet-unknown future policies, incentives, economic conditions, and technology developments. However, in round estimates of cumulative potential from 2030 to 2040, preliminary results of this study suggest the US has a technical potential to sequester up to 45 billion Mg CO_2 by BECCS by 2100. This is equivalent to about 30%, 11%, and 4% of the targeted global sequestration by BECCS by 2100 in Pathways 2, 3, and 4, respectively in IPCC (2018). This study is not exhaustive of scenarios or opportunities to increase biomass supplies in the US. For example, biomass supplies in this analysis are from the base case of biomass crop yield improvement reported by USDOE (2016), resulting in about 370 million tonnes of biomass produced in the future under adequate market incentives. However, future energy crop production increases to almost 670 million tonnes under the high-yield scenario (USDOE 2016). Further, results from USDOE (2016) do not necessarily represent the spatial distribution of demand for biomass that might respond to demand for BECCS, meaning biomass production could be better tailored to support BECCS in the future than the supplies used in this study.

7.8.3 Facts and figures

The lower forty-eight US states currently use about 330 million tonnes of biomass per year but have the potential produce an additional 0.8 to 1.1 billion tonnes per year within sustainability and economic constraints while prioritizing food, feed, fibre, and export demands (USDOE 2016, 2017). Future demands for biomass are unknown, but a portion of this biomass supply could be allocated to BECCS. This study does not propose or assume policies, but rather reports the potential quantity of CO_2 sequestration as a function of price.

To assess the economic accessibility of BECCS in the US, this study combines several key data inputs and models including: 1) potential biomass supplies from USDOE (2016), 2) CO_2 emissions outputs from Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET) (Wang et al. 2018), 3) transportation costs and associated CO_2 emissions from the Biofuel Infrastructure, Logistics and Transportation Model (BILT) (Lautala et al. 2015), 4) biorefinery siting locations with the Oak Ridge Siting Analysis for power Generation Expansion (OR-SAGE) (Omitaomu et al. 2012), and 5) costs of electricity and CO_2 sequestration from the Integrated Environmental Control Model (IECM) (Berkenpas et al. 2018).

In the modelled simulations, potential county-level feedstocks as a function of feedstock price are allocated to hypothetical biopower generating locations within saline aquifer basins where CO_2 can be sequestered. Feedstock sources include near-term resources (agricultural residues, forest residues, and small-diameter trees from thinnings or plantations) and long-term resources (same as near-term with the addition of potential biomass energy crops). Economic and environmental aspects of these potential supplies are described in detail in USDOE (2016, 2017). A summary of key scenario attributes is show in Table 4. Two biomass logistics scenarios modelled include 1) "conventional" i.e. herbaceous material processed as bales and wood processed as chips, and 2) "advanced" i.e. all biomass processed as pellets. Two carbon accounting approaches include 1) cost of BECCS after generated electricity is sold, and 2) cost of BECCS after electricity sales plus avoided CO_2 emissions from conventional power sources. Simulations solve for cost minimization across parameters of feedstock use, feedstock supply locations, and power plant size. The spatially explicit modelling accounts for supply chain costs and carbon efficiencies from biomass production through CO_2 injection into sequestration basins. Power generation systems considered include the integrated gasification combined cycle (IGCC) system and the pulverized system.

Table 4: Key parameters evaluated in the study

Parameter	Conditions included
Generation	• Pulverized • Integrated Gasification Combined Cycle (IGCC)
Biomass resources	• 2020: Agricultural residues (e.g. corn stover) and forestland resources (i.e. logging residues and forest thinnings) • 2040: Biomass energy crops in addition to 2020 resources
Biomass logistics	• Conventional (i.e., bales and chips delivered by truck) • Advanced (i.e. bales and chips delivered to depots, biomass pellets delivered to generation facilities
Carbon cost accounting	• Gross cost of sequestration • Cost of sequestration net of electricity sales • Cost of sequestration net of electricity sales with emissions avoided from conventional fossil electricity generation

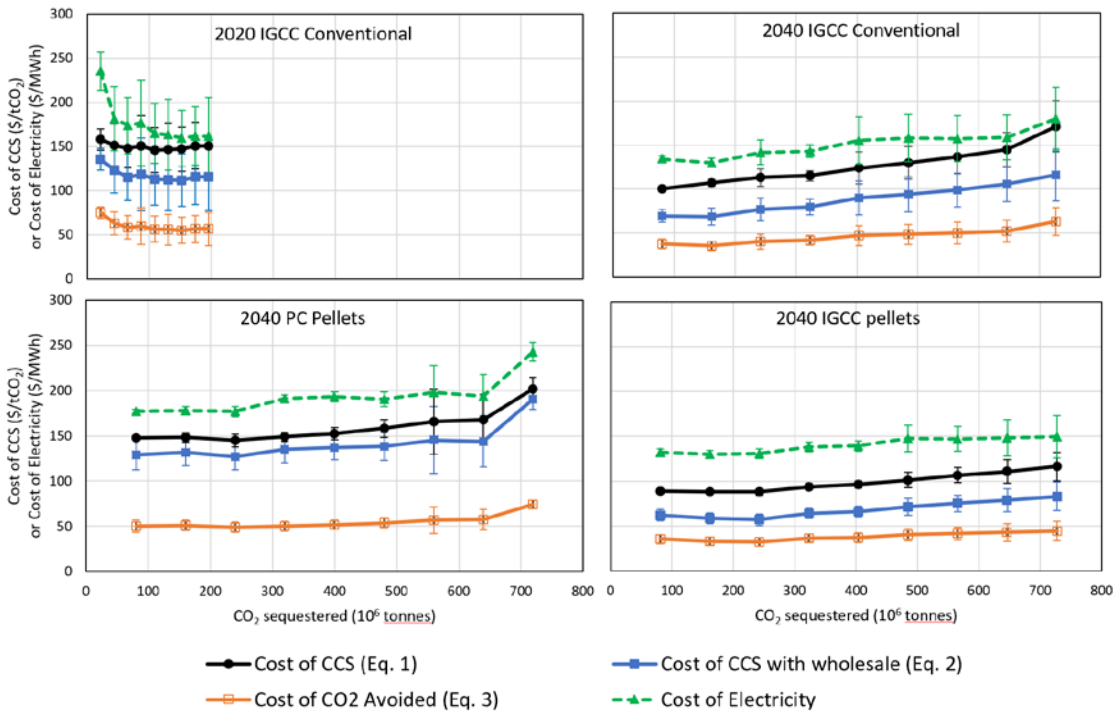


Figure 22: Preliminary results of estimated CCS potential supplies and costs in review (Langholtz et al. (submitted). BECCS sequestration scenario-average costs ($ Mg^{-1} CO_2) by CO_2 sequestered (million Mg yr^{-1}), net after supply chain emissions for four BECCS scenarios: 2020 IGCC conventional, 2040 IGCC conventional, 2040 PC pellets, and 2040 IGCC pellets. Error bars represent one standard deviation of the values provided in the Supplementary Materials in the submitted manuscript. "Conventional" refers to biomass handled as chips or bales; "pellets" refers to biomass converted to pellets in process depots. Eq. 1, Eq. 2, and Eq. 3 represent grow costs, costs net after electricity sales, and costs net after electricity sales and including CO_2 reduction due to displaced electricity generation (see Table 4).

7.8.4 Key recommendations

Results of this study and others suggest that the potential magnitude and economic accessibility of BECCS in the US warrants further consideration of BECCS as one CO_2 sequestration strategy. Of the biomass resources included in the study, some may have more obvious environmental and economic advantages than others. For example, using biomass resources such as urban wood waste, storm debris, and forest thinnings from forest habitat restoration projects could be a starting point for evaluating the technical and economic viability of BECCS in the US. If the demand for carbon sequestration grows in the future, the use of other beneficial biomass resources (e.g. Tilman et al. 2009) and woody feedstocks with short carbon payback times (e.g. Heaton et al. 2008, Norton et al. 2019) could be considered.

The goal of this study is not to suggest that BECCS is necessarily the best or most accessible approach to realize a WB2 world, but rather to assess the potential quantity and cost of carbon sequestration through BECCS in the US. It is hoped that these results will allow comparisons with other carbon drawdown strategies. Thus we recommend further analyses that could inform the role of BECCS in the US among other strategies toward a WB2 world meeting UN SDG goals.

1. Rail and barge should be added to the study to extend supplies and increase CO_2 efficiency in transporting biomass to CO_2 sequestration basins.
2. This study evaluated transporting biomass to BECCS facilities located in sequestration basins. The alternative approach of locating BECCS facilities near biomass resources and transporting CO_2 through pipelines to sequestration basins should also be explored.
3. More research is needed on feedstock partitioning to explore optimal allocation of feedstocks to

different uses. For example, herbaceous or clean woody feedstocks may be allocated to biochemical or thermochemical conversion for biofuels, while more heterogeneous feedstocks such as logging residues or urban wood waste could be more economically accessible for BECCS. The potential to allocate lignin by-products from biochemical conversion and CO_2 emissions from biofuels production to BECCS should be explored.

4. Future economic drivers such as CO_2 absorption technologies and logistical or technological innovations will change the cost results presented here and should be evaluated in the future.

7.8.5 References

Baik, E., Sanchez, D. L., Turner, P. A., Mach, K. J., Field, C. B. & Benson, S. M. (2018). Geospatial analysis of near-term potential for carbon-negative bioenergy in the United States. *Proc Natl Acad Sci U S A*, *115*(13), 3290-3295.

Berkenpas, M. B., Fry, J. J., Kietzke, K., Rubin, E. S. & Zhai, H. (2018). IECM User Documentation: User Manual. Carnegie Mellon University. Pittsburgh, PA, USA. URL: https://www.cmu.edu/epp/iecm/

Brandes, E., McNunn, G. S., Schulte, L. A., Bonner, I. J., Muth, D. J., Babcock, B. A. et al. (2016). Subfield profitability analysis reveals an economic case for cropland diversification. *Environmental Research Letters*, *11*(1), 014009.

Brandes, E., G. S. McNunn, L. A. Schulte, D. J. Muth, A. VanLoocke and E. A. Heaton (2018a). "Targeted subfield switchgrass integration could improve the farm economy, water quality, and bioenergy feedstock production." GCB Bioenergy 10(3): 199-212.

Brandes, E., Plastina, A. & Heaton, E. A. (2018b). Where can switchgrass production be more profitable than corn and soybean? An integrated subfield assessment in Iowa, USA. *Gcb Bioenergy*, *10*(7), 473-488.

Bush, I., Tsouris, C., McFarlane, J., Hilliard, M., Kasturi, A., Omitaomu, O., Kotikot, S., Allen, M., DeRolph, C., Langholtz, M., Parish, E. & Davis, M. The economic accessibility of CO2 sequestration through bioenergy with carbon capture and sequestration (BECCS) in the US. (in preparation)

Chaplin-Kramer, R., Hamel, P., Sharp, R., Kowal, V., Wolny, S., Sim, S., & Mueller, C. (2016). Landscape configuration is the primary driver of impacts on water quality associated with agricultural expansion. *Environmental Research Letters*, *11*(7), 074012.

Dale, V. H., Kline, K. L., Buford, M. A., Volk, T. A., Smith, C. T., & Stupak, I. (2016). Incorporating bioenergy into sustainable landscape designs. *Renewable and Sustainable Energy Reviews*, *56*, 1158-1171.

Efroymson, R. A., Dale, V. H., Kline, K. L., McBride, A. C., Bielicki, J. M., Smith, R. L. et al. (2013). Environmental indicators of biofuel sustainability: what about context?. *Environmental management*, *51*(2), 291-306.

Englund, O., Börjesson, P., Berndes, G., Scarlat, N., Dallemand, J. F., Grizzetti, B. et al.(2020). Beneficial land use change: Strategic expansion of new biomass plantations can reduce environmental impacts from EU agriculture. *Global Environmental Change*, *60*, 101990.

Heaton, E. A., Dohleman, F. G., & Long, S. P. (2008). Meeting US biofuel goals with less land: the potential of Miscanthus. *Global change biology*, *14*(9), 2000-2014.

IPCC (2018). Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (eds.)].

Jager, H. I., Parish, E. S., Langholtz, M. H. & King, A. W. (2020). Perennials in Flood-Prone Areas of Agricultural Landscapes: A Climate Adaptation Strategy. *BioScience*, *70*(4), 278.

Kline, K. L., Msangi, S., Dale, V. H., Woods, J., Souza, G. M., Osseweijer, P. et al. (2017). Reconciling food security and bioenergy: priorities for action. *Gcb Bioenergy*, *9*(3), 557-576.

Langholtz M., Busch I., Kasturi A., Hilliard M., McFarlane J., Tsouris C., Mukherjee S., Omitaomu O., Kotikot S., Allen M., DeRolph C., Davis M., and Parish E. The economic accessibility of CO_2 sequestration through bioenergy with carbon capture and sequestration (BECCS) in the US. *Land*. (Submitted).

Langholtz, M., Webb, E., Preston, B. L., Turhollow, A., Breuer, N. & Eaton, L. et al. (2014). Climate risk management for the US cellulosic biofuels supply chain. *Climate Risk Management*, *3*, 96-115.

Lautala, P. T., Hilliard, M. R., Webb, E., Busch, I., Hess, J. R., Roni, M. S. et al. (2015). Opportunities and challenges in the design and analysis of biomass supply chains. *Environmental management*, *56*(6), 1397-1415.

Norton, M., Baldi, A., Buda, V., Carli, B., Cudlin, P., Jones, M. B. et al. (2019). Serious mismatches continue between science and policy in forest bioenergy. *GCB Bioenergy*, *11*(11), 1256-1263.

Omitaomu, O. A., Blevins, B. R., Jochem, W. C., Mays, G. T., Belles, R., Hadley, S. W. et al. (2012). Adapting a GIS-based multicriteria decision analysis approach for evaluating new power generating sites. *Applied Energy*, *96*, 292-301.

Searchinger, T., Edwards, R., Mulligan, D., Heimlich, R. & Plevin, R. (2015). Do biofuel policies seek to cut emissions by cutting food?. *Science*, *347*(6229), 1420-1422.

Tilman, D., Socolow, R., Foley, J. A., Hill, J., Larson, E., Lynd, L. et al. (2009). Beneficial biofuels—the food, energy, and environment trilemma. *Science*, *325*(5938), 270-271.

USDA Economic Research Service. (2019). "Inflation-adjusted price indices for corn, wheat, and soybeans show long-term declines." from https://www.ers.usda.gov/data-products/chart-gallery/gallery/chart-detail/?chartId=76964.

U.S. Department of Energy (USDOE) (2016). 2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks. M. H. Langholtz, B. J. Stokes & L. M. Eaton (Leads), ORNL/TM-2016/160. Oak Ridge National Laboratory, Oak Ridge, TN. 448p. DOI: 10.2172/1271651

U.S. Department of Energy (USDOE) (2017). 2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 2: Environmental Sustainability Effects of Select Scenarios from Volume 1. R.A. Efroymson, M.H. Langholtz, K.E. Johnson, and B.J. Stokes (Leads), ORNL/TM-2016/727. Oak Ridge National Laboratory, Oak Ridge, TN. 642p. DOI: 10.2172/1338837

Wang, M., Elgowainy, A., Benavides, P. T., Burnham, A., Cai, H., Dai, Q. et al. (2018). *Summary of Expansions and Updates in GREET® 2018* (No. ANl-18/23). Argonne National Lab. (ANL), Argonne, IL (United States). Contract No.: ANL-18/38.

7.9 LEDUC (2018): *POLICY IMPACT ON BIOFUEL OR ELECTRICITY PRODUCTION FROM BIOMASS IN EUROPE **

7.9.1 Study Design

Study fact sheet	
General	
Title of the study	Policy impact on biofuel or electricity production from biomass in Europe
Contact name	Sylvain Leduc
Initiator of the study	Sylvain Leduc
Year of the study	2018 on-going
Publication	Under submission
Links	n/a
Details of the study	
Geographical system boundaries	Europe and Turkey, Moldavia, Ukraine
Temporal boundaries	Snapshot 2015
Sectors system boundaries	Electricity, heat, and transport fuel
Land use system boundaries	Forestry and agricultural
Ambition in GHG reduction	Zero emissions or -10% compared to 1990 levels by 2050
Ambition in SDG improvement	n/a
Framing of the study	Sustainable biomass production in Europe, Use of non-food feedstock
Assessment approach	Techno-economic, spatially explicit, bottom up approach, mixed integer optimization

7.9.2 Key messages

The study show that the choice of the optimal bioenergy technology mix in Europe depends on the following factors:

- *Country specific*: countries that strongly rely on fossil fuels for heat and electricity production (Poland, Turkey, Estonia and Greece) can install some bioenergy units by introducing a tax on carbon emissions (over 50 EUR/tCO_2). While for greener countries like France or Sweden the feasibility of adding new biomass production plants is more dependent on the national energy market prices. The same considerations can be applied for biofuels production, although the model results suggest that the carbon tax mechanism is more effective when applied for heat and power production rather than in the transport sector.
- *Biomass availability*: Countries around the Baltic Sea (Latvia, Estonia, Denmark) and other Central European states (Austria, Czech Republic, Hungary, Poland and Slovakia), with high forest residues potentials, stand out as important regions with high potential for biofuel production as well as for heat and power plants.

- *Policy specific*: choosing a policy on carbon cost, biofuel subsidy or fossil fuel penalty would have different consequences on the emission reduction achieved and technology deployment in Europe.

To summarize, this study shows that there is a potential conflict of interest between different parts of the overall European targets of both increased use of biofuels and decreased CO_2 emissions. Since biomass is a limited resource, policies aiming at promoting its use must for this reason be very carefully designed to reduce possible conflict between different policies and targets**.**

7.9.3 Facts and figures

Figure 23 presents how transport fuels, heat and power production develop under different policy scenarios in Europe and the resulting emissions reduction. The increasing carbon cost allows space for development of heat and power production. At the same time increased biofuel support facilitate biofuel expansion. The higher resulting emission reduction would occur either at high carbon cost (150 EUR/tCO_2), independent of the biofuel support. Combining a lower carbon cost with other biofuel support values may lower the emission reduction by 10 to 20%. Increasing the fossil fuel price on top of it may allow to choose carbon cost or policy support values less stringent as with a lower fossil fuel price.

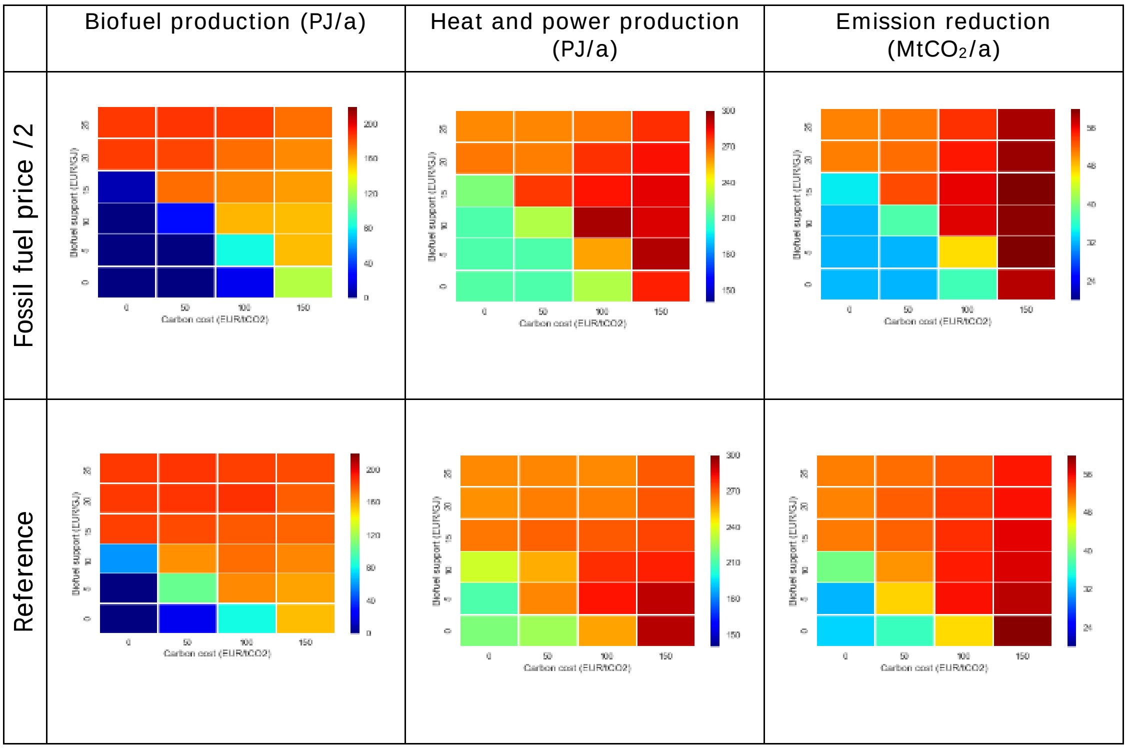
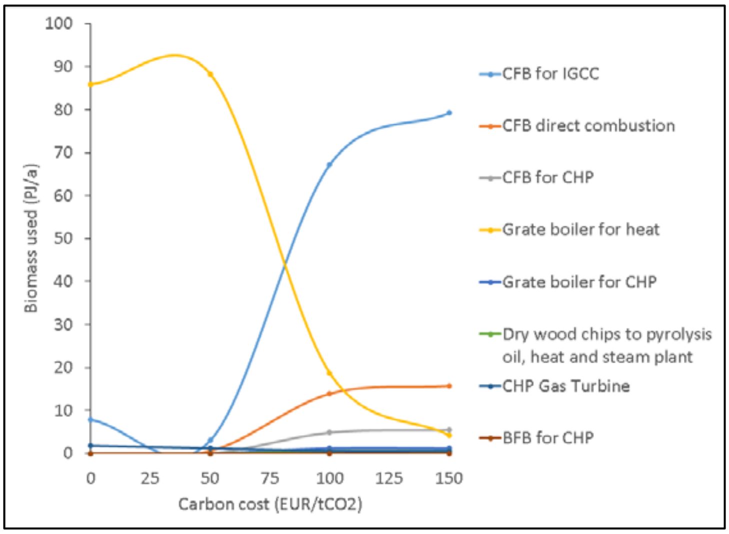


Figure 23: Development of transport fuel (left), heat and power (middle) and emission substitution with the combination of variation of carbon cost and biofuel support for a reference scenario and a decrease fossil fuel scenario.

The choice of the policy in Europe will certainly have consequences on the emission reduction potential, but also on the infrastructure that may be put in place. Figure 24 highlights how a carbon cost (a) or fossil fuel price (b) would facilitate the setup and spread of the production plants and its impact on the biomass use (mainly forest and agriculture residuals coming within Europe only). Lower size technologies may pop up for respectively lower carbon cost (<75 EUR /tCO_2) as well as lower fossil fuel prices (below fossil fuel price cost of 2015). Larger units that requires more than 5 PJ/a of biomass input (e.g. CFB for IGCC or CFB direct combustion) will dominate the market over those values.

a)



b)

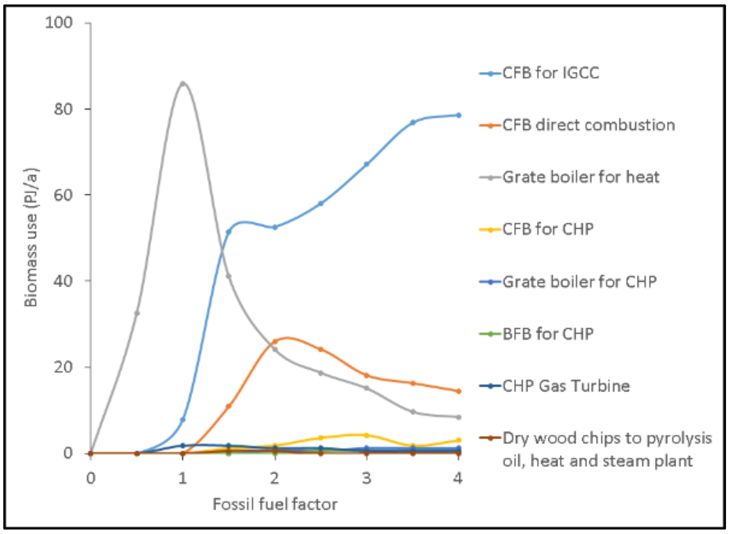


Figure 24: Example of technology development under change of carbon cost (a) and fossil fuel price (b). CFB: Circulating fluidized bed; IGCC: Integrated gasification combined cycle; BFB: Bubbling Fluidized Bed

To better understand the effect of national policies on the technologies selection (with regard to energy generation mix and energy market prices), two additional scenario have been conducted: a market oriented scenario, which foster the adoption of bioenergy technologies by radically increasing the fossil fuels market prices and a climate change oriented scenario, which focus on carbon emission mitigation by introducing a high level of carbon price. The aforementioned policies have been introduced separately and their effects on the model optimal results are presented on Figure 25. High levels of carbon price (150 EUR/tCO_2) favour the consumption of biomass particularly in Ukraine (43 PJ/a), Poland (40 PJ/a) and Italy (35 PJ/a). The figure also shows that Greece exhibits high shares of forest consumption, which is however small (10 PJ/a) when compared with the aforementioned countries. By contrast, when the fossil energy market is unfavourable the production of bioenergy is encouraged in countries having higher levels of energy demands, regardless the composition of their energy mix, like France (58 PJ/a of forest residues consumption in this scenario) and Italy (28 PJ/a).

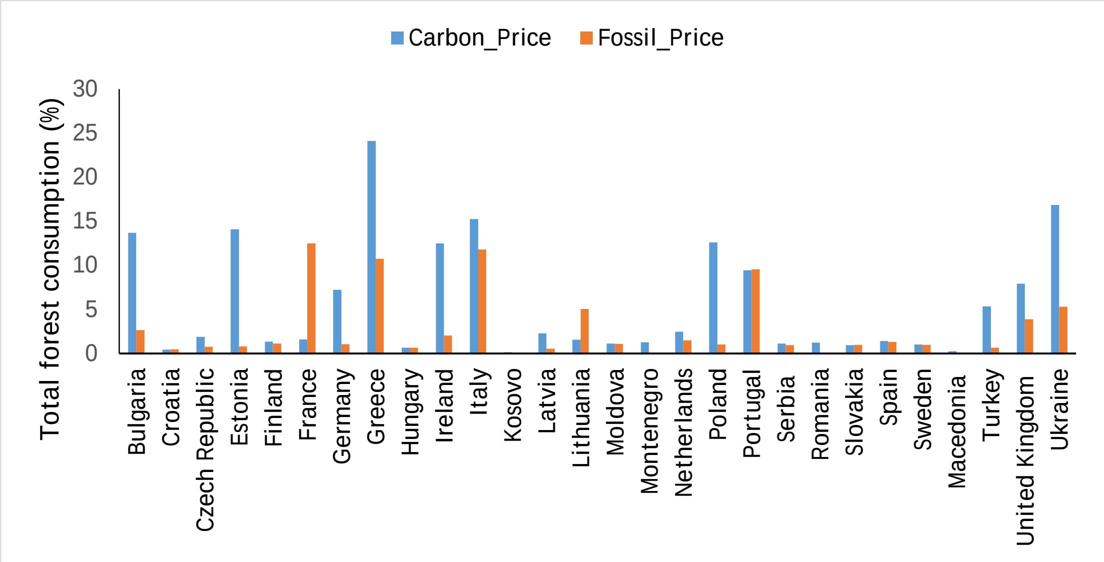


Figure 25: Effect of national policies on forest biomass consumption.

7.9.4 Key recommendations

The right combination of policies should be identified to mitigate the most emission as possible at the right time.

The bioenergy technology portfolio should anticipate the future policy, or based on the coming policies, the suitable technologies and capacities of potential production plants can be identified.

7.9.5 References

n/a

7.10 LEHTVEER (2020): *MANAGING VARIABLE RENEWABLES WITH BIOMASS IN THE EUROPEAN ELECTRICITY SYSTEM* *

7.10.1 Study Design

Study fact sheet	
General	
Title of the study	Managing Variable Renewables with Biomass in the European Electricity System: Emission Targets and Investment Preferences
Contact name	Mariliis Lehtveer & Mathias Fridahl
Initiator of the study	Mariliis Lehtveer
Year of the study	2020
Publication	Submitted to "Energy"
Links	n/a
Details of the study	
Geographical system boundaries	EU-27
Temporal boundaries	2020-2050
Sectors system boundaries	Electricity sector
Land use system boundaries	n/a
Ambition in GHG reduction	Zero emissions or -10% compared to 1990 levels by 2050
Ambition in SDG improvement	n/a
Framing of the study	Sustainable biomass production in Europe, acceptance for biomass-based electricity generation, wind and solar power as well as electricity grid expansion.
Assessment approach	Energy system modelling

7.10.2 Key messages

Biomass is an important resource that can help reaching climate targets in many sectors. If used in electricity generation, biomass can complement variable renewables as well as provide negative emissions if coupled with carbon capture and storage technologies. In this study we have investigated the need for biomass in the European electricity system based on different emission requirements posed on the electricity system (zero, net-zero and negative) and compare the results with investment preferences for biomass technologies as well as wind and solar power in selected countries.

We conclude that if only the emissions in the electricity sector are regulated, BECCS in combination with natural gas plants is the cost-effective complement to variable renewables with emissions from natural gas being compensated with some of the negative emissions created. This should be kept in mind when designing policies. Also, how emission target is formulated has a large impact on the cost-effective use of biomass: when negative emissions are possible in the system, biomass use becomes very concentrated in countries with poor variable renewable resources indicating that EU-wide emission targets would be preferable to national targets. Requiring zero emissions from all parts of the electricity system, however, facilitates larger geographic spread of biomass-based technologies to balance the variable renewables and also increases the cost-effectiveness of transmission investments as bio-based technologies are more costly to manage variations with than gas turbines that can be used in combination with BECCS. The modelling part of this study analyses the cost-effectiveness and does not thus consider social factors such as development stage of biomass markets, acceptance for technologies etc. Estimating the potential of sustainable biomass is out of the scope of this study and other studies are relied on in this matter.

Survey respondents are generally of the view that investments for the long-term transitioning of European electricity systems, towards low-carbon configurations, should primarily target variable renewables, especially wind power in western and northern Europe and solar in southern Europe. Biomass-based electricity production, with or without CCS, generally receives low priority for investments, without which at least BECCS would find it hard to prove commerciality without strong regulatory environments. While the view that biomass should be targeted for investments remain generally low among respondents from surveyed countries, adding a CCS component to biomass power technologies can make bioenergy both more and less accepted within a specific country. Between countries, however, country of residence does not influence views on BECCS. BECCS constitutes an exception to the general rule that actor type does not influence investment priorities. NGOs are consistently more sceptical to investing in BECCS than representatives of governments, indicating that controversies around BECCS have been far from resolved.

7.10.3 Facts and figures

The cost-effective electricity generation at 2050 comprises mainly of onshore wind, solar PV, hydro and nuclear power for all studied cases (Figure 26). The investment in biomass-based technologies decrease as the price of biomass increases and are mainly replaced by offshore wind and batteries. When biomass fuelled technologies with CCS are available some of the negative emissions are used (aside for meeting the emission requirement in -10% emissions case) to balance the emissions from use of gas power plants to provide the flexibility to the system as well as other existing fossil fuel plants. At biomass price 100 €/MWhth natural gas with CCS is deployed to minimize the need for biomass. In all cases existing biomass fuelled steam power plants and combined heat and power plants (CHP) are used irrespective of the biomass price. Their operational hours, however, decrease with the increasing cost of biomass and with the availability of BECCS. The new investments in bio-based technologies are made in BECCS if available and in biogas plants if biomass is cheap (less than 50 €/MWhth) or when BECCS is not available. The investments in biogas CCS plants will never become cost-effective as their total capture rate per unit of biomass is lower than for BECCS plants. Investments in BECCS plants become concentrated into few countries (Netherlands, Bulgaria, Romania), providing negative emissions also for other member states. The deployment of BECCS in Bulgaria and Romania is an effect of the weather conditions as the region has low wind potential and more diffused solar radiation compared to other southern regions making solar PV less efficient. Therefore, these regions are best suited for investing in technologies that are most cost-effective when operated continuously such as BECCS. The Netherlands on the other hand is located close to storage sites and has thus lower storage costs and is also relatively densely populated making it difficult to invest in large amounts of wind power while solar resources are relatively poor in the region. In the zero emission cases and low biomass price cases, the distribution of bio-based power plants is much more even in the system (Figure 27).

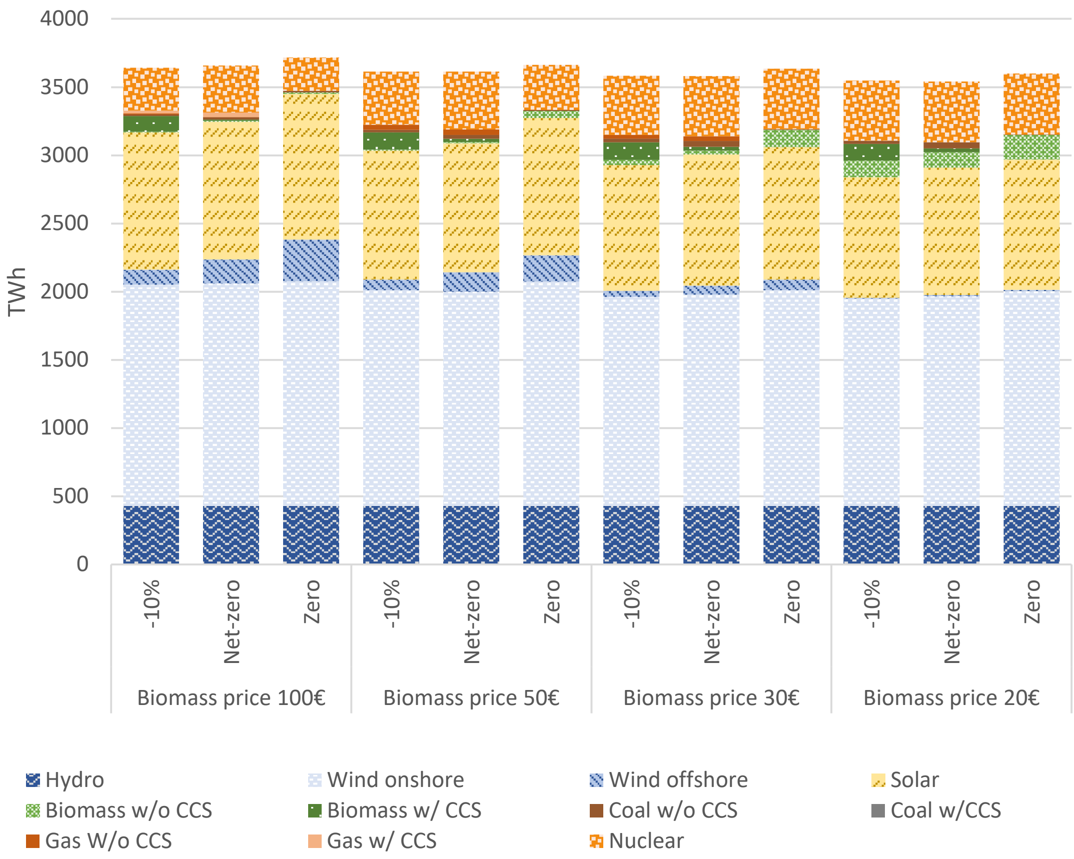


Figure 26: Electricity generation in Europe by source in different cases at 2050.

Biomass provides only a small share of total electricity generated in all the scenarios. The highest share of bio-based electricity is reached when biomass is relatively cheap (20 €/MWh$_{th}$) and −10% emissions from 1990 levels is required (7% of electricity generation) or if zero emissions are required (5% of electricity generation). However, the amount is negligible if biomass is expensive (100 €/MWh$_{th}$) and emission target is set to zero or net-zero (0.5% of the electricity generation). The total amount of biomass used by the system varies between 0.2 and 2.9 EJs.

Varying the price of biomass influences the total amount of biomass in the system but regional distribution stays roughly the same for the zero emission cases. For the net-zero and negative emissions case the spread of biomass is increased with falling price. At 20 €/MWh$_{th}$ price level all countries employ some biomass in their electricity system. The exceptions are hydro power rich regions in Sweden and Norway. One can also note that even when biomass cost is very high (100 €/MWh$_{th}$), it is still cost-efficient for the system to use some biomass in existing facilities or in BECCS plants. Contrary to common findings, competition among investments for biomass and nuclear power is not observed as the latter does not become profitable. Instead the lower price of biomass enables the extended use of existing nuclear power plants. As it is rather costly to start up and shut down nuclear power plants, having biomass available at low cost provides cheaper variation management options and thus enables to run nuclear power for longer consecutive periods compared to cases when variation management is more expensive and it is cost-efficient to shut down or postpone the start-up of nuclear power for longer periods. Instead, in the cases examined in this paper, biomass and offshore wind are competing for investments. The investments in batteries and heat pumps are also increased with higher biomass costs providing additional variation management options.

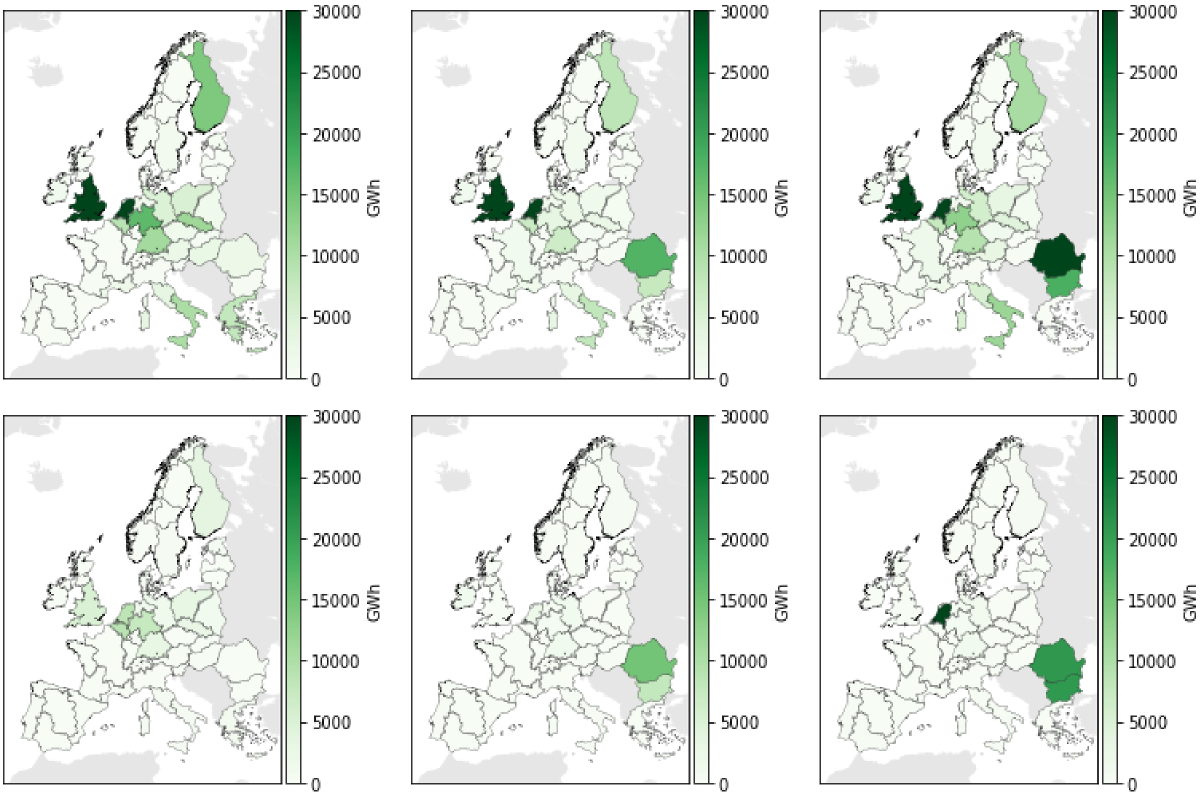


Figure 27: Electricity generation from biomass at 2050 in different regions in GWh_{el}. From left to right: zero, net-zero and −10% emissions with biomass price 20 €/MWh_{th} in the upper row and 50 €/MWh_{th} in the lower row. The colour scale has been normalized between 0 and 30 000 GWh_{el}, but the generation in the Netherlands reaches up to 80 000 GWh_{el} in −10% cases.

Requiring zero emissions from all parts of the electricity system also increases the need of transmission capacity compared to other cases as it excludes the use of natural gas compensated by negative emissions from BECCS for balancing purposes. Biomass that is used instead is mainly deployed in biogas plants with higher investment costs. Thus, it is cost-efficient to run biogas turbines for fewer hours and invest in transmission instead to manage variations. Similarly, lower biomass price makes the larger spread in biomass technologies cost-efficient and reduces the need for investments in transmission. A slight increase compared to net-zero target can also be observed in − 10% cases when a larger part of capacity consists of BECCS plants that are operated more like base load to provide negative emissions at lower price.

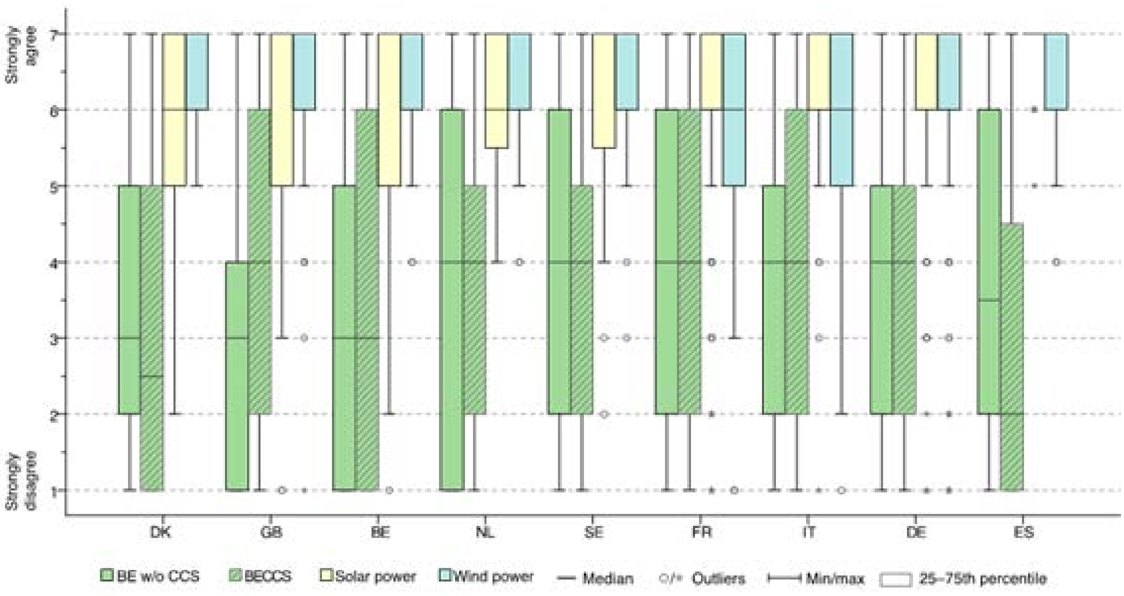


Figure 28: Attitudes of UN climate change conference delegates, from the selected countries, towards directing investments in a long-term transition to low-carbon electricity generation to bioenergy without carbon capture and storage (BE w/o CCS), BECCS, solar power, and wind power.

To analyse the attitudes towards biomass-based technologies, we look at the responses from countries that are allocated high share of BECCS by the model but also countries that have a high potential biomass resource according to de Wit and Faaij (2010). The attitudes for biomass technologies without CCS are leaning towards negative in most of the analysed countries with exception of Sweden and France. Combining bioenergy with CCS, i.e. BECCS, increases the agreement that bioenergy should be targeted for investments significantly in Great Britain and Italy but reduces it in for example Spain, Denmark and Sweden. Close to all respondents, regardless of country of residence, agree that investments should target solar and wind. Wind is favoured slightly higher than solar in most countries except in France, Italy and Spain.

7.10.4 Key recommendations

- Formulation of the emission target for European electricity system has a large impact on biomass use in electricity sector and distribution of biomass-based technologies.
- BECCS in combination with natural gas can be a cost-effective variation management option if only emissions from power sector are regulated. Attention should be paid to that while deigning policy measures for electricity system.
- Europe wide emission targets should be preferred for negative emissions in electricity system to increase the cost-efficiency.
- Investment preferences for bio-based technologies are low in all countries. Thus, policy measures are needed to support these technologies.
- NGOs are consistently more sceptical to investing in BECCS than representatives of governments, indicating that controversies around BECCS have been far from resolved.

7.10.5 References

De Wit, M. & Faaij, A. (2010). European biomass resource potential and costs. *Biomass and bioenergy*, *34*(2), 188-202. DOI: 10.1016/j.biombioe.2009.07.011

7.11 LINDROOS (2020): *VALUE-OPTIMIZED USE OF BIOMASS IN DISTRICT HEATING GRIDS **

7.11.1 Study Design

Study fact sheet	
General	
Title of the study	Value-optimized use of biomass in district heating grids
Contact name	Tomi J. Lindroos
Initiator of the study	N/A
Year of the study	2020
Publication	not yet published
Links	Part of the Vabisys project: https://www.researchgate.net/project/Value-optimised-use-of-biomass-in-a-flexible-energy-infrastructure-VaBiSys
Details of the study	
Geographical system boundaries	Model boundaries: Nordic and Baltic countries, Poland, and Germany. More Detailed modelling for district heating and cooling: Finland Results reported: Finland
Temporal boundaries	The analysis focus on year 2030
Sectors system boundaries	All model regions: Heat and power Finland only: Forest residue balance, district cooling, co-production of power, heat, cooling, and synfuels
Land use system boundaries	Estimated amount of sustainable forest biomass (forest residues and small diameter stem wood) added to the model. Otherwise no modelling of land use.
Ambition in GHG reduction	The study focuses on resource use and supply, not on GHG emission reductions.
Ambition in SDG improvement	Mainly goals 7 & 13, but gives insights also to 11 & 12.
Framing of the study	Modelling the impacts of expected developments on extended Nordic power market area and studying especially the district heating grids, replacing coal fired units by 2030, and local supply/demand balance of forest biomass in Finland.
Assessment approach	Hourly modelling of power and heat sector in the extended Nordpool market area. Integrating Finnish regional district heat modelling and forest biomass supply to the model.

7.11.2 Key messages

Biomass is an important fuel for the Finnish and Swedish power and heat sector and its importance is increasing as both countries have decided to phase out coal from power and heat sector. As a result, many companies have built and are planning to build new units to produce district heating with biomass.

According to our modelling, existing and announced units will consume more forest biomass than what is domestically available at 2030. The most limiting factor is transport distances within the country. The district heating demand is highest in the large cities in the South and West coast of Finland while most of the forest biomass supply is in the central and Eastern parts of the country. Increasing transport distances would affect negative the economy of the investments and the emission balance of the production chain. Larger integrated assessment models, where one country or larger regions is modelled as one node, often miss this limiting factor.

As a result, it is likely that the amount of imported biomass will increase. The coastal cities are already shipping wood pellets in to the biomass units within the city. The imported biomass has considerably higher costs (30-35 €/MWh) than locally produced forest biomass (20-25 €/MWh). The high cost of fuel leads to a situation where Combined Heat and Power (CHP) units are less profitable than heat only units. In addition, the low electricity market prices in the Nordic power markets strengthen this conclusion.

7.11.3 Facts and figures

Regional amounts of available forest biomass depend on several factors including available resources, transfer, assumptions on power and heat units, and policies. In our reference scenario for 2030, we assume the regional data on available forest biomass, industry waste wood, existing power and heat capacity and investment plans. We have included national climate and energy policies for 2030.

We model the value-optimized use of forest biomass in Finnish district heating grids with Backbone model (Helistö et al. 2019). Large cities along the Southern coast generate the most of the district heating while the forest biomass is collected all around the country. We have split Finland into 10 district heating areas and 19 forest biomass areas to model transport distances and local production-consumption balances of forest biomass.

To improve our modelling of the Finnish district heating grids, we have extended our modelled energy system to cover power and heat sectors of Northern Europe (Germany, Poland, Nordic countries, and Baltic countries). This allows dynamic modelling of electricity prices and optimized use of CHP plants in low carbon scenarios (Rasku et al. 2020).

We run the model for year 2030 assuming current power sector development plans and the current structure of the EU ETS. We use slightly higher prices than currently of fuels and EEAs. For Finland, we have included also the current energy taxation in heat production to better model the relative competition of different units.

In the modelled year 2030, the consumption of domestic forest biomass in power and heat sector grows from 10 TWh at 2017 to 17 TWh at 2030. Figure 29 shows the unused supply of forest biomass in the modelled 2030 run. In addition, model imports 4 TWh of wood pellets from abroad. This 11 TWh increase replaces most of the coal used at 2017 (14 TWh) while the rest is replaced by large heat pumps and natural gas. Finland aims to phase out also peat and natural gas in long term, but that requires much larger changes to the power and heat infrastructure as most biomass resources would be already used.

Scarcity of biomass influences the value of different biomass technologies. Figure 30 shows a comparison between biomass heat only boiler and biomass CHP units under and uncertainty of input parameters. Increasing price of biomass favours heat only units as CHPs would get relatively less revenues from the electricity. Similarly, low electricity prices favour heat only units.

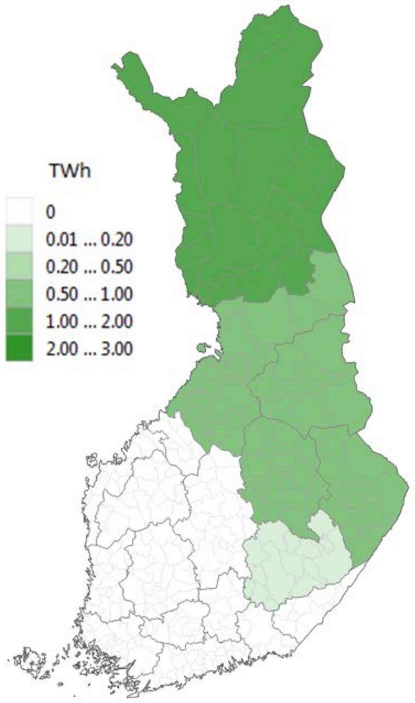


Figure 29: Regional balance of the forest biomass.

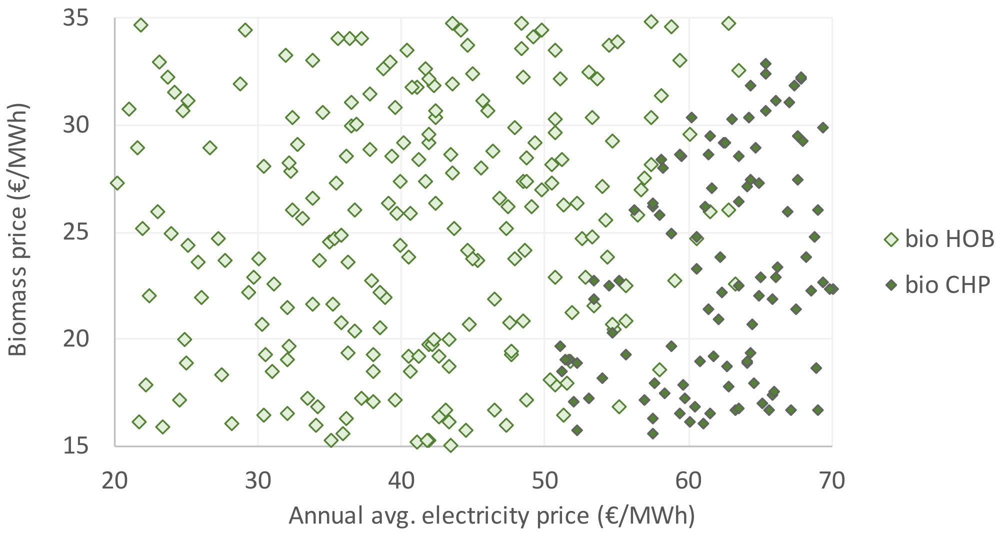


Figure 30: Comparison of the most profitable investment option assuming relatively large ranges to input parameters.

7.11.4 Key recommendations

From modelling perspective, the regional constraints of transportation should be considered as they affect the availability and/or pricing of the forest biomass.

From political perspective, it is important to recognize that forest biomass is very limited resource and its use should be optimized to maximise climate, economic and societal benefits.

From technology development perspective, emerging technologies, such as biomass with carbon capture and storage (BECCS), will face higher competition on resources and their implementation costs will be higher. On the other hand, BECCS research could consider more about retrofitting old units, as existing and planned units can consume all available forest biomass on coastal regions of Finland. Otherwise coastal location would be ideal for BECCS due to higher energy demand in big cities and lower CO_2 transportation costs to geological storages.

7.11.5 References

Helistö, N., Kiviluoma, J., Ikäheimo, J., Rasku, T., Rinne, E., O'Dwyer Ciara, Li, R., & Flynn, D. (2019). Backbone—An Adaptable Energy Systems Modelling Framework. *Energies, 12*(17), 3388; DOI: 10.3390/en12173388

Rasku, T., Miettinen, J., Rinne, E., & Kiviluoma, J. (2020). Impact of 15-day energy forecasts on the hydro-thermal scheduling of a future Nordic power system. *Energy*, *192*, 116668. DOI: 10.1016/j.energy.2019.116668h

7.12 MILLINGER (2019): *TECHNO-ECONOMIC ANALYSIS AND TRANSFORMATION PATHWAYS OF THE ENERGETIC BIOMASS POTENTIAL IN GERMANY **

7.12.1 Study Design

Study fact sheet	
General	
Title of the study	Techno-economic analysis and transformation pathways of the energetic biomass potential in Germany
Contact name	Markus Millinger
Initiator of the study	BMWi – German Federal Ministry for Economic Affairs and Energy
Year of the study	2019
Publication	Thrän, D., Lauer, M., Dotzauer, M., Kalcher, J., Oehmichen, K., Majer, S., Millinger, M. & Jordan, M., (2019). Technoökonomische Analyse und Transformationspfade des energetischen Biomassepotentials (TATBIO): Endbericht zu FKZ 03MAP362. DBFZ Deutsches Biomasseforschungszentrum gemeinnützige GmbH, Leipzig, 130p. (in German)
Links	https://www.ufz.de/index.php?de=46332 https://www.bmwi.de/Redaktion/DE/Publikationen/Studien/technooekonomische-analyse-und-transformationspfade-des-energetischen-biomassepotentials.html
Details of the study	
Geographical system boundaries	Germany, with some biomass import assumed
Temporal boundaries	Yearly resolution between 2020-2050
Sectors system boundaries	Heat, power, transportation.
Land use system boundaries	Arable land scenarios changing from current energetic use 2.35 Mha to 2.6, 4 and 1 Mha, respectively.
Ambition in GHG reduction	80% and 95% transitions scenarios
Ambition in SDG improvement	Not in focus
Framing of the study	The cost-optimal allocation of the domestic biomass potentials of Germany was assessed for 80% and 95% GHG reduction targets for 2050. Two transformation scenarios until 2050 were described, which lead to a cost-optimal biomass allocation in the target systems with an 80 % and 95 % GHG reduction. The sector-specific bioenergy contributions (electricity, heat, fuel, aviation fuel) of the project "Long-term scenarios for the transformation of the energy system" (Fraunhofer ISI et al. 2017) were set as energetic targets to be met.

	In a first step, 28 supply chains consisting of biomass type, conversion technology and the final energy carrier provided (heat, electricity, fuel) were defined to meet the biomass-specific demand for energy carriers in the various sectors. The current technical biomass potentials were described and projected up to the year 2050. In the biomass potential, both energy crops and biogenic residual and waste materials are considered. The cost and price expectations for the raw materials and their provision have also been extrapolated over time. For the same period, 28 supply chains with technical, economic and climate-gas-related parameters were described. The optimization model BENOPT then minimized the total costs for the two transformation pathways. Based on the predefined material flows, the biomass used and the associated potentials, BENOPT determines the supply chains (and the optimal composition of the cultivation areas for biomass) in order to cover the biomass-specific demand for energy sources at minimum cost.
Assessment approach	Cost-optimal focus on biomass usage for fulfilling set energetic targets in the sectors

7.12.2 Key messages

The amount of available arable land as well as the GHG target have a strong influence on the resulting cost-optimal biomass usage. Some perennials such as *Miscanthus* can dominate the crop usage, but this is sensitive to the assumed yields. However, *Miscanthus* has several other benefits, why this and other perennial crops should receive more attention in research and policy. The diffusion of methane driven vehicles in transport determine whether bio-based methane can be used to its potential and a sensitivity analysis showed that the exclusion of gaseous transport fuels reduce the bioenergy potential dramatically, due to decreased conversion efficiencies as well as unusable resource bases which are suitable for anaerobic digestion.

7.12.3 Facts and figures

In the electricity sector, the objective function of cost minimization enabled larger central conversion technologies such as biomethane-fired combined cycle power plants to prevail over decentralized technologies. Plants with smaller capacities (e.g. biogas plants) were replaced promptly. In the heating sector, in all scenarios a large part of the demand was provided by wood chip boilers. In the transport sector there was a significant upheaval. Apart from biokerosene in aviation, the remaining fuel demand was largely met with biomethane (mainly through thermo-chemical conversion), a gaseous fuel. The most important domestic biomass was *Miscanthus*, which would have to be cultivated on a large scale in Germany for the necessary quantities. The results were very sensitive to the yields of *Miscanthus*. If the yields were reduced by 20 %, biomethane was mainly produced from biogas instead of *Miscanthus*, which requires a different process. In addition, on the waste and residual materials side, forest residues and industrial waste wood were used for energy production on a large scale.

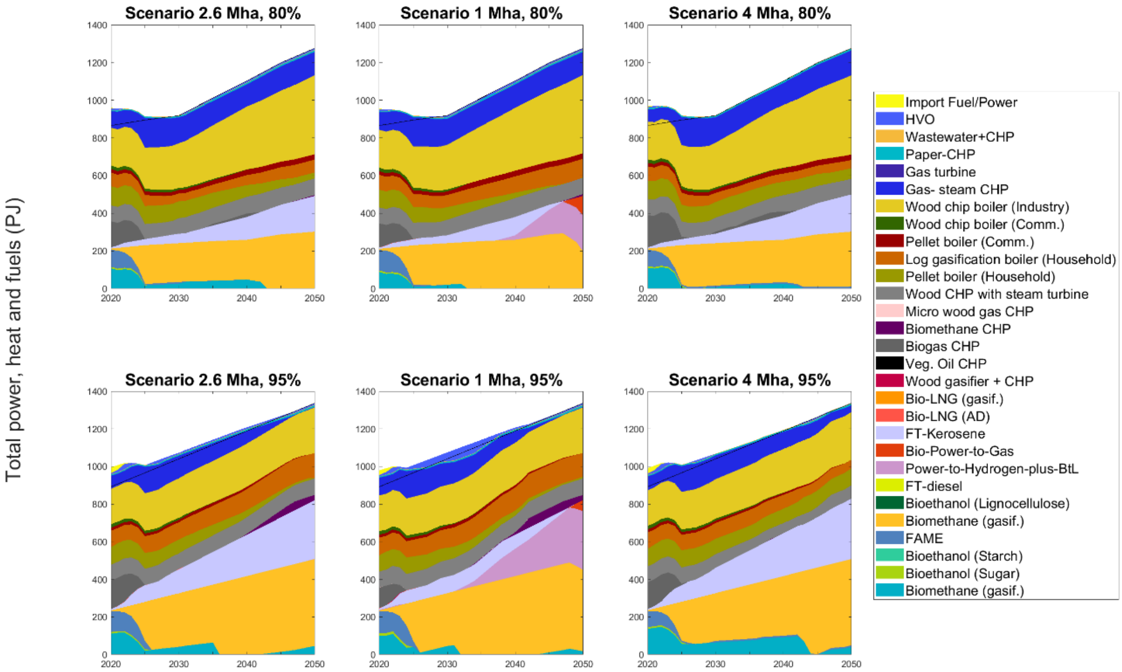


Figure 31: Total energy production for power, heat and fuels.

In the techno-economic analysis, conversion technologies showed the lowest production costs, greenhouse gas emissions and greenhouse gas avoidance costs if they used waste and residual materials instead of cultivated biomass. Therefore, a stronger energetic use of existing residual and waste material potentials should take place. Moreover, the benefits of perennial crops such as Miscanthus can only be realized if farmers are given incentives to reduce the potential risks, especially in the early years of crop establishment.

Deployment of the biofuels considered in the scenarios would cost about 1-3 % of current German GDP, depending on the cost development assumptions. Biomass scarcity was assumed to imply higher cost developments. The use of Power-to-X-options increased overall costs while at the same time increasing the potential.

The extent to which biomass is used varies greatly between the scenarios. In the 95 % transformation scenario, a reduction of the arable land from 2.4 to 1 million hectares resulted in an almost complete exhaustion of the biomass potential. The maximum available biomass potential assumed, consisting of domestic biomass residues and crops and some (max. 331 PJ) imports, varied between 1.596 PJ and 2.546 PJ with an available area of 1 and 4 million ha respectively. Accordingly, the modelling results are decisively influenced by the arable land scenarios. Without resorting to Power-to-X technologies, which increase the conversion efficiency potential through the use of hydrogen from electrolysis, the targets in the 1 million ha arable land scenarios could not be solved.

Assuming arable land availability according to present use (2.6 Mha) and biomass residue potentials, ca 1800 PJ primary energy biomass of German origin was maximally available, of which 948 PJ biomass residues and 824 PJ energy crops (*Miscanthus*).

In the study, GHG abatement or GHG abatement cost were not optimised, nor were pure electrofuels considered (ongoing). For Power-to-X, more detailed research on GHG abatement potential depending on the power source is ongoing.

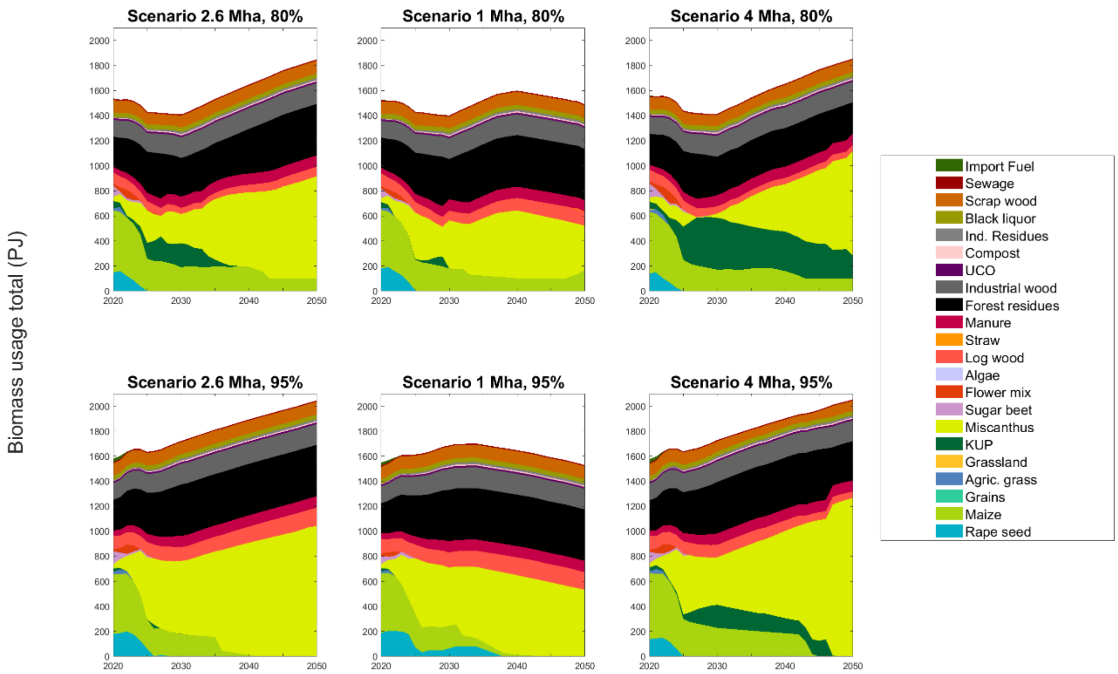


Figure 32: Total use of biomass.

7.12.4 Key recommendations

In order to meet a high demand for liquid and gaseous energy carriers in the energy sectors and beyond, it is important to focus research on crops which have potential high yields and thus requiring less land per energy unit and thereby also decreasing pressure for land use change, at the same time as they can achieve other eco-system services, such as preventing erosion, serving as a habitat and thus improving biodiversity, having a low water use and requiring relatively little fertilizer. This holds true for *Miscanthus* which proved a highly competitive crop in this study, however yield uncertainties prevail and some barriers need to be overcome, as it is a perennial culture which requires a stable policy for farmers.

Gaseous energy carriers generally can be produced with a wider range of biomass crops and residues, as well as achieving higher conversion efficiencies. Thus, it is important to stimulate a demand for gaseous or liquefied gaseous fuels in sectors which are not easily electrified, such as heavy goods transport and marine applications. Finally, a higher usage of biomass residues is required in order to cost-efficiently meet high demands for renewable hydrocarbons, both in energetic applications as well as in industry.

7.12.5 References

Fraunhofer ISI, Consentec & IFEU (2017). Langfristszenarien für die Transformation des Energiesystems in Deutschland. Modul 3: Referenzszenario und Basisszenario. Studie im Auftrag des Bundesministeriums für Wirtschaft und Energie. URL: https://www.bmwi.de/Redaktion/DE/Artikel/Energie/langfrist-und-klimaszenarien.html

7.13 PORTUGAL-PEREIRA (2019): *BRAZIL IN A WELL-BELOW 2°C WORLD* *

7.13.1 Study Design

Study fact sheet	
General	
Title of the study	Brazil in a *well-below* 2°C World
Contact name	Joana Portugal-Pereira & Francielle Carvalho
Initiator of the study	iCS - Instituto Clima e Sociedade
Year of the study	2019
Publication	Schaeffer, R., Szklo A., Lucena A., Gurlgel A., Rochedo P., Koberle A., et al. (2019). *Brazil in a well-below 2°C World – briefing*. Rio de Janeiro: iCS - Instituto Clima e Sociedade.
Links	https://docs.wixstatic.com/ugd/d19c5c_ c50eafa828de4c69ad88222de9b51447.pdf
Details of the study	
Geographical system boundaries	Brazil
Temporal boundaries	2050 and 2100
Sectors system boundaries	All sectors of the economy (Energy, Transport, Industry, AFOLU).
Land use system boundaries	The following land-based mitigation options were included: re/afforestation, forest management, sustainable intensification, bioenergy with or without BECCS.
Ambition in GHG reduction	Stabilization of global warming to 1.5°C and 2°C.
Ambition in SDG improvement	Directly: SDGs 13, 7 and 15.
Framing of the study	The study “Brazil in a Well-Below 2°C World” analyses different pathways towards a Brazilian low- or zero-emission power and transport sector, which will be crucial to achieve the Brazilian commitment within global climate protection. A reference scenario and two mitigation scenarios were considered: • National Current Policies (NCP): The NCP scenario is based on current and indicated Brazilian climate, energy and land-use policies and the expected resulting CO_2e emissions up to 2050. • Brazilian budget for 2°C (N2D): The N2D scenario explores the pathway towards achieving the Brazilian targets of the Paris Agreement, indicated by the NDC assumptions. It is based on an emissions budget of 24 $GtCO_2$ for the period between 2010 and 2050. Brazilian budget for 1.5°C (N1.5D): The N1.5D scenario considers global and regional emissions budget to limit the average global temperature increase to 1.5°C. For Brazil, an emissions budget of 17 $GtCO_2$ for the period between 2010 and 2050 was considered.

Assessment approach	The studied applied a set of computational integrated assessment models (IAMs) to evaluate scenarios related to GHG emissions and energy and land use. Two central models where employed in this study, both developed by CENERGIA/PPE researchers on the MESSAGE platform: • The COmputable Framework For Energy and the Environment – COFFEE is a global optimization model for energy and land-use systems. The COFFEE model divides the world into 18 regions, being Brazil one of them. • The Brazil Land-Use and Energy Systems model– BLUES is an optimization model for the Brazilian energy and land-use systems. In addition to the COFFEE AND BLUES models, the global economic model TEA, was applied in order to calibrate the inputs for the COFFEE model: • The Total-Economy Assessment model – TEA is a global computable equilibrium model which simulates the evolution of the global economy until 2100. The model uses the same 18 regions as COFFEE.

7.13.2 Key messages

Brazil, just as many other countries, is not on track for a *well below* 2°C world. Projections indicate that current policies will result in global cumulative emissions of 5,500 $GtCO_2$ between 2011 and 2100, leading the world to a temperature increase higher than the safe limits. The cumulative emissions in Brazil will be around 34 $GtCO_2$ between 2010 and 2050, if stricter targets are not established.

Joint efforts into the commercial availability of CCS will be crucial to the achievement of international climate change targets. In the absence of early actions, reducing emissions drastically from 2020 on, Brazil (just as many other countries) will depend on CCS in order to be able to achieve ambitious reduction targets. A global emissions budget for the 2°C target can be achieved in a cost-efficient manner with or without the commercial availability of CCS, but without CCS it calls for early actions or for drastic lifestyle changes.

Ambitious climate change targets will require a massive increase of renewable electricity generation in Brazil. Achieving the 1.5°C target will depend on supplying the Brazilian transport sector with renewable electricity. Renewable energy (hydropower, wind, solar and biomass) will continue to be the main elements of the Brazilian power mix, representing 89% of the total supply in 2030 and ranging from 82% to 94% in 2050.

The stricter the target for emission reduction, the faster will be the penetration of electric vehicles in the Brazilian transportation sector. The replacement of ethanol- and gasoline-powered vehicles by electric vehicles increases in all three scenarios, with the electric fleet representing almost 10%, 68% and 100% of the total light-duty vehicles fleet in 2050 (NCP, N2D and N1.5D scenarios, respectively). The increase in electric vehicles will lead to a significantly higher electricity demand, but to a smaller overall energy consumption from the transportation sector, since the efficiency of electric vehicles is higher than that of internal combustion engines.

A restriction on GHG emissions calls for advanced biofuels use in Brazil. Conventional sugarcane ethanol will be entirely produced with carbon capture in carbon-restricted scenarios, with significant production from second-generation technologies. Green diesel production from biomass-to-liquids with CCS (BTL CCS) gains traction after 2040 in a well below 2°C world, eliminating diesel imports by 2050.

7.13.3 Facts and figures

In the NCP scenario, all energy-related gases will continue to grow until 2050 reaching overall annual GHG emissions of 1.6 $GtCO_2eq$ in 2050, which is about 42% above the 2015 baseline emissions. In this scenario, in the absence of additional restrictions, economic advantages lead to an increased use of fossil fuels instead of clean energy alternatives. In the N2D scenario, the total GHG emissions from AFOLU, Energy and Industry will be 44% below the 2015 level by 2050, totalling 0.9 $GtCO_2eq$. A sharp decrease after 2030 is mostly caused by negative emissions from the land-use sector, related to the improvement and recuperation of pastures. Energy related GHG emissions reach around 0.5 $GtCO_2eq$ in 2050, with a relatively steady reduction rate of about 1% a year from 2030 to 2050.The N1.5D scenario would require an emissions reduction of 85% until 2050, with a total of 0.25 $GtCO_2eq$ in 2050. In this scenario, the decrease of GHG emissions after 2030 is even steeper, mainly due to an intensified use of BECCS in addition to the efforts of the negative emissions in the land-use sector, which will achieve around 0.4 $GtCO_2$ of negative emissions in 2050.

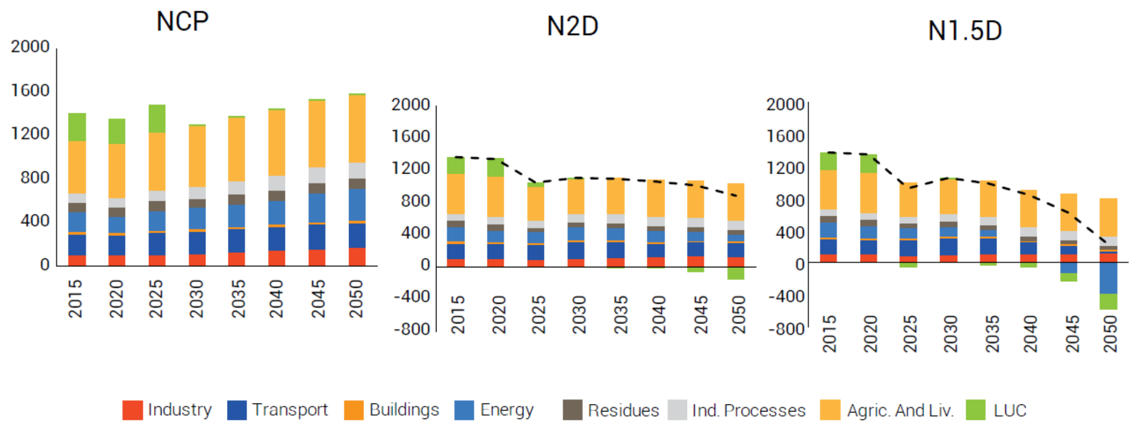


Figure 33: Brazilian GHG emissions *from AFOLU, Energy Use and Industry up to 2050 for the three analysed scenarios.*

7.13.4 Key recommendations

Brazil, just as many other countries, is not on track for a well below 2°C world. An ambitious and collective strategy should be put in motion by the Brazilian government if the country aims to fulfil its Paris Agreement mitigation targets. This would bring significant economic and environmental co-benefits. Brazil offers new markets for its ethanol production in the 1.5°C and 2°C scenarios. Our results show that electric vehicles will have significant share in domestic passenger and cargo transport in the future. The domestic use of first-generation ethanol may lose importance as final energy in Otto engines, and it can be then used as input for jet fuel production. In a 2°C or well below 2°C world, bio-kerosene production through the ATJ (Alcohol-to-Jet) route appears as an important new market for ethanol.

7.13.5 References

Schaeffer, R., Szklo A., Lucena A., Gurlgel A., Rochedo P., Koberle A., et al. (2019). *Brazil in a well-below 2°C World – briefing*. Rio de Janeiro: iCS - Instituto Clima e Sociedade. URL: https://docs.wixstatic.com/ugd/d19c5c_c50eafa828de4c69ad88222de9b51447.pdf

7.14 RÖDER (2018): UNDERSTANDING THE TIMING AND VARIATION OF GREENHOUSE GAS EMISSIONS OF FOREST BIOENERGY SYSTEMS

7.14.1 Study Design

Study fact sheet	
General	
Title of the study	Understanding the timing and variation of greenhouse gas emissions of forest bioenergy systems
Contact name	Mirjam Röder
Initiator of the study	Supergen Bioenergy Hub
Year of the study	2018
Publication	Röder, M., Thiffault, E., Martínez-Alonso, C., Senez-Gagnon, F., Paradis, L., & Thornley, P. (2019). Understanding the timing and variation of greenhouse gas emissions of forest bioenergy systems. Biomass and Bioenergy, 121, 99-114. doi:https://doi.org/10.1016/j.biombioe.2018.12.019
Links	https://doi.org/10.1016/j.biombioe.2018.12.019 https://www.supergen-bioenergy.net/
Details of the study	
Geographical system boundaries	North America, Spain, United Kingdom
Temporal boundaries	Current over 100 year timeframe
Sectors system boundaries	Power
Land use system boundaries	Forestry with some forest system expansion
Ambition in GHG reduction	Cumulative emission impact of forest-based bioenergy on national emission budgets
Ambition in SDG improvement	SDG 7, 13
Framing of the study	Assessing the temporal and cumulative climate change mitigation potential of forest-based bioelectricity generation considering different bioenergy forest locations and management systems to deliver GHG reductions in line with national emission budgets.
Assessment approach	Forest carbon modelling, lifecycle assessment, GHG balance assessment

7.14.2 Key messages

- Bioelectricity from forest-based feedstocks is a valid approach to reduce GHG emission from the energy sector.
- The assessment of the cumulative net GHG balance over the full rotation a forest shows that the GHG reduction potential can be limited depending on location, forest management and timber utilisation.

- The cumulative and temporal impact of the whole forest system, which bioenergy as part of the forest product basked, can vary strongly between different forest systems.
- The cumulative net GHG balance revealed that the GHG reduction potential is limited in fast growing forests with shorter rotations, while slow growing forest systems with longer rotations result in greater GHG reductions. Hence, depending on the forest system, climate change benefits might be delivered at different points in time.
- Depending on the system boundaries and system comparator (reference system) results can vary, in particular if feedstocks are produced in one and used in another country.
- A forest producing nation might want to maximise forest carbon stocks and carbon sequestration and therefore maintain carbon stocks in forests and any form wood products as long as possible. A use of feedstocks for bioenergy would release the previously sequestered carbon might be therefore not favourable for the net GHG balance.
- A bioenergy producing nation would reduce its overall GHG emissions by using forest-based biomass instead of a more emission intense fuel and create territorial GHG savings. The use of forest-based biomass supports therefore its cumulative emission targets.
- Expanding the system boundaries across borders and understanding all uses and timeframes all forest products, including biomass for energy is key to enable the real climate mitigation potential of forest value chains.

7.14.3 Facts and figures

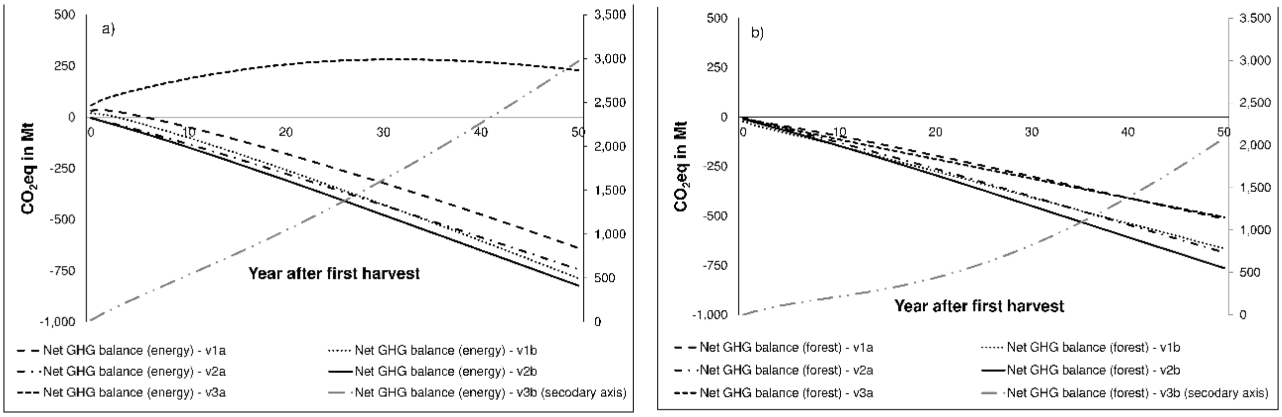


Figure 34: Comparison of the net GHG balance of the different forest management systems considering system boundaries from a a) energy producing perspective; b) forest producing perspective (Röder, M et al (2019). Understanding the timing and variation of greenhouse gas emissions of forest bioenergy systems. Biomass and Bioenergy, 121, 99-114)

7.14.4 Key recommendations

- Forest-based bioenergy electricity can provide emissions savings, but assessments are context and objective specific and cannot be transferred form one system to another.
- Consideration of the full forest system with all products is key to understand the real climate change mitigation potential of bioenergy.
- System boundaries of bioenergy or systems bioenergy is part of should be extended where possible and transparently communicated.
- Biomass feedstock users are unlikely to have control over the final use of the other forest products and services, including alternative uses for the feestock feasible for bioenergy use. Governance and regulations are required at forest level considering wider impacts and counterfactuals.
- With various actors, sectors and potentially countries tapping into the same biomass resource pool, a multi-level governance framework that monitors and tracks the multi-functional (including

services), multi-sectoral and international dimension of forests and bioenergy beyond energy and carbon is needed

7.14.5 References

Röder, M., Thiffault, E., Martínez-Alonso, C., Senez-Gagnon, F., Paradis, L., & Thornley, P. (2019). Understanding the timing and variation of greenhouse gas emissions of forest bioenergy systems. Biomass and Bioenergy, 121, 99-114. doi:https://doi.org/10.1016/j.biombioe.2018.12.019

7.15 SCHIPFER (2017): *SUSTAINABLE AND OPTIMAL USE OF BIOMASS FOR ENERGY IN THE EU BEYOND 2020 **

7.15.1 Study Design

Study fact sheet	
General	
Title of the study	Sustainable and optimal use of biomass for energy in the EU beyond 2020
Contact name	Fabian Schipfer (submitted for consortium of EC Tender project)
Initiator of the study	PricewaterhouseCoopers EU
Year of the study	2017
Publication	PWC (2017). Sustainable and optimal use of biomass for energy in the EU beyond 2020 – BioSustain. Annex of the Final Report: Hoefnagels, R., Kluts, I., Junginger, M., Visser, L., Resch, G., Mantau, U. et al. (2017). Sustainable and optimal use of biomass for energy in the EU beyond 2020.
Links	https://ec.europa.eu/energy/en/studies/sustainable-and-optimal-use-biomass-energy-eu-beyond-2020
Details of the study	
Geographical system boundaries	EU28 with extra-EU imports of solid biomass and liquid biofuels from existing and emerging biomass export regions.
Temporal boundaries	2016 - 2030
Sectors system boundaries	Input scenarios for: 1. Supply side incl. forest, agriculture, waste 2. Demand side incl. food, feed, fibre and biochemicals Modelling of bioenergy demand (solid – incl. densified bioenergy carriers, liquid, gaseous), for electricity, space heating, transport and industry Different policy options have been discussed regarding their impact on: • Biomass supply and demand • Extra-EU imports • Direct GHG savings • Land use • Overall investment and operational costs • Support expenditures & household energy costs • Gross value added • Employment (including SMEs) Administrative costs
Land use system boundaries	*Modelling is constrained to the EU energy system:* Actual competition effects between energy and other markets are not covered in the modelling. In the assessment of biomass supply scenarios, amounts of biomass required in other biomass markets such as food and feed and materials (including novel industrial use for biochemical

	production) were considered not available for EU energy use, so in fact these other markets are prioritised over energy use. Availability of extra-EU biomass imports is also exogenous to the model.
Ambition in GHG reduction	Outdated EU 2030 Climate and Energy Framework • 40% GHG savings • Renewable energy target 27% of final energy consump. • Min. 27% Energy Efficiency
Ambition in SDG improvement	No ambitions but "risk-based approach" regarding forestry biomass. With the MULTIREG-model furthermore assessed the impacts on deployment, income and national budget.
Framing of the study	This study was an input to the EU Impact Assessment on sustainable bioenergy (SWD (2016) 418 final) to assess different policy options and revised sustainability criteria in preparation of the revised Renewable Energy Directive ((EU)2018/2001). The study presents the supply potential of EU28 sustainable biomass supply for energy purposes and assessed the evolution of demand to 2030 under the proposed policy scenarios. It is framed by the EU-wide target for renewable energy of at least 27% final energy consumption and the biomass contribution of almost two-thirds of the 28MS's primary combined renewable energy production today which is expected to further increase through 2030. The possible future development is discussed in three scenarios: (1) Restricted: EU wood availability under the condition of stronger utilisation restrictions and larger set aside areas. Higher global competition for Extra-EU solid biomass and lack of investments in infrastructure to mobilise alternative wood biomass. Low export capacity of liquid biofuels outside the EU. (2) Reference: EU wood availability is given under today's circumstances. Extra-EU solid biomass development follows a BAU-trend. Medium export capacity of liquid biofuels. (3) Resource: maximum possible utilisation of wood in the EU under long-term sustainable conditions. Strong development of supply and infrastructure of Extra-EU solid biomass, perennial crops cultivated for export markets. High export capacity of liquid biofuels to the EU.
Assessment approach	• Assessment of Biomass Supply Scenarios • Development of bioenergy demand scenarios and assessing related impacts 1) Energy system modelling in the Green-X Model 2) Modelling biomass transport chains in and to Europe in a geospatial network 3) Assessment of socio-economic impacts in the MULTIREG model

7.15.2 Key messages

Six central issues were defined in relation to the gap analysis with regard to the COM(2014)15 policy framework proposal of the European Commission (European Commission 2014):

- Some bioenergy options may have limited **life cycle GHG emission reductions** compared to the fossil reference. In particular, there are currently no binding GHG saving requirements for solid and gaseous biomass for electricity and heat.

- **Carbon stocks** (particularly in forests) can be reduced when certain feedstocks are used for bioenergy.
- Harvesting biomass for bioenergy may have an impact on **biodiversity** (through land use change, or changes in management of forests or agricultural land).
- Bioenergy applications can have non-optimal **energy conversion efficiency** in heat and power plants.
- Bioenergy may **compete** with other applications of biomass (e.g. food, roundwood). For waste material, waste hierarchy principles can be applied, however, these principles do not apply to fresh material like roundwood (the use of food crops is limited by the iLUC directive).
- Different requirements/approaches of MS's may lead to **Intra-EU market distortions**.

The options for EU action have been developed in collaboration with the EC and address one or more of the above key problems and objectives (see Table 5).

Table 5: Policy options for EU action.

Option	Policy action
Option 1	• Current situation, e.g. sustainability criteria for biofuels and bioliquids. • No additional EU action on biomass for heat and power.
Option 2	• Biofuels as in Option 1 • Sustainability criteria extended to solid biomass and biogas for heat and power. • The land criteria and cross-compliance rules for agricultural biomass are identical to the criteria for biofuels and bioliquids. • Threshold for GHG savings of heat and power applications: 70% (large scale plants, base case: 4-5 MW thermal biomass input).
Option 3a	• Similar to Option 2 (land criteria for agricultural biomass and GHG saving criteria). • For forestry biomass, land criteria are replaced by a new criterion on Sustainable Forest Management (SFM) (all forest biomass used for energy generation should demonstrate compliance through SFM certification).
Option 3b	• The SFM criterion is applied through a risk-based approach • Evidence of compliance with SFM standards would be gathered at national or sub-national level, when not available, operators would be required to provide evidence at the forest holding level).
Option 4	• Criteria of Option 2 • Plus a minimum efficiency standard (base case of 65%) for the conversion of biomass in new large-scale electricity and heat installations.
Option 5	• Criteria of Option 2 • Plus a cap on the use of stemwood for bioenergy at MS level. • Does not cover firewood currently used for residential heating.

7.15.3 Facts and figures

A semi-quantitative comparison is performed on the five policy options against baseline, using the following assessment criteria:

- Effectiveness: the extent to which the option achieves the specified objectives that are relevant for the problem addressed by the option;
- Cost-efficiency: the extent to which the specified objectives can be achieved for a given level of resources at least cost. Within this study, the cost-efficiency indicator is CAPEX in €/tonne of CO_2eq avoided for new post-2020 installations. This criterion also addresses the administrative burden of the option in general terms; specific administrative costs are discussed under the economic impacts;
- Consistency: the extent to which options are coherent with the overarching objectives of EU CEP as well as other climate and energy policies;
- Environmental, Economic and Social impact.

Advantages and drawbacks are identified for each policy option in terms of its impacts in the following table:

Table 6: Policy options impact comparison.

Impacts on: (compared to option 1 - baseline)	Policy option 2 EU biomass criteria for heat and power	Policy option 3a SFM certification	Policy option 3b Risk-based approach for forest biomass	Policy option 4 Energy efficiency requirement	Policy option 5 Stemwood cap
Biomass supply and demand	0.5% decline in biomass demand.	16% decline in biomass demand. Strong shift from RES heat to (non-biomass) RES electricity and biofuels. Strong decline of forest biomass supply (under modelling assumptions), only partly offset by an increased use of agricultural biomass.	3.0% decline of biomass demand. Small shift from RES heat to (non-biomass) RES electricity. Strong reduction of Extra-EU import of forest biomass (under modelling assumptions).	1.5% decline of overall biomass demand.	2.3% decline of overall biomass demand, in particular for heat production from biomass (-4%). Mainly counter-balanced by a growth of (non-biomass) electricity.
Direct GHG savings	+0.1% GHG savings	+4.4% GHG savings	+1.5% GHG savings	no impact	+1.1% GHG savings
Land use change	No additional agricultural land use.	Reduced supply of forest biomass results in shift to energy crops (+1.4 Mha).	Reduced supply of forest biomass results in shift to energy crops (+0.4 Mha).	No additional agricultural land use.	Reduced supply of forest biomass results in shift to energy crops (+0.3 Mha).
Overall investments and operational costs	+€0.4bln pa increase in CAPEX for RES. Combined effect of CAPEX+OPEX of +€0.3bln pa.	+€12.7bln pa increase in CAPEX for RES. Combined effect of CAPEX+OPEX of +€10.0bln pa.	+€2.9bln pa increase in CAPEX for RES, minor impact on OPEX. Combined effect of CAPEX+OPEX of +€3.0bln pa.	+€1.1bln pa increase in CAPEX for RES. Combined effect of CAPEX+OPEX of +€0.6bln pa.	+€2.3bln pa increase in CAPEX; OPEX increases. Combined effect of CAPEX+OPEX of +€3.2bln pa.
Support expenditures/household energy costs	+0.1% (€0.06bln pa) increase of renewable energy support expenditures	+23% (€14.0bln pa) increase of renewable energy support expenditures	+6% (€3.6bln pa) increase of renewable energy support expenditures	+0.3% (€0.2bln pa) increase of renewable energy support expenditures	+4.0% (€2.2bln pa) increase of renewable energy support expenditures
Gross value added	Value added increase of €0.33bln	Value added increase of €4.80bln	Value added increase of €1.40bln	Value added increase of €0.90bln	Value added increase of €2.1bln
Employment (including SMEs)	4,400 extra jobs SMEs: 3,500 extra jobs	6,000 extra jobs SMEs: 2,000 extra jobs	7,000 extra jobs SMEs: 5,000 extra jobs	3,000 extra jobs SMEs: 2,200 extra jobs	20,000 extra jobs SMEs: 13,000 extra jobs
Administrative costs *(Private recurring costs are dominant)*	Administrative cost estimation on average €30mln pa higher than baseline	Administrative cost estimation on average €55mln pa higher than baseline	Administrative cost estimation on average €22mln pa higher than baseline	Administrative cost estimation on average €43mln pa higher than baseline	Administrative cost estimation on average €43mln pa higher than baseline
Extra-EU Imports	Marginal impact on Extra-EU imports (+0.1%)	66% (6.9Mtoe) reduction of solid biomass imports from non-EU countries. 18% (1.0 Mtoe) higher Extra-EU imports of liquid biofuels	66% (6.9Mtoe) reduction of solid biomass imports from non-EU countries. 4% (0.2 Mtoe) lower Extra-EU imports of liquid biofuels	Limited increase of Extra-EU imports (+1%, +0.2Mtoe)	8% (0.8Mtoe) reduction of solid biomass imports from non-EU countries. 5% (0.3 Mtoe) lower Extra-EU imports of liquid biofuels

7.15.4 Key recommendations

This study does not provide recommendations but assesses the quantitative and qualitative impacts of selected policy options for providing an objective discussion basis for the contracting authority, the European Commission.

7.15.5 References

European Commission (2014). A policy framework for climate and energy in the period from 2020 to 2030. *COM (2014) 15 final/2*. URL: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52014DC0015&from=EN

PWC (2017). *Sustainable and optimal use of biomass for energy in the EU beyond 2020 - Final report*. URL: https://ec.europa.eu/energy/en/studies/sustainable-and-optimal-use-biomass-energy-eu-beyond-2020

Hoefnagels, R., Kluts, I., Junginger, M., Visser, L., Resch, G., Mantau, U. et al. (2017). *Sustainable and optimal use of biomass for energy in the EU beyond 2020. Annexes of the Final Report*. URL: https://ec.europa.eu/energy/en/studies/sustainable-and-optimal-use-biomass-energy-eu-beyond-2020

7.16 SOUZA (2019): *RELEVANCE OF LACAF BIOFUELS FOR GLOBAL SUSTAINABILITY*

7.16.1 Study Design

Study fact sheet	
General	
Title of the study	Relevance of LACAf Biofuels for Global Sustainability
Contact name	Glaucia Mendes Souza (University of São Paulo and FAPESP BIOEN), Luiz Augusto Horta Nogueira (UNICAMP and FAPESP BIOEN), Rubens Maciel (UNICAMP and FAPESP BIOEN), Heitor Cantarella (IAC and FAPESP BIOEN),Luis Cassinelli (FAPESP BIOEN)
Initiator of the study	Glaucia Mendes Souza
Year of the study	2019
Publication	Trindade, S. C., Nogueira, L. A. H., & Souza, G. M. (2019). Relevance of LACAf biofuels for global sustainability. *Biofuels*, 1-11. DOI: 10.1080/17597269.2019.1679566
Links	http://bioenfapesp.org/scopebioenergy/index.php
Details of the study	
Geographical system boundaries	We report a study on bioenergy for 25 Latin America and Africa countries and describe the status and potential for Angola, Ethiopia, Kenya, Malawi, South Africa, Uganda, Zimbabwe, Argentina, Bolivia, Brazil, Colombia, Costa Rica, Ecuador, Mexico, Paraguay, Peru, Uruguay, among others.
Temporal boundaries	Short term (in the range of 5 to 10 years)
Sectors system boundaries	Sugarcane production and conversion to produce biofuels; Pasture land substitution contribution; emissions reduction.
Land use system boundaries	We focus our study on sugarcane since it is largely used for sugar production in the world (more than 100 countries) and consider its large potential for CO_2 emissions mitigation an important asset to highlight. To further argue the case, we estimated the CO_2 emissions reduction that can be obtained through gasoline substitution by ethanol from sugarcane, assuming its production in a selected group of countries of Latin America, the Caribbean and Southern Africa. We propose the use of 1% of pastureland for sugarcane ethanol production in each country.
Ambition in GHG reduction	50 Mtoe CO_2 Two scenarios were studied, exploring the short term and improved prospects of ethanol production, particularly with regards to feedstock availability and using pastureland.
Ambition in SDG improvement	The substitution of pastures with sugarcane can have broader effects within local economies, decrease the environmental impacts of fossil fuel use and contribute with many of the SDGs (Nogueira et al., 2015). Sustainable bioenergy can be deployed in large scale and provide energy security in the transportation services space in a short period of time. Locally produced transportation fuels made with local biomass allow countries to do an ‘end-run’ around

	energy security challenges. Besides the reduction of GHG emissions sugarcane can also help improve the quality of soils. This could contribute with efforts to prevent soil erosion. In fact, there are reports that sugarcane can decrease up to 99% soil erosion when substituting pastures (Youlton et a., 2016). The concomitant increase in the production, use and export of bioenergy and other bio-products has directly contributed to improved economic development, infrastructure and employment opportunities and increased income in both rural and urban areas that help aid food security (Souza et al., 2018). The option to use their feedstocks for bioenergy or other bio-products has helped farmers to stabilize their income. This option has also had indirect social benefits to these countries: Technological gains (e.g. know-how, improvement in academic performance, technology jobs, patents); GDP and education improvements (in Brazil, in areas where the sugarcane industry is established, Moraes et al., 2015); increased resilience to economic disruption (in Argentina, switching to using sugarcane for biofuel helped farmers in Tucuman Province withstand the economic disruption) of low sugar prices and create resilience in the community). Cities can largely benefit when using bioethanol for transportation. Air pollution in urban areas affects millions of people worldwide. Recent estimates indicate that 92% of the world's population lives where air pollutants exceed WHO limits (WHO, 2016). The use of ethanol instead of gasoline has been shown to reduce emissions of CO, NOx and ultrafine particles that can cause health problems including cancer (Salvo et al., 2017).
Framing of the study	The study focuses on the development prospects of sustainable biofuels markets in Latin America and Sub-Saharan Africa, regions with large potential to become global suppliers of biofuels, where 500–900 million hectares of land are available for bioenergy production while simultaneously enhancing food security and biodiversity.
Assessment approach	Business as usual (BAU): considers ethanol produced only from sugarcane molasses based on the existing sugarcane production with a yield of 10 liter per ton of cane (tc), not affecting the sugar production. New framework (NF): considers sugarcane cultivated on 1% of the current pastureland, with an average yield of 80 t/ha. Pasture lands are usually underutilized and by applying better practices, such as rotational grazing and integrated crop-livestock-forestry systems, it is possible to increase the productivity without compromising the grazing activity. In this scenario, it is assumed that ethanol is produced from molasses in existing sugar mills with a yield of 10 liter/tc and direct juice in new sugar mills with a yield of 80 L/tc.

7.16.2 Key messages

We estimate that in 25 countries from Latin America and Africa a total of 437 Mt of sugarcane could be produced annually using only 1% of their pastureland. About 50 Mt CO_2eq of avoided emissions could be achieved if ethanol production and use were to be adopted, promoting domestic use and trade of surpluses, bringing positive impacts in several levels (Trindade et al. 2019).

In fact, sustainable bioenergy deployment in Latin America and Africa and in the world at large:

- plays a critical role in global sustainable development
- is crucial to reach a renewable energy mix
- has unique features over and beyond hydro, solar and wind provision of electricity
- has large scalability and sustainability potential
- promotes local production and agricultural growth and broader rural development
- expands and can co-exist with food security and biodiversity
- improves soil quality when energy crops substitute pastures
- produces feedstock that can be combined with forest preservation/recovery
- promotes business innovation
- drives the bioeconomy supported by international cooperation and trade

7.16.3 Facts and figures

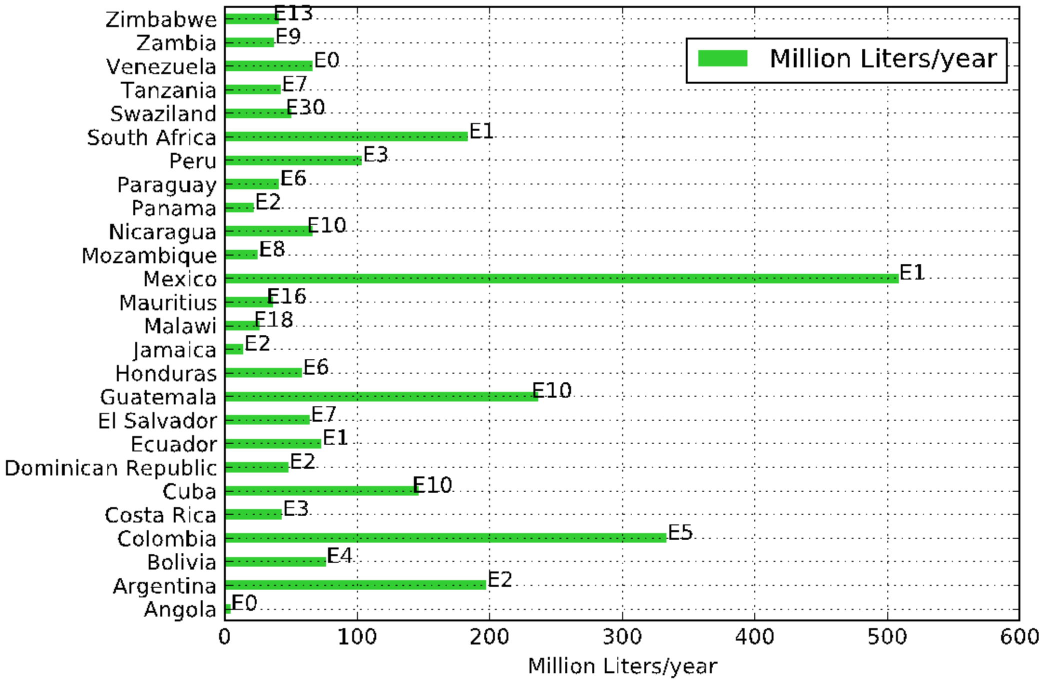
Table 7: One percent of the pastureland and sugarcane potential production in selected countries of Latin America and Southern Africa with corresponding emission reductions (Cutz et al. 2018), pasture land from (FAO, 2012).

Country	1% of pasture area (1000 ha)[a]	Sugarcane potential production (1000 t)[b]	GHG emission annually mitigated (Mt CO2/year)[c]
Latin America and the Caribbean			
Argentina	1085	86,800	9.90
Bolivia	330	26,400	3.01
Colombia	392	31,360	3.58
Costa Rica	13	1040	0.12
Cuba	28	2240	0.26
Dominican Republic	12	960	0.11
Ecuador	50	4000	0.46
El Salvador	6	480	0.05
Guatemala	20	1600	0.18
Honduras	18	1440	0.16
Mexico	2	160	0.02
Nicaragua	809	64,720	7.38
Panama	33	2640	0.30
Paraguay	15	1200	0.14
Peru	170	13,600	1.55
Venezuela	188	15,040	1.71
Subtotal	3171	253,680	28.92
Southern Africa			
Angola	571	45,696	5.21
Malawi	20	1568	0.18
Mauritius	<1	8	0.00
Mozambique	465	37,232	4.24
South Africa	888	71,016	8.10
Swaziland	11	872	0.10
Tanzania	0,3	24	0.00
Zambia	211	16,920	1.93
Zimbabwe	128	10,240	1.17
Subtotal	2295	183,576	20.93
Total	5466	437,256	49.85

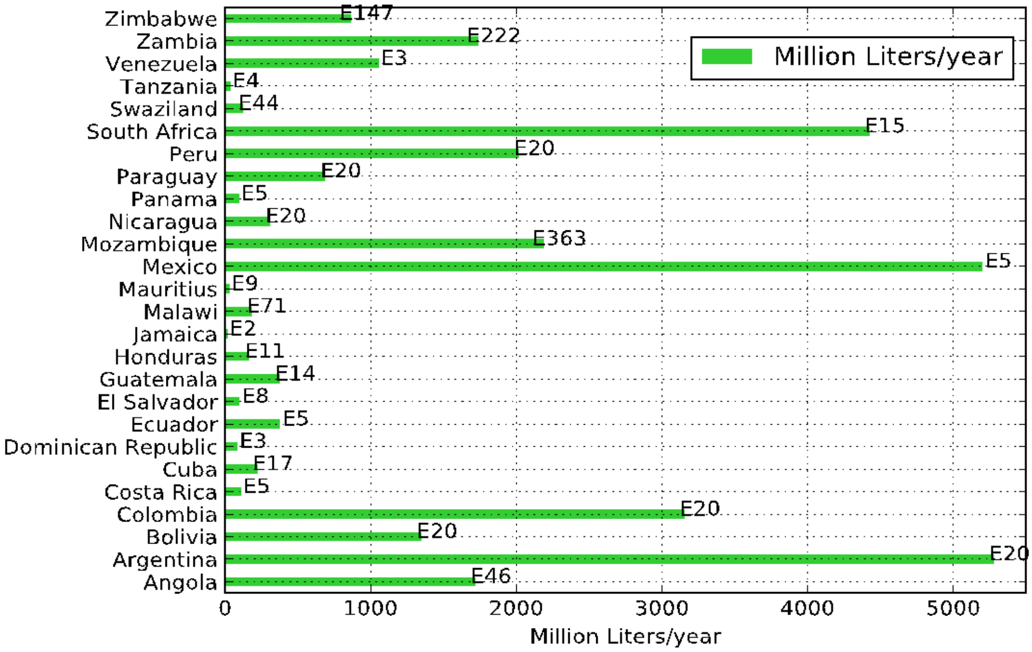
a FAO. Production, crops. FAOStat. FAO; 2018 [consulted in Sep [65] 2018].

URL: http://faostat3.fao.org/download/Q/QC/Efor year 2015.

b Assuming 80 ton/ha. c Assuming 0.114 t CO2eq/t cane.



a) BAU scenario



b) NF scenario

Figure 35: Potential ethanol supply in Latin America, the Caribbean and Southern Africa and blending level that can be accomplished considering the national gasoline demand. Ex indicates the potential gasoline blend that could be achieved in each country, from 2015 data in Cutz & Nogueira (2018).

We estimate the mitigation potential of using 1% of pasture for bioethanol production with gasoline substitution. We assume a sugarcane yield of 80 ton/ha, ethanol yields of 85 liters/ton, and an emission reduction of 1,347 gCO_2/liter anhydrous ethanol (60.4 gCO_2eq/MJ emission reduction), the reference case used in the Brazilian National Biofuel Policy (RenovaBio), where this parameter is called environmental efficiency of a biofuel. It adopts a calorific value of 22.3 MJ/liter for ethanol. With these values we estimated an annual mitigation of 0.114 t CO_2eq/ton cane when ethanol is used displacing gasoline.

For these 25 countries we estimate a potential production of 2.9 billion tons of sugarcane in 1% of pastureland and about 49.85 Mtons CO_2eq of avoided emissions (with E20). In the case of Brazil, for an average annual production of 600 Mton of sugarcane crop, 60 Mton of CO_2 emissions would be avoided (the transport sector total emissions were 209 Mt).

We foresee that emissions of CO_2 may be further significantly decreased with improvements in several steps of the whole ethanol production process, improvements on sugarcane productivity, more efficient conversion process considering different types of sugarcane as energy cane, increasing the portfolio of products (ethanol for fuels, other chemicals that are dense energy carries and electricity) (Zetty-Arenas et al. 2019, Klein et al 2019a). Improvements in the biochemical route have been reported (Yamagawa et al. 2019, Dias et al 2015) as well as some options to use residual streams of ethanol production plants (Klein et al. 2019b). Many options for the thermochemical routes are possible, especially when applied to the energy cane which contains a significantly higher amount of cellulose, hemicellulose and lignin compared to the conventional one (Motta et al., 2019).

Sugarcane has several advantages over other energy crops. The agricultural energy ratio (the ratio between biomass energy content and the amount of energy to crop production) of sugar cane compared to corn, for instance. The amount of energy to produce corn is around 18.9 GJ/ha*yr while for ethanol is about 13.9 GJ/ha*yr and the energy content for the corn is 149.5 GJ/ha*yr and for the sugarcane is 297.1 GJ/ha*yr. With these numbers the agricultural ratio is 7.9 and 21.3, for corn and sugarcane, respectively. In other words, sugarcane is by far a very efficient crop and this leads to the final biofuel to be more sustainable (both economically and environmentally)

There is an added consequence when we substitute pastures with sugarcane. Pasture lands, especially the degraded ones, usually accumulate more C in the soil when replaced by sugarcane (Melo et al. 2014). Sugarcane, because of its high biomass production and organic residues that are returned to soils, can help to maintain or improve soil quality, increase the C storage, and help reduce erosion.

Dry biomass production is of the order of 30 to more than 60 t/ha. Besides the stems that are harvested to produce sugar/ethanol, approximately 8-15 t DM/ha of straw are left on the field, in addition to the strong root system (approximately 3-6 t DM/ha), which add C to soils. This contribution is well documented (Galdos et al. 2009). Even if part of the straw is collected to produce electricity of 2G ethanol, sizeable amounts of organic residue remains in the field. Bagasse (125 kg DM per tonne of crushed cane) is used to produce energy but its ashes (~6 kg) are returned to the soil. Other organic residues of the sugar/ethanol industry, produced in large amounts, are recycled in the soil, thus contributing to improve soil quality (filter cake at approximately 30 kg per tonne of crushed cane) and vinasse (10-13 L per L of ethanol) contains nutrients and organic matter that enriches the soil in addition to reducing the need of chemical fertilizers (Cantarella & Rossetto 2012).

Fertilizer application with the use of vinasse fertirrigation reduces Nitrogen application rates from 90 to 75 kg/ha, phosphorus from 115 to zero and potassium from 25 to zero.

7.16.4 Key recommendations

Existing policy and current status of biofuel programs in said 25 countries were evaluated and discussed (Trindade et al. 2019). From the diverse experiences of introducing biofuels, particularly more mature in Latin America, where successes and failures are observed, it is possible to get some relevant lessons:

a) Ethanol generally comes first, its production is easier and can be readily deployed associated to sugarcane sugar mills;

b) Blending mandates are an effective strategy for introducing biofuels, but should be defined carefully and adopted progressively, considering the supply conditions and constraints;

c) Clear government willingness to implement a sustainable biofuels market and a consistent legislation/regulatory framework are essential, possibly establishing pricing mechanisms, tax structure and incentives to investment, as well as promoting the dialog among all stakeholders and including measures for assuring environment and worker's rights protection;

d) The oil company attitude is crucial, as owners of fuels terminals where the blending operation should be done; directly related to the value chain of fuels market, their perception of losses or gains with the biofuel expansion constituted a main obstacle or a decisive factor of success.

e) Public communication and information are also important, to reduce misinformation about biofuels impacts in production and use, as well as to inform about the drives to implement this change and benefits to expect.

f) Although it is interesting and desirable to implement jointly biofuels mandatory use and local production, imports and exports can play a role in stabilizing the biofuels market, thus trade barriers should be avoided.

7.16.5 References

Cantarella, H. & Rossetto, R. (2012). Fertilizer concerns. In M.K. Poppe and L. A.B. Cortez, eds., Sustainability of Sugarcane Bioenergy, pp. 71-94. CGEE - Center for Strategic Studies and Management, Brasilia.

Cortez, L.A.B., Leal, M.R.L.V. & Nogueira, L.A.H. (2018). Sugarcane bioenergy for sustainable development (book).

Cutz, L. and Nogueira, L.A.H. (2018). The potential of bioenergy from sugarcane in Latin America, the Caribbean and Southern Africa In Cortez, L.A.B. et al., 2018 (op. cit.)

Dias, M. O. S., Cavalett, O., Maciel Filho, R. & Bonomi, A. (2015). Integrated first-and second-generation processes for bioethanol production from sugarcane. *Chemical Engineering Transactions 37*, 445-450.

Galdos, M. V., Cerri, C. C., Cerri, C. E. P., Paustian, K. & Van Antwerpen, R. (2009). Simulation of Soil Carbon Dynamics under Sugarcane with the CENTURY Model. *Soil Science Society of America Journal, 73*, 802-811. https://climatepolicyinitiative.org/publication/sugarcanes-role-fueling-economy/

Klein, B. C., Sampaio, I.L.M., Mantelatto, P.E., Maciel Filho, R. & Bonomi, A. (2019a). Beyond ethanol, sugar, and electricity: a critical review of product diversification in Brazilian sugarcane mills. Biofuels, Bioproducts and Biorefining, v. 12, p. 10.

Klein, B. C., Chagas, M. F., Watanabe, M. D. B. Bonomi, A. et al (2019b). Renewable and Sustainable Energy Reviews. Low carbon biofuels and the New Brazilian National Biofuel Policy (RenovaBio): A case study for sugarcane mills and integrated sugarcane-microalgae biorefineries.

Mello, F. F. C., Cerri, C. E. P., Davies, C. A., Holbrook, N. M., Paustian, K., Maia, S. M. F., Galdos, M. V., Bernoux, M. & Cerri, C. C. (2014). Payback time for soil carbon and sugar-cane ethanol. *Nature Climate Change, 4*, 605-609.

Moraes, M.A.F.D.I., Oliveira, F.C.R. & Diaz-Chavez, R.A. (2015). Socio-economic impacts of Brazilian sugar cane industry. *Environ. Dev. 16*, 31-43

Motta, I. L., Miranda, N. T., Maciel Filho, R. & Maciel, M. R. W. (2018). Biomass gasification in fluidized beds: A review of biomass moisture content and operating pressure effects. *Renewable and Sustainable Energy Reviews 94*, 998-1023

Motta, I., Lopes Miranda, N.T., Maciel Filho, R., Maciel, M.R.W. (2019). Sugarcane bagasse gasification: Simulation and analysis of different operating parameters, fluidizing media, and gasifier types. Biomass & Bioenergy, v. 122, p. 433-445.

Nogueira, L. A. H., Leal ,M. R. L. V., Fernandes, E., Chumd, H. L., Diaz-Chavez, R., Endres, J., Mahakhantg, A., Ottoh, M., Seebalucki, V. & van der Wielenj, L. (2015). Sustainable development and

Innovation. *In* Bioenergy & Sustainability: bridging the gaps. Eds. Souza, G. M. et al. SCOPE vol. 72.pp 184-217. Paris. France. ISBN 978-2-9545557-0-6

IRENA (2019). Sugarcane bioenergy in Southern Africa. Economic potential for sustainable scale up. International Renewable Energy Agency, Abu Dhabi. URL: https://www.irena.org/publications/2019/Mar/Sugarcane-bioenergy-in-Southern-Africa-Economic-potential-for-sustainable-scale-up

Salvo, A., Brito, J., Artaxo, P. & Geiger, F. M. (2017). Reduced ultrafine particle levels in São Paulo's atmosphere during shifts from gasoline to ethanol use. *Nature Communications 8,* 77.

Souza, M.O., Maciel Filho, R., Mantelatto, P.E., Cavalett, O., Rossell, C.E.V, Bonomi, A., Leal, M.R.L.V. (2015). Sugarcane processing for ethanol and sugar in Brazil. Environmental Development, v. 15, p. 35-51, 2015.

Souza, G. M., Victoria, R., Joly, C., Verdade, L. (Eds.). (2015). Bioenergy & Sustainability: Bridging the gaps (Vol.72, 779 p.). Paris: SCOPE. ISBN 978-2-9545557-0-6. URL: http://bioenfapesp.org/scopebioenergy/index.php/chapters

Souza G.M. et al. (2018). Sustainable Bioenergy: Latin America and Africa. ISSN2412-0286. URL: http://bioenfapesp.org/scopebioenergy/index.php/policy-brief/2018

Trindade, S.C., Nogueira, L.A.H. & Souza, G.M. (2019). Relevance of LACAf Biofuels for Global Sustainability, Biofuel, November 2019, DOI: 10.1080/17597269.2019.1679566

WHO releases country estimates on air pollution exposure and health impact. World Health Organization (2016). URL: http://www.who.int/mediacen- tre/news/releases/2016/air-pollution-estimates/en/

Yamakawa, C. K., Rivera, E. C., Kwon, H., Agudelo, W. E. H., Saad, M. B., Leal, J. et al. (2019). Study of influence of yeast cells treatment on sugarcane ethanol fermentation: Operating conditions and kinetics. *Biochemical engineering journal*, *147*, 1-10.

Youlton, C., Wendland, E., Anache, J. A. A., Poblete-Echeverría, C. & Dabney, S. (2016). Changes in Erosion and Runoff due to Replacement of Pasture Land with Sugarcane Crops. *Sustainability 8*, 685. DOI: 10.3390/su8070685 Zetty-Arenas, A. M., Alves, R. F., Portela, C. A.

F., Mariano, A. P., Basso, T. O., Tovar, L. P. et al. (2019). Towards enhanced n-butanol production from sugarcane bagasse hemicellulosic hydrolysate: Strain screening, and the effects of sugar concentration and butanol tolerance. *Biomass and Bioenergy, 126,* 190-198.

7.17 YUWONO (2019): *INDONESIA'S EQUITABLE EMISSIONS & OPPORTUNITIES FOR EMISSIONS 'HEADROOM' WITH BECCS **

7.17.1 Study Design

Study fact sheet	
General	
Title of the study	Indonesia's equitable emissions & opportunities for emissions 'headroom' with BECCS
Contact name	Bintang Budi Yuwono
Initiator of the study	IIASA – International Institute for Applied Systems Analysis
Year of the study	2019
Publication	Working paper
Links	n/a
Details of the study	
Geographical system boundaries	Indonesia
Temporal boundaries	2020 up to 2100
Sectors system boundaries	National energy, industry, and land-use emissions
Land use system boundaries	Classification of key sources of emissions, i.e. Peat fires and decomposition
Ambition in GHG reduction	Stabilization of global warming to 1.5°C and 2°C.
Ambition in SDG improvement	Directly: SDGs 13, 7 and 15.
Framing of the study	The study "Indonesia's equitable emissions & opportunities for emissions 'headroom' with BECCS" analyses different scenarios of international emissions allocation in Indonesia under an emissions constrained world of 2/1.5-C. The analysis explicitly describes the effect of various equity-frameworks of emissions allocation to national pathways of emissions, with also considering the uncertainties of future social and economic developments. This include the stresses for negative emissions in various allocation scenarios. The results of this analysis will provide the grounds where national ambition and strategies are positioned in the frameworks of international cooperation and equity for climate.
Assessment approach	There are 32 scenarios of 2/1.5-C global emissions (RCP2.6 and RCP1.9) considered in this study. The allocations of international emissions use the elements of responsibility, capacity, and equity elements of fairness in the common efforts of mitigation and consider various Global Shared Socio-economic Pathways (SSPs). Moreover, discounting for peat fires and decomposition emissions in the responsibility factor of Indonesia's allocation of

	emissions is considered as part of the discussion.

7.17.2 Key messages

Indonesia have limited to 50 (25) Gton CO_2-eq budget under a 2°C (1.5°C) pathway of international equitable-climate regime. With considering the current level and pathway of emissions, this implies to faster budget depletion — alas requiring higher rates of reductions compared to existing policies, where current NDCs does not indicate peaking of emissions earlier than 2030. Indonesia aims to improve their mitigation effort in line with the goals and characteristics of the Paris Agreement, for the coming First Global Stocktake in 2023.

Indonesia needs to cut emissions very fast, followed with peaking of emissions before mid-century and reaching a balance of emissions sources and sinks before the end of century, and furthermore, going 'net-negative'. Transitioning towards net-zero and net-negative emissions at these rates of reduction increases the risks of hampering economic development. In the context of developing economy, this becomes more challenging. Let alone transitioning to 'net-zero' around 2085 (2060) under 2°C (1.5°C), if effectively implemented, budget will deplete around mid-century, the earliest around 2075 (2035) with budget deficits of about 1 (6) Gton CO_2-eq.

In principle, gross-emissions can be larger than the net-emissions budget as long as they are simultaneously compensated with sufficient amount of negative emissions (Azar et al. 2010, van Vuuren et al. 2013, Kriegler et al. 2014, Eom et al. 2015, Riahi et al. 2015). Negative emissions, or net-removal of CO_2 from the atmosphere, provide important 'emissions-headroom' as Indonesia transitions towards zero-carbon. The additional 'emission-space' afforded by negative emissions could offset the emissions from sectors that are more difficult and expensive to decarbonise, such as heavy-duty transport and aviation; in addition to sectors that holds national strategic interest, such as the coal sector. This will add flexibility into any national decarbonisation plan (Fuss et al. 2014).

Aiming for WB2, Indonesia have the opportunity to transition its energy system by steeply reduce the carbon-intensity in all sectors of the economy. In the energy sector, improvement in energy efficiency and conservancy and decarbonisation of energy carriers and switch to low-/zero- carbon energies are the three main objectives for decarbonisation. Adding the option for negative emissions using BECCS shall complement or compensate other more costly mitigation actions, in line with the national strategy for increasing bioenergy utilization and CC(U)S deployment. However, there are risks hindering BECCS deployment, availability of sustainable biomass feedstock, suitability of CO_2-injection/storage, and other enabling policies that needs to be assessed for the optimal roll-out and scale-up of BECCS in Indonesia.

7.17.3 Facts and figures

- Calculated national 'fair' carbon budgets and related emissions trajectories

The allocation of national carbon budget is derived from the calculation of equitable shares of international emissions scenarios based on principles of fairness, namely, responsibility, capacity and equity. The allocation considers ranges of uncertainties in the future development of the social economy in terms of countries population and income (GDP) as well as global emissions pathways—with special focus on global peak, net-zero and net-negative emissions. Under 2°C warming, the calculated Indonesia's carbon budget ranges (20th – 80th percentile and average shown in brackets) between 48.6 – 73.8 (avg. 63.4) Gton CO_2eq, which varied widely across categories, from 66.6 – 74.1 (69.4) under 'RES', 40.4 – 48.5 (44.4) under 'CAP', 62.3 – 69.0 (65.2) Gton CO_2eq for 'EPC', 71.7 – 79.35 (74.8) Gton CO_2eq under 'ECPC', and to under 'CER'. When the global target shifts to a stricter 1.5°C warming, the allocated carbon budgets decrease significantly to ranges between 33.4 – 49.8 (42.7) Gton CO_2eq (46.0 'RES'-avg.; 31.1 'CAP'-avg.; 42.6 'EPC'-avg.; 51.6 'ECPC'-avg.). Implicating to a shorter budget depletion to 42.7 years, in the case where 2015 emissions level—excluding the emissions related 'peat fires and decomposition', a rough-total of 1 Gton CO_2eq continues—compared to 63.4 years, under 2°C warming budgets average. The higher range of budgets corresponds to the scenarios with high fossil-fuel reliance (SSP5), of which also corresponds to larger accumulation of net-negative emissions.

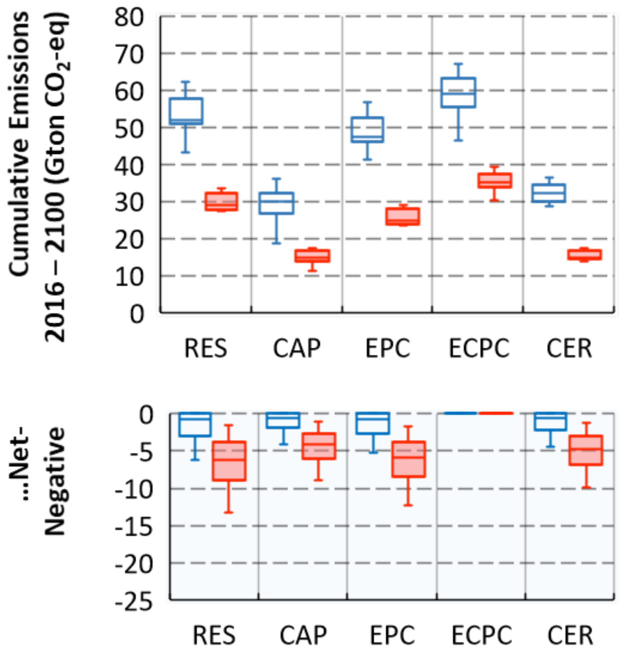


Figure 36: Indonesia's carbon budgets between 2016 and 2100 calculated from cumulative 'fair' allocation of global cost-optimal emissions scenarios in Gton CO_2eq (blue=2°C, red=1.5°C). Accumulation of net-negative emissions in all allocation scenarios are also presented.

It is important to note that the resulted emissions trajectories from the calculated 'fair'-allocation of international emissions does not dictate countries' pathways of development and related emissions. The allocated emissions pathways indicate peaking of emissions by around 2020. Furthermore, emissions must reduce to zero by the end of century, or even faster, around mid-century, followed with accumulation of net-negative emissions to abate the emissions debts (budget deficits)—returning the budget to zero-balance by the end of 2100. With including Global-SSPs into perspective; under SSP4 ('Inequality'), emissions budgets are on the lowest-possible range. In contrast, under SSP1 ('Sustainability') budgets are on the highest-possible range. SSP2 and SSP5 resulted to mediocre range of budgets, however, SSP5 ('Fossil-Fuelled Development') pathways indicate slower pace in reaching net-zero, implicating to faster budget depletion and complemented with larger stress on 'going negative'.

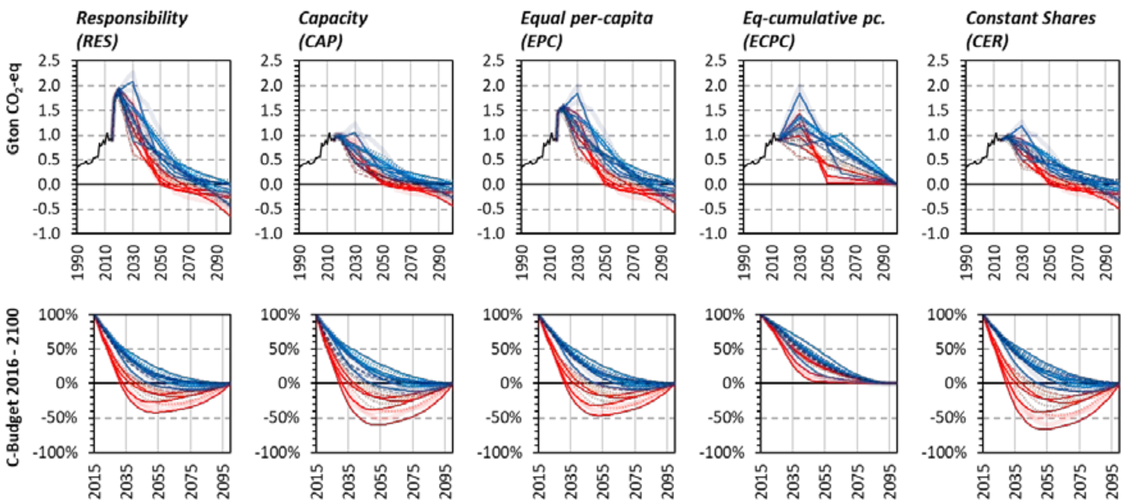


Figure 37: Indonesia's pathways of national Energy and AFOLU GHGs emissions under five frameworks of 'fair' allocation consistent with global 2°C (RCP2.6, blue) and 1.5°C (RCP1.9, red) emissions scenarios. Scenarios are classified under different SSPs (SSP1=dotted line, SSP2=most visible, SSP4=dashed, SSP5=least visible) in Gton CO_2-eq.

Shaded lines in the back represents scenarios of emissions allocation with accounting for peat fires and decomposition emissions responsibilities.

- Influence of 'peat fires and decomposition' emissions

The amount of peat fires and decomposition emissions are significant in influencing the 'fair' distribution of international emissions. Including 'peat' into national responsibility have resulted to significant decrease of emissions budget and stressing more on to going for negative emissions for Indonesia. Discounting 'peat' grants Indonesia an additional 10–15 Gton budget. Indonesia's peat fires and decomposition emissions are considered as a disruptive catastrophe that does not provide direct links to socio-economic developments. Moreover, large 'unequal' regional distribution of peat lands and accounting uncertainties may distort the fair allocation of international emissions.

Indonesia's emissions profile indicates that most of the emissions occurred in Indonesia are not coming from sectors that are highly contributing to the national economy. In 2015, Indonesia's energy-emissions intensity of 0.48 kg CO_2eq/US$_{2010}$ was close to the global average (0.46 kg CO_2eq/US$_{2010}$) and still considered low amongst non-OECD countries in Asia (0.91 kg CO_2eq/US$_{2010}$). However, Indonesia's per-capita combined energy- and AFOLU-emissions of 7.99 ton CO_2-eq is almost double the average of non-OECD countries in Asia (4.64 ton CO_2eq) and global (5.85 ton CO_2eq). This analysis resulted to a unique situation in Indonesia, where low-energy intensive economy may have high emissions per-capita; due to the high rates of emissions in the non-energy related sectors such as agriculture, forestry and land-use sectors, especially the 'disruptive' and 'catastrophic' emissions from 'peat'-fires and -decomposition. When accounting for 'peat' related emissions in Indonesia, Indonesia could lose about 10 to 20 Gton CO_2eq of the budget, compared to discounting for 'peat'-emissions under allocations that consider countries' responsibility of past-emissions ('RES' and 'ECPC'). The lowering of budgets also represents larger net-negative emissions.

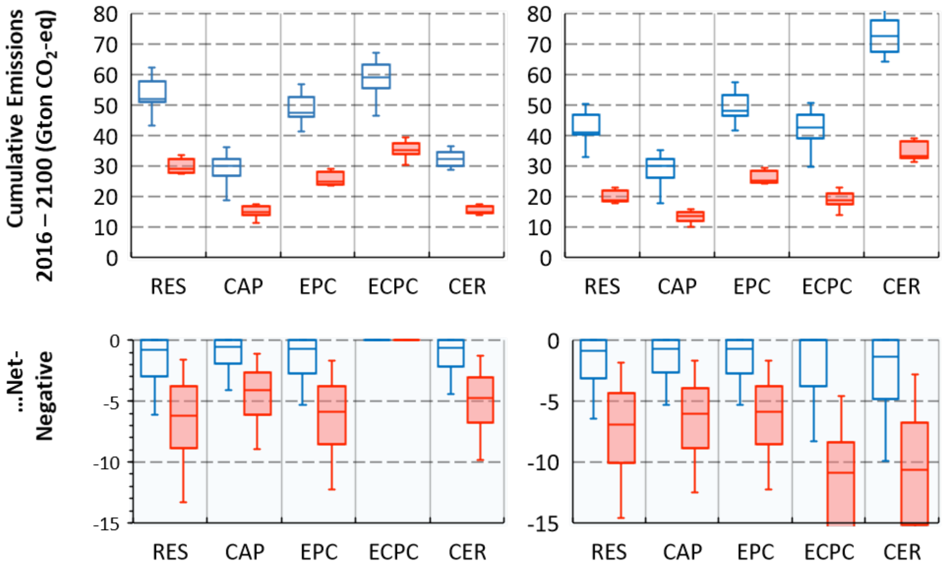


Figure 38: Indonesia's carbon budgets between 2016 and 2100 calculated from 'fair' allocation of global cost-optimal emissions scenarios, without (left) and with (right) considering historical responsibility of national 'peat' emissions in Gton CO_2-eq (blue=2°C, red=1.5°C).

7.17.4 Key recommendations

- The results of this study bring a strategic insight for the long-term management of national emission. The results indicate various ranges of Energy and Land-Use GHGs emissions budgets that Indonesia can have up to the end of the 21st century, to make sufficient and equitable contributions to the global efforts to achieve 2/1.5°C targets. With respect to the stringent climate targets and international ‘equitable’-efforts, Indonesia has limited emissions budgets that may deplete earlier than mid-half of the century (under 1.5°C). And to effectively spend-out the budget up to the end of 21st century, Indonesia need to cut deep on emissions, by means of effectively mobilize decarbonization measures, and more importantly, to accumulate negative emissions. Negative emissions, by means of removing GHGs emissions from the atmosphere can be achieved through natural climate solution (e.g. afforestation), and technological solution, such as bioenergy coupled with carbon capture and storage – BECCS, considering the strategic goals of domestic bioenergy sector as well as the opportunities in improving sustainable forest management, moreover, complemented with the potential co-benefits for the society (jobs, rural development, value added, and more).

- Negative emissions strategy is critical for Indonesia’s 2/1.5°C pathways of development, especially for considering the current planned- and existing-development of Indonesia’s coal sector (RUPTL 2018-2027, 2018), in addition to sectors that are difficult to decarbonize (naval and air transport, agriculture). Negative emissions technologies (NETs) could ‘offset’ the carbon budget to provide emissions space for ‘hard-to-decarbonize’ sectors and provide ‘buffer’ for the transition from high-emitting economy to low-, zero-, or negative-emissions economy. However, there are other impacts of NETs towards the society, industry, economy, natural resource, and environment sustainability that needs to be well-understood in strategic implementation of ‘safe’ and ‘sustainable’ NETs. The extent of negative emissions needed are much dependent on the emissions pathway’s ‘budget’ and ‘archetype’. In ‘late action’ pathways, emissions may overshoot for a short time, implicating to fast depletion carbon budget. Thus, increasing the needs for accumulating negative emissions to return the carbon budget’s effective health.
- ‘Peat fires and decomposition emissions’ in Indonesia are not directly contributing to the improved social and economic welfare of the country. In addition, the amount of peat’ related emissions are significant in influencing the ‘fair’ distribution of the GCB. Including ‘peat’ into national responsibility have resulted to Indonesia losing significant emissions budget and stressing more on to going for negative emissions. Due to its significance and unequal distribution across regions, ‘Peat’ related emissions should be addressed in a specialized international support framework.
- There are further research opportunities including the analysis of carbon budgets using improved frameworks of ‘fair’ allocations and updated global and countries projections and historical data (i.e. emissions and socio-economic indicators); which will become available around the period of global stock-take and updates within the IPCC. And to use many other ‘target’ global scenarios that have unique characteristics in describing the future on how society, economy, technology, and environment develops, in which are suitable for country-specific conditions. Moreover, to adapt the frameworks with country-specific types of emissions; In this case, ‘disruptive emissions’ that requires specialized framework to address the ‘fairness’ in the distribution of international emissions.

7.17.5 References

Azar, C., Lindgren, K., Obersteiner, M., Riahi, K., van Vuuren, D. P., den Elzen, K. M. G. et al. (2010). The feasibility of low CO 2 concentration targets and the role of bio-energy with carbon capture and storage (BECCS). *Climatic Change*, *100*(1), 195-202.

Eom, J., Edmonds, J., Krey, V., Johnson, N., Longden, T., Luderer, G. et al. (2015). The impact of near-term climate policy choices on technology and emission transition pathways. *Technological Forecasting and Social Change*, *90*, 73-88.

Fuss, S. et al. (2014) ‘COMMENTARY: Betting on negative emissions’, Nature Climate Change. Nature Publishing Group, 4(10), pp. 850–853. doi: 10.1038/nclimate2392.

Kriegler, E., Edenhofer, O., Reuster, L., Luderer, G. & Klein, D. (2013). Is atmospheric carbon dioxide removal a game changer for climate change mitigation? *Climatic Change*, *118*(1), 45-57.

Riahi, K., Kriegler, E., Johnson, N., Bertram, C., Den Elzen, M., Eom, J. et al. (2015). Locked into Copenhagen pledges—implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technological Forecasting and Social Change*, *90*, 8-23.

van Vuuren, D. P., Deetman, S., van Vliet, J., van den Berg, M., van Ruijven, B. J. & Koelbl, B. (2013). The role of negative CO_2 emissions for reaching 2°C—insights from integrated assessment modelling. *Climatic Change*, *118*(1), 15-27.

References

acatech (2019a). Biomass: striking a balance between energy and climate policies. Strategies for sustainable bioenergy use. Series on Science-Based Policy Advice URL: https://en.acatech.de/publication/biomass-striking-a-balance-between-energy-and-climate-policies-strategies-for-sustainable-bioenergy-use/

acatech (2019b). *CCU and CCS – Building Blocks for Climate Protection in Industry.* Munich: acatech. URL: https://www.acatech.de/wp-content/uploads/2018/09/acatech_POSITION_CCU_CCS_engl_Web.pdf

Alcalde, J., Flude, S., Wilkinson, M., Johnson, G., Edlmann, K., Bond, C. E. et al. (2018). Estimating geological CO_2 storage security to deliver on climate mitigation. *Nature communications*, *9*(1), 1-13. DOI: 10.1038/s41467-018-04423-1

Arning, K., van Heek, J. & Ziefle, M. (2017). Risk perception and acceptance of CDU consumer products in Germany. *Energy Procedia*, *114*, 7186-7196. DOI: 10.1016/j.egypro.2017.03.1823

Asbjornsen, H., Hernandez-Santana, V., Liebman, M., Bayala, J., Chen, J., Helmers, M., Ong, C.K. & Schulte, L.A. (2014). Targeting perennial vegetation in agricultural land- scapes for enhancing ecosystem services. *Renewable Agric. Food Syst. 29*, 101–125. DOI: 10.1017/S1742170512000385

Baik, E., Sanchez, D. L., Turner, P. A., Mach, K. J., Field, C. B. & Benson, S. M. (2018). Geospatial analysis of near-term potential for carbon-negative bioenergy in the United States. *Proceedings of the National Academy of Sciences*, *115*(13), 3290-3295. DOI: 10.1073/pnas.1720338115

Bauer, N., Rose, S. K., Fujimori, S., Van Vuuren, D. P., Weyant, J., Wise, M. et al. (2018). Global energy sector emission reductions and bioenergy use: overview of the bioenergy demand phase of the EMF-33 model comparison. *Climatic Change*, 1-16. DOI: 10.1007/s10584-018-2226-y

BBIC (2018). *Bioeconomy and the UN Sustainable Development Goals.* Bio-based Industries Consortium Working Paper. Brussels. URL: https://biconsortium.eu/sites/biconsortium.eu/files/documents/Bioeconomy_and_the_SDGs_July%202018.pdf

Berndes, G., Börjesson, P., Ostwald, M. & Palm, M. (2008). Multifunctional biomass production systems -an overview with presentation of specific applications in India and Sweden. *Biofuels Bioprod. Bioref. 2*, 16–25. DOI: 10.1002/bbb.52

Beuchelt, T. D. & Nassl, M. (2019). Applying a Sustainable Development Lens to Global Biomass Potentials. *Sustainability*, *11*(18), 5078. DOI: 10.3390/su11185078

Billig, E., Decker, M., Benzinger, W., Ketelsen, F., Pfeifer, P., Peters, R. et al. (2019). Non-fossil CO2 recycling — The technical potential for the present and future utilization for fuels in Germany. *Journal of CO2 Utilization*, *30*, 130-141. DOI: 10.1016/j.jcou.2019.01.012

Blackard, J. A., Finco, M. V., Helmer, E. H., Holden, G. R., Hoppus, M. L., Jacobs, D. M. et al. (2008). Mapping US forest biomass using nationwide forest inventory data and moderate resolution information. *Remote sensing of Environment*, *112*(4), 1658-1677. DOI: 10.1016/j.rse.2007.08.021

Bracco, Stefania et al. (2019). I*ndicators to monitor and evaluate the sustainability of bioeconomy. Overview and a proposed way forward.* Food and Agriculture Organization of the United Nations. Rome. URL: www.fao.org/3/ca6048en/ca6048en.pdf

Breyer, C., Fasihi, M. & Aghahosseini, A. (2019). Carbon dioxide direct air capture for effective climate change mitigation based on renewable electricity: a new type of energy system sector coupling. *Mitigation and Adaptation Strategies for Global Change*, 1-23. DOI: 10.1007/s11027-019-9847-y

Brosowski, A. (2015). Methodology for determination of biomass potentials. In Thrän & Pfeiffer (eds.), *Method handbook — material flow-oriented assessment of greenhouse gas effects* (pp. 40-48). URL: https://www.energetische-biomassenutzung.de/fileadmin/media/6_Publikationen/04_MHB_en_web.pdf

Brosowski, A., Thrän, D., Mantau, U., Mahro, B., Erdmann, G., Adler, P. et al. (2016). A review of biomass potential and current utilisation–Status quo for 93 biogenic wastes and residues in Germany. *Biomass and Bioenergy*, *95*, 257-272. DOI: 10.1016/j.biombioe.2016.10.017

Brosowski, A., Krause, T., Mantau, U., Mahro, B., Noke, A., Richter, F. et al. (2019). How to measure the impact of biogenic residues, wastes and by-products: Development of a national resource monitoring based on the example of Germany. *Biomass and Bioenergy*, *127*, 105275. DOI: 10.1016/j.biombioe.2019.105275

Budzinski, M., Cavalett, O., Nitzsche, R. & Strømman, A. H. (2019). Assessment of lignocellulosic biorefineries in Germany using a hybrid LCA multi-objective optimization model. *Journal of Industrial Ecology*, *23*(5), 1172-1185. DOI: 10.1111/jiec.12857

Cacho, J.F., Negri, M.C., Zumpf, C.R. & Campbell, P. (2017). Introducing perennial biomass crops into agricultural landscapes to address water quality challenges and provide other environmental services. *Wiley Interdiscip. Rev.: Energy Environ. 7*, e275.

Cames, M., Graichen, J., Siemons, A. & Cook, V. (2015). *Emission reduction targets for international aviation and shipping.* Brussels: European Parliament. URL: https://www.europarl.europa.eu/RegData/etudes/STUD/2015/569964/IPOL_STU(2015)569964_EN.pdf

Child, M., Kemfert, C., Bogdanov, D. & Breyer, C. (2019). Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe. *Renewable energy*, *139*, 80-101. DOI: 10.1016/j.renene.2019.02.077

Christen, B. & Dalgaard, T. (2013). Buffers for biomass production in temperate European agriculture: a review and synthesis on function, ecosystem services and implementation. *Biomass Bioenergy 55*, 53–67. DOI: 10.1016/j.biombioe. 2012.09.053

Clarke, L., Jiang, K., Akimoto, K., Babiker, M., Blanford, G., Fisher-Vanden, K. et al. (2014). Assessing transformation pathways. In Edenhofer et al. (eds.) *Climate change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth assessment Report of the Intergovernmental Panel on Climate Change.* URL: https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_full.pdf

Clariant International (2019). *Clariant bioethanol plant in Podari enters new phase*. Media release, accessed on Feb 26, 2020. URL: https://www.sunliquid-project-fp7.eu/wp-content/uploads/2019/10/Press-Release-bioethanol-plant-podari.pdf

Connolly, D., Lund, H., Mathiesen, B. V., Werner, S., Möller, B., Persson, U. et al. (2014). Heat Roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system. *Energy policy*, *65*, 475-489. DOI: 10.1016/j.enpol.2013.10.035

Consoli, C. (2019). *Bioenergy and Carbon Capture and Storage*. *Appendix 1.* Global CCS Institute publications. URL: https://www.globalccsinstitute.com/wp-content/uploads/2019/03/BECCS-Perspective_FINAL_18-March.pdf

Cowie, A.L., Orr, B.J., Sanchez, V.M.C., Chasek, P., Crossman, N.D., Erlewein, A., Louwagie, G., Maron, M., Metternicht, G.I., Minelli, S. and Tengberg, A.E., 2018. Land in balance: The scientific conceptual framework for Land Degradation Neutrality. Environmental Science & Policy, 79, pp.25-35.

Creutzig, Felix et al. (2019). The mutual dependence of negative emission technologies and energy systems. Energy Environ. Sci. 12, 1805-1817. DOI: 10.1039/c8ee03682a

Dauber, J., Brown, C., Fernando, A. L., Finnan, J., Krasuska, E., Ponitka, J. et al. (2012). Bioenergy from "surplus" land: environmental and socio-economic implications. *BioRisk*, *7*, 5-50. DOI: 10.3897/biorisk.7.3036

Dauber, J. & Miyake, S. (2016). To integrate or to segregate food crop and energy crop cultivation at the landscape scale? Perspectives on biodiversity conservation in agriculture in Europe. *Energy Sustain. Soc. 6* (1), 6 201625. DOI: 10.1186/s13705-016-0089-5

Dahmen, N., Lewandowski, I., Zibek, S. & Weidtmann, A. (2019). Integrated lignocellulosic value chains in a growing bioeconomy: Status quo and perspectives. *GCB Bioenergy*, *11*(1), 107-117. DOI: 10.1111/gcbb.12586

Dees, M., Elbersen, B., Fitzgerald, J., Vis, M., Anttila, P., Forsell, N. et al. (2017a). *Atlas with regional cost supply biomass potentials for EU 28, Western Balkan Countries, Moldavia, Turkey and Ukraine. Project Report, S2BIOM.* URL: https://www.s2biom.eu/images/Publications/D1.8_S2Biom_Atlas_of_regional_cost_supply_biomass_potential_Final.pdf

Dees, M., Datta, P., Fitzgerald, J., Verkerk, H., Lindner, M., Elbersen, B. S. et al. (2017b). *Roadmap for regional end-users on how to collect, process, store and maintain biomass supply data. Project Report, S2BIOM.* URL: https://www.s2biom.eu/images/Publications/D1.1_S2Biom_Roadmap_on_biomass_data_Final.pdf

Delivand, M.K., Cammerino, A.B., Garofalo, P. & Monteleone, M. (2015). Optimal locations of bioenergy facilities, biomass spatial availability, logistics costs and GHG (greenhouse gas) emissions: a case study on electricity productions in South Italy. *Journal of Cleaner Production 99*, 129-139. DOI: 10.1016/j.jclepro.2015.03.018

Edrisi, S. A. & Abhilash, P. C. (2016). Exploring marginal and degraded lands for biomass and bioenergy production: an Indian scenario. *Renewable and Sustainable Energy Reviews*, *54*, 1537-1551. DOI: 10.1016/j.rser.2015.10.050

Egenolf, V. & Bringezu, S. (2019). Conceptualization of an Indicator System for Assessing the Sustainability of the Bioeconomy. *Sustainability, 11*(2), 443. DOI: 10.3390/su11020443

equinor (2019). Northern Lights Project Concept report. URL: https://northernlightsccs.com/assets/documents/Northern-Lights-Project-Concept-report.pdf

FAO (2019). *Towards Sustainable Bioeconomy Guidelines - Brief.* Food and Agriculture Organization of the United Nations. Rome. URL: http://www.fao.org/3/ca5145en/CA5145EN.pdf

Fiorese, G. & Guariso, G. (2010). A GIS-based approach to evaluate biomass potential from energy crops at regional scale. *Environmental Modelling & Software*, *25*(6), 702-711. DOI: 10.1016/j.envsoft.2009.11.008

Flores Hernández, U., Jaeger, D. & Islas Samperio, J. (2017). Bioenergy potential and utilization costs for the supply of forest woody biomass for energetic use at a regional scale in Mexico. *Energies*, *10*(8), 1192. DOI: 10.3390/en10081192

Florin, Marie Valentine; Bunting, Christopher (2009). Risk governance guidelines for bioenergy policies. Journal of Cleaner Production, 17, 106-108. DOI: 10.1016/j.jclepro.2008.08.010

Fridahl, M. (2018). *Bioenergy with carbon capture and storage: From global potentials to domestic realities.* Brussels: European Liberal Forum. URL: https://liu.diva-portal.org/smash/get/diva2:1261268/FULLTEXT01.pdf

Fritsche, U. R., Berndes, G., Cowie, A. L., Dale, V. H., Kline, K. L., Johnson, F. X. et al.(2017). Energy and land use. Working Paper for the Global Land Outlook. Bonn: UN Convention to Combat Desertification.

Fritsche, U. et al. (2018). Linkages between the Sustainable Development Goals (SDGs) and the GBEP Sustainability Indictors for Bioenergy (GSI). Technical Paper for the GBEP Task Force on Sustainability. IINAS & IFEU. Darmstadt & Heidelberg. URL: http://www.globalbioenergy.org/fileadmin/user_upload/gbep/docs/Indicators/IINAS_IFEU__2018__Linkages_SDGs_and_GSIs_-_final.pdf

Fritsche, U. R., Eppler, U., Fehrenbach, H. & Giegrich, J. (2018). *Linkages between the Sustainable Development Goals (SDGs) and the GBEP Sustainability Indicators for Bioenergy (GSI). Technical Paper for the GBEP Task Force on Sustainability.* Darmstadt, Berlin, Heidelberg: IINAS & ifeu. URL: http://www.globalbioenergy.org/fileadmin/user_upload/gbep/docs/Indicators/IINAS_IFEU__2018__Linkages_SDGs_and_GSIs_-_final.pdf

Fritsche, U. & Rösch, C. (2020). The conditions for a sustainable bioeconomy. In Pietzsch (ed.) *Bioeconomy for Beginners*. Berlin, Heidelberg: 177-202. URL: 10.1007/978-3-662-60390-1_9

Gabrielle, B., Wernsdorfer, H., Marron, N. & Deleuze, C. (2016). Biomass feedstocks. In Holm-Nielson & Ehimen (ed.) *Biomass Supply Chains for Bioenergy and Biorefining.* DOI: 10.1016/B978-1-78242-366-9.00002-2

GBEP (2011). The global bioenergy partnership sustainability indicators for bioenergy. First Edition. DOI: 10.13140/RG.2.1.3023.5761

GBEP (2020). Global Bioenergy Partnership Sustainability Indicators for Bioenergy: Implementation Guide. Final Draft. URL: http://www.globalbioenergy.org/fileadmin/user_upload/gbep/docs/Implementation_Guide/Final_Draft_Implementation_Guide_updated_14.01.2020.pdf

Geurts, J. J., van Duinen, G. J. A., van Belle, J., Wichmann, S., Wichtmann, W. & Fritz, C. (2019). Recognize the high potential of paludiculture on rewetted peat soils to mitigate climate change. *Landbauforschung*, *69*(1), 5-8. DOI: 10.3220/LBF1576769203000

Global CCS Institute (2018). *The Global Status of CCS: 2019.* URL: https://www.globalccsinstitute.com/wp-content/uploads/2019/12/GCC_GLOBAL_STATUS_REPORT_2019.pdf

Goop, J. (2017): *Modelling interactions between distributed energy technologies and the centralised electricity supply*. Doctoral thesis. Chalmers University of Technology, Göteborg, Sweden. Department of Space, Earth and Environment, Division of Energy Technology. URL: http://publications.lib.chalmers.se/records/fulltext/251520/251520.pdf

Gough, C. & Mander, S. (2019). Beyond Social Acceptability: Applying Lessons from CCS Social Science to Support Deployment of BECCS. *Current Sustainable/Renewable Energy Reports*, *6*(4), 116-123. DOI: 10.1007/s40518-019-00137-0

Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A. et al. (2017). Natural climate solutions. *Proceedings of the National Academy of Sciences*, *114*(44), 11645-11650. DOI: 10.1073/pnas.1710465114

Haberl, H. & Geissler, S. (2000). Cascade utilization of biomass: strategies for a more efficient use of a scarce resource. *Ecological Engineering*, *16*(1, SI), S111-S121. DOI: 10.1016/S0925-8574(00)00059-8

Haberl, H., Erb, K. H., Krausmann, F., Bondeau, A., Lauk, C., Müller, C. et al. (2011). Global bioenergy potentials from agricultural land in 2050: Sensitivity to climate change, diets and yields. *Biomass and bioenergy*, *35*(12), 4753-4769. DOI: 10.1016/j.biombioe.2011.04.035

Hansson, A., Fridahl, M., Haikola, S., Yanda, P., Pauline, N. & Mabhuye, E. (2019). Preconditions for bioenergy with carbon capture and storage (BECCS) in sub-Saharan Africa: the case of Tanzania. *Environment, Development and Sustainability*, 1-25. DOI: 10.1007/s10668-019-00517-y

van Heek, J., Arning, K. & Ziefle, M. (2017). Reduce, reuse, recycle: Acceptance of CO2-utilization for plastic products. *Energy Policy*, *105*, 53-66. DOI: 10.1016/j.enpol.2017.02.016

Holland, R.A., Eigenbrod, F., Muggeridge, A., Brown, G., Clarke, D. & Taylor, G. (2015). A synthesis of the ecosystem services impact of second generation bioenergy crop production. Renewable Sustainable Energy Rev. 46, 30–40. DOI: 10.1016/ j.rser.2015.02.003

Hoogwijk, M., Faaij, A., Van Den Broek, R., Berndes, G., Gielen, D. & Turkenburg, W. (2003). Exploration of the ranges of the global potential of biomass for energy. *Biomass and bioenergy*, *25*(2), 119-133. DOI: 10.1016/S0961-9534(02)00191-5

Huppmann, D., Kriegler, E., Krey, V., Riahi, K., Rogelj, J., Rose, S. K. et al. (2018). *IAMC 1.5 C Scenario Explorer and Data hosted by IIASA.* Integrated Assessment Modeling Consortium & International Institute for Applied Systems Analysis. DOI: 10.5281/zenodo.3363345

IATA (2015). *IATA Sustainable Aviation Fuel Roadmap.* Montreal, Geneva: International Air Transport Association. URL: https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/safr-1-2015.pdf

IEA (2014). The power of transformation. Wind, sun and the economics of flexible power systems. Paris: OECD Publishing. URL: https://www.oecd.org/publications/the-power-of-transformation-9789264208032-en.htm

IEA (2017a). *Energy Technology Perspectives 2017*. Paris: IEA. URL: https://www.iea.org/reports/energy-technology-perspectives-2017

IEA (2017b). *Technology roadmap: Delivering sustainable bioenergy*. URL: https://www.ieabioenergy.com/wp-content/uploads/2017/11/Technology_Roadmap_Delivering_Sustainable_Bioenergy.pdf

IEA (2017c). *The Future of Trucks - Implications for Energy and the Environment.* France: International Energy Agency. URL: https://www.oecd.org/publications/the-future-of-trucks-9789264279452-en.htm

IEA Bioenergy (2020). Developing business models for efficient use of biomass- Summary and conclusions from the IEA Bioenergy workshop, Tallinn (Estonia), 22 October 2019. IEA Bioenergy: ExCo: 2020:01. URL: https://www.ieabioenergy.com/publications/new-publication-exco84-workshop-developing-business-models-for-efficient-use-of-biomass-summary-and-conclusions/

IEA Hydropower (2019): Flexible hydropower providing value to renewable energy integration. IEA Hydropower Annex IX - White paper No 1 - October 2019. URL: https://www.ieahydro.org/media/51145259/IEAHydroTCP_AnnexIX_White%20Paper_Oct2019.pdf

IOGP (2019). *The potential for CCS and CCU in Europe. Report to the thirty second meeting of the European Gas Regulatory Forum 5-6 June 2019.* URL: https://ec.europa.eu/info/sites/info/files/iogp_-_report_-_ccs_ccu.pdf

IPCC AR4 (2007). *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment.* Report of the Intergovernmental Panel on Climate Change. [Pachauri, R.K & Reisinger, A. (eds.)]. Geneva, Switzerland: IPCC. URL: https://www.ipcc.ch/site/assets/uploads/2018/02/ar4_syr_full_report.pdf

IPCC SRREN (2011). *Renewable energy sources and climate change mitigation: Special report of the intergovernmental panel on climate change*. [Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Kadner, S., Zwickel, T. et al. (eds.)]. URL: http://www.ukm.my/ipi/wp-content/uploads/2013/07/23.2011Global-bioenergy-potentials-from-agricultural-land-in-2050_sensivity-to-climate-chnage.pdf

IPCC AR5 (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment* Report of the Intergovernmental Panel on Climate Change [Pachauri, R. K. & Meyer, L. A. (eds.)]. Geneva, Switzerland : IPCC. URL: https://www.ipcc.ch/site/assets/uploads/2018/02/SYR_AR5_FINAL_full.pdf

IPCC SR1.5 (2018). *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.* [Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R. et al. (eds.)]. URL : https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_High_Res.pdf

IPCC (2019). *Climate Change and Land : an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.* [Shukla, P.R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D. C. et al. (eds.)]. URL : https://www.ipcc.ch/site/assets/uploads/2019/11/SRCCL-Full-Report-Compiled-191128.pdf

IRENA (2016). *Boosting biofuels. Sustainable Paths to Greater Energy Security.* URL: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_Boosting_Biofuels_2016.pdf

Iriarte, L. & Fritsche, U. (2019). *SDG implementation in selected Latin America and Caribbean countries and possibilities to link with the GBEP Sustainability Indicators.* Technical Report by IINAS for the GBEP Task Force on Sustainability. Pamplona, Darmstadt URL: http://iinas.org/tl_files/iinas/downloads/bio/IINAS_2019_%20SDG_and_GSI_opportunities.pdf

Johnson, N., Parker, N. & Ogden, J. (2014). How negative can biofuels with CCS take us and at what cost? Refining the economic potential of biofuel production with CCS using spatially-explicit modeling. *Energy Procedia*, *63*, 6770-6791. DOI: 10.1016/j.egypro.2014.11.712

Junginger, M. et al. (2019). *Measuring, governing and gaining support for sustainable bioenergy supply chains - Main findings and recommendations.* IEA Bioenergy: ExCo: 2019: 05. URL : http://itp-sustainable.ieabioenergy.com/wp-content/uploads/2019/06/Intertask-Sustainability-Main-findings-and-recommendations-17.5.2019-1.pdf

Karlsson, S., Srebotnjak, T. & Gonzales, P. (2007). Understanding the North–South knowledge divide and its implications for policy: a quantitative analysis of the generation of scientific knowledge in the environmental sciences. *Environmental Science & Policy*, *10*(7-8), 668-684. DOI: 10.1016/j.envsci.2007.04.001

Karlsson, H., Delahaye, T., Johnsson, F., Kjärstad, J. & Rootzén, J. (2017). Immediate deployment opportunities for negative emissions with BECCS: A Swedish case study. *arXiv preprint arXiv:1705.07894*. URL: https://arxiv.org/pdf/1705.07894.pdf

Kraxner, F., Leduc, S., Fuss, S., Aoki, K., Kindermann, G. & Yamagata, Y. (2014a). Energy resilient solutions for Japan-a BECCS case study. *Energy Procedia*, *61*, 2791-2796. DOI: 10.1016/j.egypro.2014.12.316

Kraxner, F., Aoki, K., Leduc, S., Kindermann, G., Fuss, S., Yang, J. et al (2014b). BECCS in South Korea—analyzing the negative emissions potential of bioenergy as a mitigation tool. *Renewable Energy*, *61*, 102-108. DOI: 10.1016/j.renene.2012.09.064

Kraxner, F., Fuss, S., Leduc, S., Yowargana, P., Kindermann, G., Pietsch, S. & Hetland, J. (2015). Driving clean energy and green economy with the help of forest-based bioenergy with CCS (BECCS)-A case study on Indonesia. *XIV World Forestry Congress*, 7-11 September 2015, Durban, South Africa. URL: http://foris.fao.org/wfc2015/api/file/5547ee1615ae74130aee6aca/contents/aaffd844-ebc7-4088-811b-aa627b40fdbb.pdf

Lask, J., Wagner, M., Trindade, L. M. & Lewandowski, I. (2019). Life cycle assessment of ethanol production from miscanthus: A comparison of production pathways at two European sites. *GCB Bioenergy*, *11*(1), 269-288. DOI: 10.1111/gcbb.12551

Lemus, R. & Lal, R. (2005). Bioenergy crops and carbon sequestration. *Critical Reviews in Plant Sciences*, *24*(1), 1-21. DOI: 10.1080/07352680590910393

Long, H., Li, X., Wang, H. & Jia, J. (2013). Biomass resources and their bioenergy potential estimation: A review. *Renewable and Sustainable Energy Reviews*, *26*, 344-352. DOI: 10.1016/j.rser.2013.05.035

Lozano-García, D. F., Santibañez-Aguilar, J. E., Lozano, F. J. & Flores-Tlacuahuac, A. (2020). GIS-based modeling of residual biomass availability for energy and production in Mexico. *Renewable and Sustainable Energy Reviews*, *120*, 109610. DOI: 10.1016/j.rser.2019.109610

McCarl, B. A. & Plieninger, T. (2008). *AICGS Policy Report. Bioenergy in the United States and Germany.* Baltimore: AICGS. URL: https://www.aicgs.org/site/wp-content/uploads/2008/06/PR-36-Daimler-Bioenergy-FINAL.pdf

Millinger, M., (2018): Systems assessment of biofuels: modelling of future cost and greenhouse gas abatement competitiveness between biofuels for transport on the case of Germany. Dissertation, Universität Leipzig, Wirtschaftswissenschaftliche Fakultät. PhD Dissertation 3/2018. Helmholtz-Zentrum für Umweltforschung - UFZ, Leipzig, XVII, 92 pp.

Millinger, M., Tafarte, P., Jordan, M., Hahn, A., Meisel, K., Thrän, D. (2020): Electrofuels from excess renewable electricity at high variable renewable shares: cost, greenhouse gas abatement, carbon use and competition. Pre-print, DOI: 10.26434/chemrxiv.12287504

Milner, S., Holland, R.A., Lovett, A., Sunnenberg, G., Hastings, A., Smith, P., Wang, S. & Taylor, G. (2016). Potential impacts on ecosystem services of land use transitions to second-generation bioenergy crops in GB. *GCB Bioenergy 8*, 317–333. DOI: 10.1111/gcbb.12263

Moreira, J. R., Romeiro, V., Fuss, S., Kraxner, F. & Pacca, S. A. (2016). BECCS potential in Brazil: Achieving negative emissions in ethanol and electricity production based on sugar cane bagasse and other residues. *Applied Energy*, *179*, 55-63. DOI: 10.1016/j.apenergy.2016.06.044

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., Van Vuuren, D. P. et al. (2010). The next generation of scenarios for climate change research and assessment. *Nature*, *463*(7282), 747-756. DOI: 10.1038/nature08823

Noothout, Paul et al. (2019). *Assessment of bio-CCS in 2°C compatible scenarios. Ecofys & Bellona on behalf of the German Environment Agency.* UBA CLIMATE CHANGE 09/2019. Dessau. URL: https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2019-04-01_cc_09-2019_bio-ccs.pdf

Olmer, N., Comer, B., Roy, B., Mao, X. & Rutherford, D. (2017). *Greenhouse gas emissions from global shipping, 2013–2015*. Washington: International Council on Clean Transportation. URL: https://theicct.org/publications/GHG-emissions-global-shipping-2013-2015

OECD (2019). Environment Database - Greenhouse gas emissions. URL: https://stats.oecd.org/Index.aspx?DataSetCode=AIR_GHG (accessed on Feb 27, 2020)

O'Keeffe, S. & Thrän. D. (2020). Energy Crops in Regional Biogas Systems: An Integrative Spatial LCA to Assess the Influence of Crop Mix and Location on Cultivation GHG Emissions. *Sustainability*. 2020; 12(1), 237. DOI: 10.3390/su12010237

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S. et al. (2017). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change*, *42*, 169-180. DOI: 10.1016/j.gloenvcha.2015.01.004

Olsson, O., Bang, C., Borchers, M., Hahn, A., Karjunen, H., Thrän, D. & Tynjälä, T. (2020). *Deployment of BECCS value chains: technological pathways, policy options and business models*, IEA Bioenergy Task 40 Report (2020). URL: https://www.ieabioenergy.com/wp-content/uploads/2020/06/Deployment-of-BECCS-Value-Chains-IEA-Bioenergy-Task-40.pdf

Pan, X., Chen, W., Wang, L., Lin, L. & Li, N. (2018). The role of biomass in China's long-term mitigation toward the Paris climate goals. *Environmental Research Letters*, *13*(12), 124028. DOI: 10.1088/1748-9326/aaf06c

Pasgaard, M., Dalsgaard, B., Maruyama, P. K., Sandel, B. & Strange, N. (2015). Geographical imbalances and divides in the scientific production of climate change knowledge. *Global Environmental Change*, *35*, 279-288. DOI: 10.1016/j.gloenvcha.2015.09.018

Pelkmans, L., Berndes, G. & Fritsche, U. (2019). Governing sustainability in biomass supply chains for the bioeconomy - Summary and conclusions from the IEA Bioenergy workshop, Utrecht (Netherlands), 23 May 2019. URL: https://www.ieabioenergy.com/wp-content/uploads/2019/10/ExCo83-Governing-sustainability-in-biomass-supply-chains-for-the-bioeconomy-Summary-and-Conclusions.pdf

Perpiña Castillo, C., Baranzelli, C., Maes, J., Zulian, G., Lopes Barbosa, A., Vandecasteele, I. et al. (2015). An assessment of dedicated energy crops in Europe under the EU Energy Reference Scenario 2013. Application of the LUISA modelling platform–Updated Configuration 2014. *EUR*, *27644*, 1807-1825. DOI: 10.2788/64726

Pfeiffer, D. & Thrän, D. (2018). One century of bioenergy in Germany: wildcard and advanced technology. *Chemie Ingenieur Technik*, *90*(11), 1676-1698. DOI: 10.1002/cite.201800154

Pfeiffer, A., Krause, T., Horschig, T., Avdibegović, M., Čustović, H., Ljuša, M., et al. (2019). *Biomass Potential Monitoring Bosnia and Herzegovina*. DOI: 10.13140/RG.2.2.22757.96486

POST (2020). *Bioenergy with Carbon Capture & Storage*. POSTNOTE Number 618. Parliamentary Office of Science and Technology. London. URL: http://researchbriefings.files.parliament.uk/documents/POST-PN-0618/POST-PN-0618.pdf

Redpoint Energy (2012). *Assessment of the appropriate uses of bioenergy feedstocks in the UK energy market. Final Report for the UK Department of Energy and Climate Change, and the Committee on Climate Change.* London: Redpoint and Ecofys. URL: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/48340/5128-assessment-of-the-appropriate-uses-of-bioenergy-fe.pdf

Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V. et al. (2018). Mitigation pathways compatible with 1.5 C in the context of sustainable development. In IPCC (ed.), *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. URL: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/02/SR15_Chapter2_Low_Res.pdf

Ronzon, T. & Sanjuán, A. (2020). Friends or foes? A compatibility assessment of bioeconomy-related Sustainable Development Goals for European policy coherence. Journal of Cleaner Production 254, 119832. DOI: 10.1016/j.jclepro.2019.119832

Rosales-Calderon, O. & Arantes, V. (2019). A review on commercial-scale high-value products that can be produced alongside cellulosic ethanol. *Biotechnology for biofuels*, *12*(1), 240. DOI: 10.1186/s13068-019-1529-1

Sanchez, D. L., Johnson, N., McCoy, S. T., Turner, P. A. & Mach, K. J. (2018). Near-term deployment of carbon capture and sequestration from biorefineries in the United States. *Proceedings of the National Academy of Sciences*, *115*(19), 4875-4880. DOI: 10.1073/pnas.1719695115

Schaber, K., Steinke, F. & Hamacher, T. (2012). Transmission grid extensions for the integration of variable renewable energies in Europe: Who benefits where? *Energy Policy*, *43*, 123-135. DOI: 10.1016/j.enpol.2011.12.040

Schmidt, J., Leduc, S., Dotzauer, E., Kindermann, G. & Schmid, E. (2010). Cost-effective CO2 emission reduction through heat, power and biofuel production from woody biomass: A spatially explicit comparison of conversion technologies. *Applied Energy*, *87*(7), 2128-2141. DOI: 10.1016/j.apenergy.2009.11.007

Schmidt, H.-P. et al. (2019). Pyrogenic carbon capture and storage. *GCB Bioenergy 11*(4), 573-591. DOI: 10.1111/gcbb.12553

Searle, S., Petrenko, C., Baz, E. & Malins, C. (2016). *Crops of the biofrontier: In search of opportunities for sustainable energy cropping.* Washington D.C.: The International Council on Clean Transportation. URL: https://theicct.org/sites/default/files/publications/Energy%20Crop%20White%20Paper%20vF.pdf

Shukla, P.R., Skea, J., Slade, R., van Diemen, R., Haughey, E., Malley, J., Pathak, M., Portugal Pereira, J. (eds.) Technical Summary, 2019. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M, Belkacemi, J. Malley, (eds.)]. In Press.

Ssegane, H., Negri, M.C., Quinn, J. & Urgun-Demirtas, M. (2015). Multifunctional landscapes: site characterization and field-scale design to incorporate biomass production into an agricultural system. Biomass-Bioenergy 80, 179–190. DOI: 10.1016/j.biombioe.2015.04.012

Ssegane, H. & Negri, M.C. (2016). An integrated landscape designed for commodity and bioenergy crops for a tile-drained agricultural watershed. J. Environ. Qual. 45, 1588–1596. DOI: 10.2134/jeq2015.10.0518

da Silva, F. T., Carvalho, F. M., Correa Jr, J. L. G., Merschmann, P. R. D. C., Tagomori, I. S., Szklo, A. & Schaeffer, R. (2018). CO2 capture in ethanol distilleries in Brazil: Designing the optimum carbon transportation network by integrating hubs, pipelines and trucks. *International Journal of Greenhouse Gas Control*, *71*, 168-183. DOI: 10.1016/j.ijggc.2018.02.018

Singlitico, A., Goggins, J. & Monaghan, R. F. (2018). Evaluation of the potential and geospatial distribution of waste and residues for bio-SNG production: A case study for the Republic of Ireland. *Renewable and Sustainable Energy Reviews*, *98*, 288-301. DOI: 10.1016/j.rser.2018.09.032

Smeets, E. M., Faaij, A. P., Lewandowski, I. M. & Turkenburg, W. C. (2007). A bottom-up assessment and review of global bio-energy potentials to 2050. *Progress in Energy and combustion science*, *33*(1), 56-106. DOI: 10.1016/j.pecs.2006.08.001

SOU (2020). The pathway to a climate-positive future – strategy and action plan for achieving negative greenhouse gas emissions after 2045. Swedish Government Official Reports - SOU 2020:4, Stockholm.

Styles, D., Börjesson, P., D'Hertefeldt, T., Birkhofer, K., Dauber, J., Adams P. et al. (2016). Climate regulation, energy provisioning and water purification: quantifying ecosystem service delivery of bioenergy willow grown on riparian buffer zones using life cycle assessment. *Ambio 45*, 872–884. DOI: 10.1007/s13280-016-0790-9

Szarka, N., Eichhorn, M., Kittler, R., Bezama, A. & Thrän, D. (2017). Interpreting long-term energy scenarios and the role of bioenergy in Germany. *Renewable and Sustainable Energy Reviews*, *68*, 1222-1233. DOI: 10.1016/j.rser.2016.02.016

Thomas, G., Pidgeon, N. & Roberts, E. (2018). Ambivalence, naturalness and normality in public perceptions of carbon capture and storage in biomass, fossil energy, and industrial applications in the United Kingdom. *Energy Research & Social Science*, *46*, 1-9. DOI: 10.1016/j.erss.2018.06.007

Thrän, D. (2015). *Smart Bioenergy. Technologies and concepts for a more flexible bioenergy provision in future energy systems.* Cham: Springer. DOI: 10.1007/978-3-319-16193-8

Thrän, D., Pfeiffer, D. (eds.) (2015). Method Handbook - Material flow-oriented assessment of greenhouse gas effects. Methods for determination of technology indicators, levelized costs of energy, and greenhouse gas effects of projects in the funding programme "Biomass energy use". Series of the funding programme "Biomass energy use", Vol. 4. ISSN 2364-897X. Available online: https://www.energetische-biomassenutzung.de/fileadmin/media/6_Publikationen/04_MHB_en_web.pdf

Trieb, F., Fichter, T. & Moser, M. (2014). Concentrating solar power in a sustainable future electricity mix. *Sustainability science*, *9*(1), 47-60. DOI: 10.1007/s11625-013-0229-1

UK Government (2017). The Clean Growth Strategy. Leading the way to a low carbon future. URL: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/700496/clean-growth-strategy-correction-april-2018.pdf

UNCTAD (2017): Review of maritime transport 2017. Geneva: United Nations Conference on Trade and Development. URL: https://unctad.org/en/PublicationsLibrary/rmt2017_en.pdf

UNEP (2019). *Emissions Gap Report 2019.* Nairobi: UNEP. URL: https://wedocs.unep.org/bitstream/handle/20.500.11822/30797/EGR2019.pdf

UNFCCC (2015): Adoption of the Paris Agreement. FCCC/CP/2015/L.9/Rev.1: United Nations Framework Convention on Climate Change. URL: https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf

Verkerk, P. J., Fitzgerald, J. B., Datta, P., Dees, M., Hengeveld, G. M., Lindner, M. & Zudin, S. (2019). Spatial distribution of the potential forest biomass availability in Europe. *Forest Ecosystems*, *6*(1), 5. DOI: 10.1186/s40663-019-0163-5

De Wit, M. & Faaij, A. (2010). European biomass resource potential and costs. *Biomass and bioenergy*, *34*(2), 188-202. DOI: 10.1016/j.biombioe.2009.07.011

Woo, H., Acuna, M., Moroni, M., Taskhiri, M. S. & Turner, P. (2018). Optimizing the location of biomass energy facilities by integrating Multi-Criteria Analysis (MCA) and Geographical Information Systems (GIS). *Forests, 9*(10), 585. DOI: 10.3390/f9100585

World Bank (2019). Health Nutrition and Population Statistics: Population estimates and projections. Database last updated 09/19/2019. URL: https://databank.worldbank.org/source/health-nutrition-and-population-statistics:-population-estimates-and-projections (accessed on Mar 27, 2020)

Zeug, W., Bezama, A., Moesenfechtel, U., Jähkel, A., Thrän, D., (2019). Stakeholders' interests and perceptions of bioeconomy monitoring using a sustainable development goal framework
Sustainability 11 (6), art. 1511

Zhang, D., Bu, M., Fajardy, M., Patrizio, P., Kraxner, F. & Mac Dowell, N. (2020). Unlocking the potential of BECCS with indigenous sources of biomass at a national scale. *Sustainable Energy & Fuels*, *4*(1), 226-253. DOI: 10.1039/C9SE00609E

Zhuang, D., Jiang, D., Liu, L. & Huang, Y. (2011). Assessment of bioenergy potential on marginal land in China. *Renewable and Sustainable Energy Reviews*, *15*(2), 1050-1056. DOI: 10.1016/j.rser.2010.11.041

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