

BECCS deployment: a reality check

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Headlines

- Bioenergy with carbon capture and storage (BECCS) is presented as a pivotal technology in most pathways for limiting global warming to 1.5 or 2°C. However, it is doubtful that BECCS can fulfil this role alone.
- BECCS is not a single technology. Understanding the value and challenges associated with each BECCS technology is complex but vital.
- Depending on the conditions of its deployment, BECCS may be beneficial but it can also be detrimental to climate change mitigation, due to its lifecycle CO₂ balance, energy balance and resource use.
- It is challenging to ensure that BECCS delivers timely and sustainable net carbon removal, while also generating energy at an appropriate scale.
- Considering these uncertainties and the potential impact on resources, biodiversity and soil health, the scale of BECCS deployment should be limited only to circumstances where it is proven to be beneficial.
- Good governance and financial incentives are required to stimulate high-quality BECCS at this limited scale.
- Policy makers should be sceptical about a future that is uniquely or heavily reliant on BECCS, and instead prepare for and implement alternative mitigation options as soon as possible.

Introduction

The Paris Agreement, ratified by 181 countries, agrees to limit global warming to “well below” 2°C. To fulfil this pledge, total global carbon dioxide (CO₂) emissions post-2010 must keep below 1,200 gigatons (Gt). This is known as a carbon budget⁸. Keeping within 1.5°C warming since pre-industrial times requires even more drastic action: a lower carbon budget of about 400 to 600Gt of CO₂, leading to a 45% emission reduction by 2030 and net zero CO₂ emissions by 2050¹⁰. Current annual total CO₂ emissions are close to 40Gt (2007-2016 average¹²), and deploying the technologies and policies required to roughly halve these annual emissions is a challenging task for two reasons.

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First, while commercially viable alternatives to carbon-intensive power-generation technologies already exist, decarbonising industry, transport and agriculture remains a challenge. Second, the pace of change required to keep within Paris Agreement temperature limits is larger than both current trends and historic precedents. If we cannot reduce our emissions quickly enough, some degree of carbon dioxide removal (CDR) from the atmosphere may be required¹³.

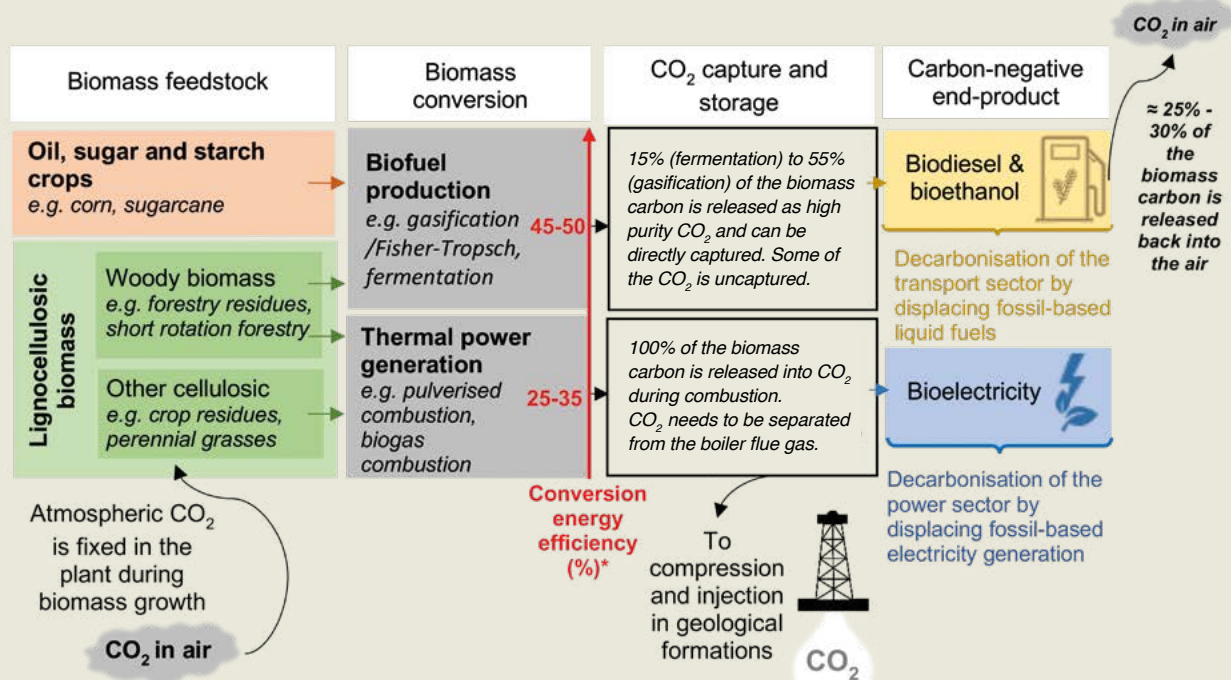
CDR technologies deliver net negative emissions by actively removing more CO₂ than they emit through their operation. They are also referred to as negative emissions technologies, or NETs^{16, 17, 18}. Scenarios featuring NETs deployment were first summarised in the Intergovernmental Panel on Climate Change's 4th Assessment Report²⁰, but grew to prominence during the 5th Assessment Report cycle², when many of the climate mitigation scenarios that were published featured large amounts of BECCS¹⁸. Afforestation (planting new forests) is another, equally prominent NET.

BECCS is a group of technologies that span many sectors, and often several geographical regions. In a BECCS chain, CO₂ from the atmosphere is absorbed via photosynthesis into

the biomass of plant materials. It is then burned or converted (e.g. via gasification) in power plants, industrial facilities or biorefineries equipped with technologies that capture the CO₂, preventing the gas from returning to the atmosphere²². The captured CO₂ is then injected in deep geological formations. This process results in a net transfer of CO₂ from the atmosphere to the ground, provided that emissions associated with supplying the biomass and capturing the CO₂ do not exceed the amount removed from the air by photosynthesis. In theory, by delivering net-negative emissions in the long-term, BECCS compensates for any short-term increases of greenhouse gas emissions caused by delays in implementation of climate policy.

This paper explores some of the questions that emerge in relation to BECCS – a technology that has not been deployed at scale but might be required to meet global climate change goals. Key questions, only some of which are covered here, include the uncertainties as to the actual carbon removal potential of BECCS, wider sustainability considerations of biomass production, the ability to scale up such a complex technology, and balancing reliance on BECCS in the long-term with other short-term greenhouse gas-reduction priorities.

Box 1: Two examples of biomass conversion routes for BECCS: bioelectricity and biofuels



Box 2: BECCS in Integrated Assessment Models (IAMs)

IAMs combine energy, economy, and climate system models into a single framework to project the trend of CO₂ emissions and their impact on the world climate. CO₂ emissions pathways, as currently projected by IAMs, feature massive deployment of BECCS, thereby raising questions about the sustainable scalability of the technology^{1,2}.

- Across IPCC scenarios with a 66% or better chance of limiting temperature increase to 1.5°C, median CO₂ removal by BECCS is 12Gt of CO₂ per year (1/4 of current emissions)^{3,4}. For the 1.5°C target, CO₂ removal by BECCS has been evaluated to 0-22.5Gt of CO₂ per year by 2100, while agriculture, forestry and land-use related NETs remove 1-5Gt of CO₂ per year in 2100^{5,8}.
- This massive deployment of BECCS would require between 0.4 and 1.2 billion hectares of land (25% to 80% of current global cropland)^{3,4}.
- BECCS requires significant inputs of land, nitrogen, phosphorus and water, with substantial CO₂ and nitrous oxide emissions arising from these inputs⁷. It also raises the prospect that BECCS “may largely transfer environmental risk from the atmosphere to the land”⁹.
- The deployment of BECCS is not limited to the power sector. In fact, on average, IAMs project at least 60% of primary energy from BECCS going to production of liquid biofuels¹¹. Different IAMs make different assumptions about BECCS, and therefore deploy different shares of liquid biofuels, which emerge as an important strategy to offset emissions from freight and air transportation, where low-carbon options are lacking.
- Importantly, the extent to which IAMs properly consider and account for energy demand and CO₂ emissions from the biomass supply chain – growing, processing, transporting the biomass – is unclear. From most recent scenarios^{5,8}, 400 exajoules of BECCS are required to remove 22.5Gt of CO₂ per year. Assuming 60% of primary energy going into biofuels and 40% to bioelectricity, and carbon efficiencies of 90% and 55% (theoretical maxima), 26Gt of CO₂ could be removed, which suggest that some level of supply chain emissions are considered in IAMs.
- Land productivity (yield) is the key assumption governing deployment of BECCS in IAM scenarios, but the literature is scant and not very transparent. However, it does indicate that sustained yield improvements are assumed through to the end of the century in these scenarios. Smith and Torn⁷ report that current yields would need to improve by 0.6% to 2.3% per year for 90 years to reach end-of-century yields assumed in one IAM. This pattern is most likely general across IAMs.
- FAOSTAT^{14,15} data shows historical crop yield growth of 1.6% per year over the last 50 years, but yield improvements have been declining lately, suggesting most of the easy improvements have been made¹⁹. On the other hand, the crop yield gap in some underperforming regions could be closed through institutional innovations and capacity building, particularly in sub-Saharan Africa, Ukraine and south-west Russia¹⁸, but this is fraught with non-technical challenges²¹. If successful, however, it could relieve pressure from land and enhance the sustainability of BECCS. Genetically modified crops have the potential to be yield game-changers, although they tend to raise economic and biological concerns.
- What emerges from the literature regarding BECCS in IAM results echoes the conclusion from Minx et al.¹⁸ that “any single NET is unlikely to sustainably achieve the large NETs deployment observed in many 1.5°C and 2°C mitigation scenarios. Yet, portfolios of multiple NETs, each deployed at modest scales, could be invaluable for reaching the climate goals”.

Understanding the role of BECCS in decarbonising the economy

BECCS can be deployed via a range of technologies. So far, research and industrial efforts have focussed on two main routes:

- 1) BECCS via liquid biofuel production (biodiesel or bioethanol²³) and
- 2) BECCS via biomass conversion to heat and power, with direct pulverised combustion of biomass being the most common approach²⁴.

Other niche options include CO₂ capture from biogenic industrial emissions, e.g. in the pulp and paper industry²⁵. Box 1 illustrates the different steps of the power and fuel routes, representing the different biomass feedstock options, biomass conversion technologies and carbon-negative end-products.

Because of inherent differences in biomass conversion technologies, the quantity of useful energy (biofuel or bioelectricity) and the amount of CO₂ removed from the atmosphere per unit of feedstock differ from one route to another.

For example, in the fuel route, 25-30% of the biomass carbon is not released during biomass conversion to biofuel but as unabated CO₂ when the biofuel is used²⁶⁻²⁸. Of the CO₂ released during the conversion process, 15% (fermentation²⁸) to 55% (gasification²⁷) comes out at a high purity²³, and can be directly captured, sent for compression and injection for storage. Some of the CO₂ is released in a more diluted form and can be captured, but at a higher cost.

In the bioenergy to power route, however, all of the carbon fixed in the biomass is released as CO₂ during combustion, but in diluted form in the exhaust gas. Further separation and more energy use is required before compression and injection.

The energy efficiencies of the conversion of biomass to either power or fuels reflect the percentage of the energy content in the original biomass that is available in the final energy carrier and not lost in the conversion process. Power generation efficiencies for biomass firing with post-combustion capture and storage can be as low as 17%²⁹ and as high as 38%³⁰. The energy efficiency of fuel production is typically higher, around 45-50%^{27, 28, 31, 32}.

Furthermore, because both routes produce energy in addition to providing negative emissions, they can further decarbonise different sectors – such as power and transport – by displacing other fossil-based electricity and fuels. Rather than considering BECCS as a single ‘black box’ technology, identifying the challenges and opportunities of individual BECCS technology routes is key to understanding its value in decarbonising the economy.

BECCS: a controversial solution

Theoretically, BECCS permanently removes CO₂ from the atmosphere and provides reliable low-carbon energy, while displacing fossil-based fuel and power. We assume that BECCS can be deployed in the medium-term at a relatively low cost, as it partly relies on existing or mature technologies³³. For these reasons, BECCS has been consistently featured in projected greenhouse gas emissions pathways, reaching levels of deployment as high as 400 exajoules (EJ) per year in terms of primary energy production, and 22.5Gt of CO₂ per year of carbon removal^{5,8}. However, understanding the assumptions about BECCS in these pathways can be challenging. Box 2 provides insight into BECCS’ representation in integrated assessment models (IAMs) that produce greenhouse gas mitigation pathways.

Such a high reliance on a technology which has not yet been deployed at scale has triggered questions regarding sustainability and risks. These concerns include:

- the potential scale of the industry – some IAMs have BECCS deployed at a scale that is two thirds of the size of today’s fossil industry by the end of the century,
- the related reliance of BECCS at this scale on a significant quantity of sustainable biomass, water, land and nutrients,
- the possibility of encouraging delays in mitigation action, and
- if BECCS failed to deliver, it would result in missing the 2100 temperature target³⁴.

The next section explores these caveats in more details.

The risks of BECCS deployment

The energy and carbon costs of supplying biomass

Supplying biomass will incur different energy costs and associated CO₂ emissions, depending on the feedstock and end process. For each process, biomass feedstock might differ by type – grasses, wood, oil crops or sugar and starch – and by quality – high or low moisture, ash content. In all cases feedstock needs to be collected from a source – farm, waste plant, forest – conditioned into a proper fuel for transport – pellet, bale – and transported to the biomass conversion facility. Each of these steps incurs an energy and CO₂ cost.

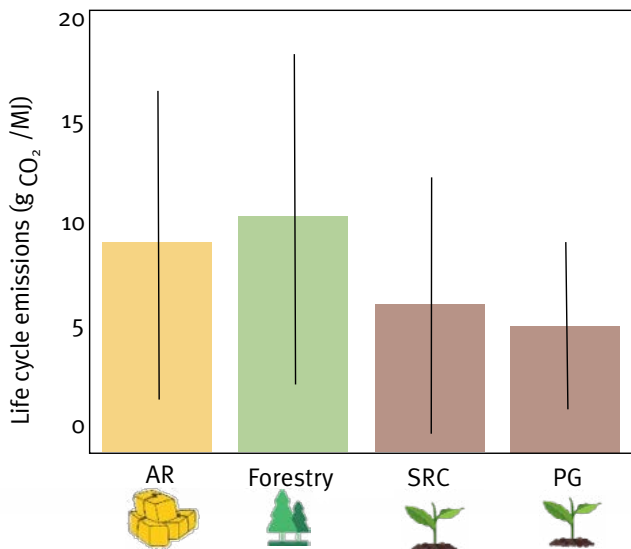


Figure 1: average (bars) and ranges of life cycle greenhouse gas emissions of agriculture residues (AR), forestry products, short rotation coppice woody biomass (SRC) and perennial grasses (PG), adapted from Creutzig et al.⁶

The life-cycle impacts of the biomass supply-chain have been studied intensively, both in the context of BECCS^{6,26,35} and bioenergy alone³⁶⁻³⁹. The results strongly depend on the boundaries of each case study and on the feedstock – dedicated agriculture, crop residue, forestry residue, algae. Figure 1 highlights the potentially high supply-chain emissions of different biomass feedstock and the uncertainty of these calculations. Similar ranges can be obtained for the whole life-cycle final primary energy use of biomass. Factors such as biomass yield, fertiliser application, and biomass drying for high moisture biomass (such as woody biomass) have been found to have a great impact on both emissions and energy use of the biomass life cycle⁴⁰.

Conversion of land for bioenergy production purposes – defined as direct land use change (LUC) and indirect land use change (iLUC) – may cause greenhouse gas emissions which must be added to these supply chain emissions, as illustrated in Figure 2. LUC is the change in total carbon stock present in the vegetation and soil of converted land, while iLUC emissions occur when the previous activity on land that is converted to bioenergy moves to a different location and causes land use change, and emissions, elsewhere. LUC emissions are a function of the vegetation types, and can be found to be as low as 6kg of CO₂ per hectare for marginal land and as high as 3,052,000kg of CO₂ per hectare for a peatland forest⁴¹. On the other hand, iLUC emissions are much more difficult to evaluate with certainty, as they are highly dependent on the economic conditions, activity displaced, time horizon, etc. These factors have been found to have a great impact on feedstock life-cycle emissions^{3,6,40}.

Is BECCS actually carbon negative and energy positive?

Including the biomass life-cycle energy use in the BECCS energy balance can dramatically decrease estimates of potential net energy production. Furthermore, the combination of a lower quality fuel – biomass – and the carbon capture and storage process, means the conversion efficiency of a BECCS facility would be lower than an unabated fossil fuel based power plant. Considering this low efficiency in combination with the potentially high energy demand of the biomass supply chain, the energy ‘positivity’ of BECCS, i.e. its ability to yield more energy than it requires to operate, has been subject to scrutiny⁴². The energy balance can be referred to as energy return on investment (EROI). EROI values below one mean that the system requires more energy as input, than it provides as output. However, EROI values less than three are often considered problematic. There is debate about the possible and optimal average global EROI⁴³. For example, a BECCS system using low yield and high-moisture woody biomass pellets transported from distant sources could have a low EROI⁴⁴.

The same observation can be made for net carbon balance of BECCS. High biomass life cycle CO₂ emissions in the carbon balance of BECCS could potentially outweigh the amount of CO₂ captured. A BECCS power plant importing low yield and high moisture woody biomass from a grassland could, for example, result in a ‘carbon positive’ BECCS system, i.e. with ultimately a larger amount of CO₂ emitted than captured⁴⁰. In the case of liquid biofuel, life-cycle emissions need to be even more limited for the system to be carbon negative, because less CO₂ is captured upon conversion of the biomass to biofuel. For example, in the case of biomass to ethanol via fermentation, if only the fermentation process emissions (15% of the biomass carbon content) are captured^a, the biomass life cycle emissions need to be very low for the overall process to be carbon negative⁴⁵.

Direct and indirect emissions associated with land use change from cropland to bioenergy production

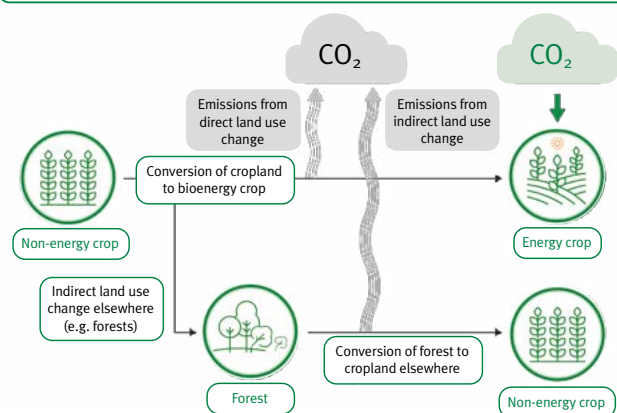


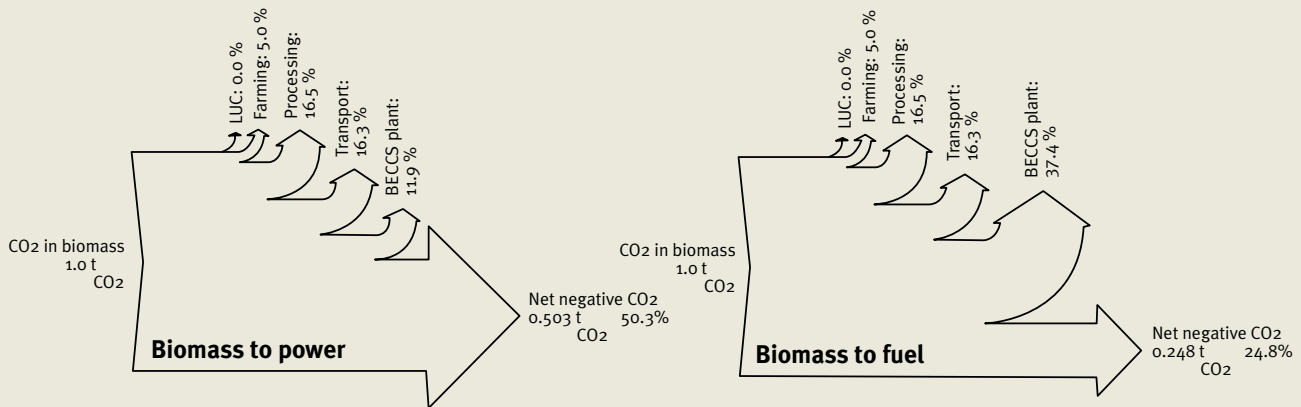
Figure 2: Direct and indirect land use change emissions might occur when land is converted to bioenergy production.

a The lowest cost option, but not the technical limit. An additional 52% of emissions can be captured but at higher cost.

Box 3^b: BECCS efficiencies: converting raw biomass into CO₂ removal and useful energy

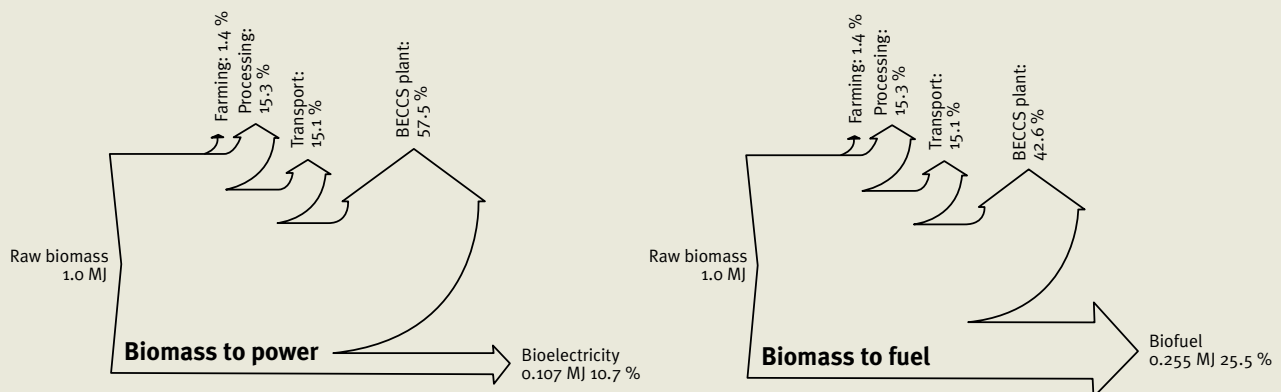
BECCS carbon efficiency measures how much of the CO₂ fixed in the biomass is removed from the atmosphere.

Figure 2: carbon flow diagram of BECCS. The power route leads to a higher carbon efficiency (50%) than the biofuel route (25%).



BECCS net energy efficiency measures how much of the primary energy from biomass is converted into useful energy (biofuel or electricity).

Figure 3: energy flow diagram of BECCS. The power route leads to a lower energy efficiency (11%) than the biofuel (26%).



^bSupply chain energy demand and emissions data, as well as power generation efficiency (26%) were obtained from the MONET framework for miscanthus production in Brazil transported to the UK, to illustrate the potential impact of long distance transport³⁸. For the biofuel route, an energy efficiency of 45%, and a CO₂ efficiency of 55% for biomass conversion to biofuels were assumed^{22,29}.

BECCS' performance can be measured by how much net carbon it captures (carbon efficiency) and how much net energy it produces (energy efficiency) along the whole supply chain. As illustrated in Box 3, while the power route yields higher carbon efficiency – more CO₂ is removed per unit of feedstock – biofuel routes deliver more energy per unit of feedstock. Therefore, there are trade-offs to consider when comparing BECCS deployment options.

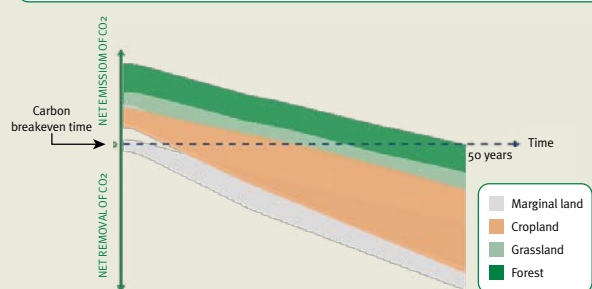
Carbon and energy efficiency are not the only trade-offs to consider. As illustrated in Box 3, while BECCS in the power sector could achieve more negative emissions, carbon negative biofuels, can displace carbon intensive fuels, such as aviation fuels, for which fewer alternative technologies are available⁴⁶. The cost of CO₂ capture also differs on each route, with the cost of capturing one tonne of CO₂ typically lower in biofuel routes than in power routes, because of the higher CO₂ purity in the biomass-to-fuel routes¹¹.

Time also matters

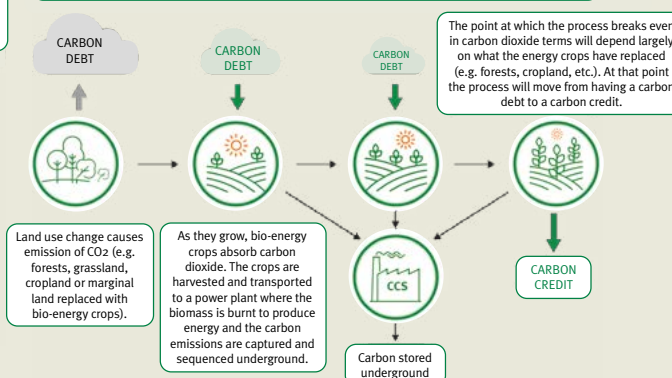
If land use change occurs at the beginning of a BECCS project resulting in emissions, an initial 'carbon debt' is incurred in the system, which needs to be paid off before the project brings net negative emissions. The time taken to pay off this debt is referred to as 'carbon breakeven time'. Box 4 shows that, while cultivating biomass on marginal land leads to breakeven times of one or two years, breakeven times can be greater than 50 years when converting forests⁴⁰. Carefully evaluating the impact of land use change is crucial from both a land-competition perspective, and a carbon-accounting perspective.

Box 4: The impact of land use change on BECCS carbon breakeven time

Breakeven time for the carbon debt when converting different land use types to bioenergy crops. Data based on the conversion of Southern US land to miscanthus production, taken from the MONET framework (Fajardy et al. 2018).



Dynamic carbon balance of Bio-energy with Carbon Capture and Storage



Broader environmental challenges

The impact of BECCS on resources, soil health and biodiversity have been identified as important limitations for its projected deployment^{7,49,47,48}.

Land use, in particular, has been raised as a major concern. As illustrated in Figure 3, to remain within 1.5°C of warming, scenarios project significant land areas could be allocated to bioenergy production by the end of the century. Estimates of land required range from between 100 million hectares in scenarios with limited (P2) or no BECCS (P1), to up to about 800 million hectares in scenarios where BECCS is deployed at a large scale (P4)^{5,8}.

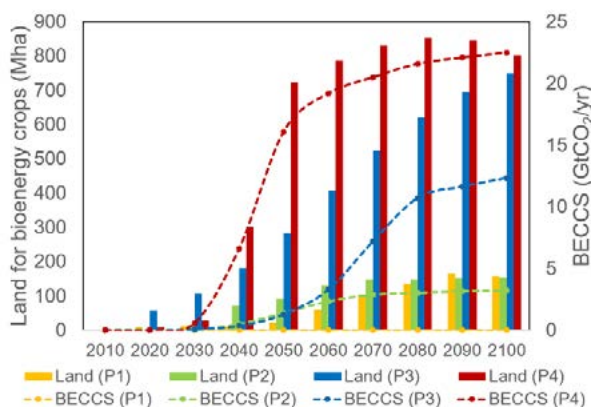


Figure 3: BECCS (lines) and land requirements for bioenergy crops (bars) in four representative pathways to 1.5°C: low energy demand (P1), sustainability oriented (P2), middle-of-the-road (P3), fossil-fuel intensive (P4)^{5,8}.

The world cropland area is around 1.5 gigahectares today; using high quality land such as grassland or cropland to grow bioenergy crops for BECCS is likely to result in competition with other land-based activities, such as food production, potentially increasing food prices^{49,50}. This negative effect can be partially mitigated through agricultural intensification – increasing crop yields in general, reducing the amount of land required to produce the same quantity of products. This approach can lead to biodiversity loss and increased biochemical flows, both critical indicators of the environmental impacts of BECCS deployment. It is also possible to avoid land use change without relying on agricultural intensification by, for example, using crop residues as biomass feedstock or growing biomass on so-called ‘marginal land’. However, the extent to which crop residues can be sustainably removed from the field without causing soil depletion and erosion remains uncertain. Marginal lands, on the other hand, are diverse in quality and type, which makes it difficult to predict how much marginal land is actually available, and what the biomass productivity response could be⁵¹⁻⁵⁴. Using algae to substitute for and/or in addition to lignocellulosic biomass in a biofuel route could also relieve pressure on land use^{6,35}, although concerns of high water and nutrient use remain.

Water use is another challenge to the sustainability of BECCS.

Water-use intensity includes the water used for crop growth, water pollution resulting from fertiliser application at the farm level, and the intensity of water use in the BECCS power plant. Table 1 provides ranges of water requirements needed to meet the middle-of-the-road level of BECCS deployment of 12Gt of CO₂ per year (P3).

Table 1: Water implications of removing 12Gt CO₂/yr via BECCS

	Water use (Bm ³ /yr)
Smith & Torn 2013 ⁵⁵	5.3 – 24.4
Smith et al. 2016 ⁴⁷	0.72
MONET ⁴⁰	3.6 – 9.7

The water footprint for BECCS was found to be highly dependent on the biomass type and region of production⁴⁰, which explains the wide range of values. To put these numbers in context, current total water consumption in agriculture is close to 8 billion m³ per year⁵⁶.

Considering these potentially large impacts on resource use, soil health, and forest and nature conservation, it is unlikely that levels of BECCS deployment as projected in middle-of-the-road (P₃), let alone fossil-fuel intensive (P₄), scenarios to 1.5°C, may be achieved sustainably.

The scale up challenge

Because the biomass supply chain has such a dramatic impact on the environmental and technical performance of BECCS, it is crucial to not only define what sustainable biomass is, but more importantly how much biomass can be sustainably produced. Controversy around what truly is sustainable explains the wide range reported in the literature. For example, the potential for using agricultural residue depends on how much can be removed from the field without compromising soil quality⁵⁷. Studies on biomass potential in Brazil point to about 50% of residues being physically harvestable, and of those, only 10% are available for bioenergy^{58,59}.

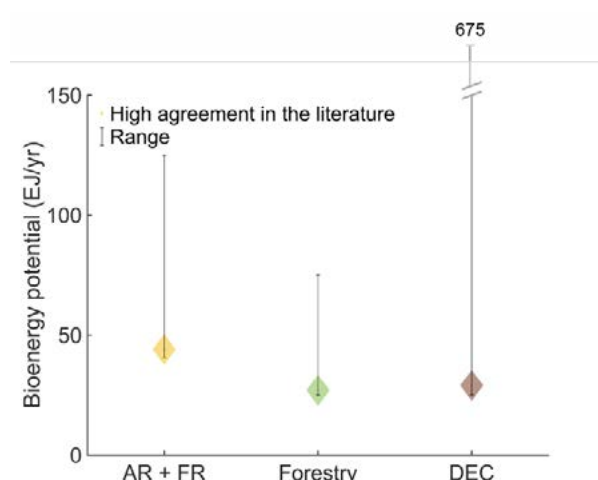


Figure 4: Ranges (bars) and high literature agreement (diamond) on global sustainable bioenergy potential per feedstock type (AR + FR = Agriculture and Forestry residues, DEC = dedicated energy crops). Adapted from Creutzig et al.⁶.

The technical potential of energy crops depends on the productivity of land available for bioenergy, but this is also subject to debate. IAMs project significant agricultural yield gains in the future, which helps improve the competitiveness of bioenergy options in the modelled scenarios. Some scenarios project future yield growth rates above historical levels, which averaged 1.9% per year between 1961 and 2007⁶⁰. However, there is much controversy around the future growth rate of global average yields, with perhaps the easy improvements having already been achieved¹⁹. The yield improvements of the past were enabled by measures such as fertilizer application, irrigation and land-ownership concentration. Extending the yield gains of the last 50 years into the future may require higher inputs of fertilizers, biocides, and irrigation, exacerbating the environmental problems caused by the so-called Green Revolution. In that way, we may be solving one problem by creating another, transferring the climate problem from the atmosphere to the land⁹.

There are many assessments of global bioenergy potential in the literature^{6,19,61-63}. Figure 4 represents ranges of uncertainty of global sustainable bioenergy potential by sector (bars), as well as the availability levels with high agreement in the literature (diamonds). The figure implies that only about 100 exajoules (EJ) per year, or likely less, can be sustainably produced globally⁶. This sustainable potential, with high agreement in the literature, sits at the lower end of the biomass production range in existing scenarios, although other studies point to somewhat higher sustainable potentials (see for example⁶³, who point to a 80-160EJ per year potential).

Other studies point to even higher biomass availability and, with such a high range of uncertainty, one could easily overestimate the amount of sustainable biomass available for BECCS. However, the consensus seems to be on the conservative side.

Adding up residues, forestry biomass and bioenergy crops, less than 100EJ of modern bioenergy could be sustainably sourced, which still represents a fivefold increase to what is currently produced⁶⁴. Assuming these 100EJ are deployed with carbon capture and storage, and that 60% of bioenergy goes to biofuel production, and 40% to bioelectricity, three to four gigatons of CO₂ could be removed from the atmosphere per year within this constrained bioenergy supply.

The CCS dimension

BECCS deployment is intrinsically **dependent on the existence of carbon capture and storage (CCS) infrastructure. To date, there are 17 operating CCS projects in the world**, reaching a cumulative capture capacity of 31.5Mt of CO₂ per year, of which only 3.7 is stored in geological formations⁶⁵. Though technology advances have brought down the cost of capture⁶⁶, low investor confidence remains the main bottleneck in the way of unlocking a CCS economy. Currently, medium-term physical and financial risks associated with full CCS chain integration^c represent a significant fraction of CCS project capital investment⁶⁷. In addition to lowering this financial risk, other opportunities to lower the cost of CCS include the clustering of CO₂ sources to facilitate economies of scale for the transport and storage of CO₂, and the retrofitting of large power stations to benefit from technology learning³³.

BECCS: a governance problem

While climate change mitigation scenarios propose that large-scale BECCS deployment might help avoid dangerous climate change, it would also **steer the world closer to the planetary boundary of freshwater use**. This large-scale deployment of BECCS would push us beyond other planetary boundaries such as land-system change, biosphere integrity and soil health⁴⁸. The first and foremost **challenges** are therefore to **(a) limit BECCS deployment to a sustainable scale, both in models and policy frameworks, and (b) ensure that the most sustainable BECCS options get deployed within this scale, by setting clear resource, carbon and energy efficiency guidance and constraints**.

Another challenge is to make BECCS economically feasible. Deployment is tied to the deployment of CCS, and therefore directly affected by the difficulty in financing a CCS project. With reduced financial risks for CCS, a carbon price in the range \$30-280 per ton of CO₂ would be required to make a BECCS power production project economically attractive^{22,68}. So far, carbon prices such as those of the EU Emissions Trading Systems have been insufficient in incentivising CCS deployment, let alone BECCS⁶². **The implementation of a carbon credit**, such as the '45Q' budget allocation in the US, which was recently upgraded to credit up to \$50 a ton of CO₂ sequestered, and \$35 a ton of CO₂ used for 'enhanced oil recovery', could well help **jumpstart CCS projects**.

Financing carbon removal through BECCS is made more challenging because the value chain is likely to be geographically dispersed. Regions with high biomass potential such as South America and sub-Saharan Africa⁶⁹ are not necessarily regions with well characterised CO₂ storage capacity compared with the USA, Japan or northern Europe⁶³. It is also complex to ensure fair allocation of the share of carbon removal across all stakeholders of the BECCS value chain, from both a

political (fulfilling individual national carbon removal targets) and a financial (cascading carbon credits to all stakeholders) point of view.

In channelling financial support towards BECCS, it is important for policy makers to weigh up this support against other proven mitigation options that might cost less, and have less damaging side effects.

BECCS deployment will need assistance – even to deliver at this limited scale

Even with a more limited ambition for BECCS deployment, going from today's megaton-scale industry to removing a few gigatons of CO₂ by the end of the century remains an important challenge. Reaching these levels of sustainable activity in a timely fashion requires the right regulation and incentive frameworks to be put in place. Some ideas about where the policy focus should lie to unlock sustainable BECCS deployment are provided below.

Broadening the scope of the biomass sustainability standard

Establishing sustainability standards is essential to ensure that the most sustainable options are deployed instead of focusing only on what is commercially viable.

Strong policies are needed to set clear standards for biomass sustainability, not only on carbon intensity of biomass feedstocks, but also on water, CO₂, and energy efficiencies, as well as carbon breakeven time.

For example, the low carbon fuel standard in California, enables fuels demonstrating a lower carbon footprint than the gasoline standard to earn a carbon credit. Compliance to the fuel standard is evaluated through life cycle analysis with the GREET tool⁷⁰. Applying this method but broadening the scope of indices evaluated, could be a useful way to discriminate unsustainable from sustainable scenarios.

In a European context, the UK Bioenergy strategy includes a sustainability criterion ensuring a minimum of 60% emission reduction from the average European power carbon-intensity for bioelectricity⁷¹. This target represents a maximum carbon intensity of 79g of CO₂/MJe (i.e. electric energy delivered), which translates into a minimal carbon efficiency between 47% and 60%. The more recent European RED II directive goes further by stating that large scale heat and power biomass plants deliver an 80% emissions reduction compared to fossil fuel, with a life cycle emissions accounting framework that includes land-use change emissions. Such constraints could limit BECCS deployment to sustainable routes, thereby making room for other low-carbon technologies, or emphasising the merit of more stringent mitigation action today.

^c Where a single entity owns and operates the full CCS chain and long-term risk associated with monitoring the dispersion or movement of the CO₂ in storage sites.

Deploying BECCS instead of bioenergy, not in addition to it

It is likely that only a limited amount of bioenergy will be available if social and environmental sustainability constraints of feedstock production are met. Therefore, this sustainable potential should be allocated in a way that yields the most benefits. One way to maximise CO₂ removal is to impose a requirement that any bioenergy deployment should be accompanied by capture and storage of as much CO₂ as possible, effectively requiring that any bioenergy used from now on should be in the form of BECCS, or BECCS enabled.

Thinking in terms of carbon negative products and their value

With a bioenergy supply that is likely to be limited, careful consideration should be made about where to use this bioenergy – power generation or liquids.

Although BECCS via biofuels is less carbon efficient than BECCS via bioelectricity, it presents the advantages of being more energy efficient and decarbonising the transport sector, for which fewer low-carbon alternatives are available than in the power sector.

Aviation stands out as having very few decarbonisation options, and biofuels are the main alternative for the sector. From this perspective, biofuel production proves to be a better business case than power production. As an illustration, the only operating BECCS plant to date is the Decatur corn-bioethanol CCS plant⁷². However, being more carbon efficient, power production enables more carbon removal per unit of resource – biomass, water and land. The trade-offs between BECCS deployment options therefore need to be better understood when valuing its contribution to climate change mitigation. These trade-offs are likely to manifest themselves on a case-by-case basis.

Lowering the financial risks of CCS

A transfer of some of the risks and liabilities associated with CCS value chain integration and long-term CO₂ storage monitoring from the private to the public sector would lower the risks for investors, and therefore the financial costs associated with a CCS project, thereby encouraging private capital to be invested in the CCS economy³³.

Conclusions

Before BECCS is implemented in the hope it will play a role in climate change mitigation, it is crucial to establish whether it works as a means of generating net energy to sequester net carbon. For this it is crucial to have clarity about the value and challenges of each BECCS technology route, and to understand what makes the value chain sustainable. Relevant regional regulations with regard to water, energy and carbon will be required to make sure deployment does not compromise other societal objectives such as the Sustainable Development Goals. This will encourage the deployment of a regionally tailored mix of technologies, including but not limited to BECCS, instead of blindly betting on a single one.

Importantly, we have shown that BECCS cannot deliver the scale of negative emissions required in current emissions projections. The BECCS value chain is complex with significant energy and carbon inputs, among other factors. Therefore, we should expect BECCS to make a necessary but only limited contribution to meeting our climate change targets. Counting on BECCS to singlehandedly solve the climate change mitigation problem detracts attention from higher levels of short-term effort based on known low-carbon solutions that are already available today.

Glossary

Bioenergy potential	Bioenergy potential: how much bioenergy could be produced per year globally.
Carbon negative (positive)	Carbon negative (positive): said of a BECCS value chain which leads to a net removal (emission) of CO ₂ from (to) the atmosphere, all life cycle CO ₂ emissions considered.
Carbon (or CO ₂) breakeven time	Time required for a BECCS value chain to be carbon negative.
Carbon (or CO ₂) efficiency	The fraction of the carbon fixed in the biomass which becomes net negative emissions, all life cycle CO ₂ emissions considered.
Energy efficiency (net)	The fraction of the biomass primary energy turned into useful energy, all life cycle energy inputs and outputs considered.
Energy positive (negative)	Said of a BECCS value chain which leads to a net production (consumption) of energy, all life cycle energy inputs and outputs considered.
EROI	The ratio between energy input to energy output.
High agreement in the literature	Many scientific studies pointing to a particular result.

References

1. Rogelj, J., et al., *Paris Agreement climate proposals need a boost to keep warming well below 2 °C*. Nature, 2016. 534(7609): p. 631-639.
2. IPCC, *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. 2014: Cambridge University Press.
3. Harper, A.B., et al., *Land-use emissions play a critical role in land-based mitigation for Paris climate targets*. Nature Communications, 2018. 9(1): p. 2938-2938.
4. Field, C.B. and K.J. Mach, *Rightsizing carbon dioxide removal*. Science, 2017. 356(6339): p. 706 LP-707.
5. Huppmann, D., et al., *IAMC 1.5°C Scenario Explorer and Data hosted by IIASA*. 2018, Integrated Assessment Modeling Consortium & International Institute for Applied Systems Analysis.
6. Creutzig, F., et al., *Bioenergy and climate change mitigation: An assessment*. GCB Bioenergy, 2015. 7(5): p. 916-944.
7. Smith, S.L., K.D. Thelen, and S.J. MacDonald, *Yield and quality analyses of bioenergy crops grown on a regulatory brownfield*. Biomass and Bioenergy, 2013. 49: p. 123-130.
8. Rogelj, J., et al., *Mitigation pathways compatible with 1.5°C in the context of sustainable development*, in *Special Report on the impacts of global warming of 1.5 °C*. 2018, **Intergovernmental Panel on Climate Change**: Geneva.
9. Tavoni, M. and R. Socolow, *Modeling meets science and technology: an introduction to a special issue on negative emissions*. Climatic Change, 2013. 118(1): p. 1-14.
10. Rogelj, J., et al., *Energy system transformations for limiting end-of-century warming to below 1.5 °C*. Nature Climate Change, 2015. 5(6): p. 519-527.
11. Muratori, M., et al., *Carbon capture and storage across fuels and sectors in energy system transformation pathways*. International Journal of Greenhouse Gas Control, 2017. 57: p. 34-41.
12. Le Quéré, C., et al., *Global Carbon Budget 2017*. Earth System Science Data, 2018. 1010333739(10): p. 405-448.
13. de Coninck, H., et al., *Chapter 4: Strengthening and Implementing the Global Response, in 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*, V. Masson-Delmotte, et al., Editors. 2018, Intergovernmental Panel on Climate Change (IPCC): Geneva, Switzerland.
14. FAO. FAOSTAT. Available from: <http://faostat.fao.org/site/339/default.aspx>.
15. Johnson, N., N. Parker, and J. Ogden, *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, 2014. 63: p. 6770-6791.
16. Fuss, S., et al., *Negative emissions — Part 2 : Costs, potentials and side effects*. Environmental Research Letters, 2018.
17. Nemet, G.F., et al., *Negative emissions — Part 3: Innovation and upscaling*. Environmental Research Letters, 2018. 13(6): p. 063003.
18. Minx, J.C., et al., *Negative emissions: Part 1 – Research landscape, ethics and synthesis*. Environmental Research Letters, 2018. submitted.
19. Slade, R., A. Bauen, and R. Gross, *Global bioenergy resources*. Nature Climate Change, 2014. 4(2): p. 99-105.
20. IPCC, *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change 2007*, Cambridge, United Kingdom: Cambridge University Press.
21. Schnurr, M.A., *GMOs and poverty: yield gaps, differentiated impacts and the search for alternative questions*. Canadian Journal of Development Studies/Revue canadienne d'études du développement, 2017. 38(1): p. 149-157.
22. Gough, C., et al., *Challenges to the use of BECCS as a keystone technology in pursuit of 1.5c*. Global Sustainability, 2018(forthcoming): p. 1-9.
23. Laude, A., et al., *CO₂ capture and storage from a bioethanol plant: Carbon and energy footprint and economic assessment*. International Journal of Greenhouse Gas Control, 2011. 5(5): p. 1220-1231.
24. Bhawe, A., et al., *Screening and techno-economic assessment of biomass-based power generation with CCS technologies to meet 2050 CO₂ targets*. Applied Energy, 2017. 190: p. 481-489.
25. Onarheim, K., et al., *Performance and costs of CCS in the pulp and paper industry part 1: Performance of amine-based post-combustion CO₂ capture*. International Journal of Greenhouse Gas Control, 2017. 59: p. 58-73.
26. Lu, X., et al., *Biomass logistics analysis for large scale biofuel production: Case study of loblolly pine and switchgrass*. Bioresource Technology, 2015. 183: p. 1-9.
27. Liu, G., et al., *Making Fischer-Tropsch Fuels and Electricity from Coal and Biomass: Performance and Cost Analysis*. Energy & Fuels, 2011. 25(1): p. 415-437.

28. Humbird, D., et al., *Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol*. 2011. p. 147-147.
29. Hetland, J., et al., *Carbon-negative emissions: Systemic impacts of biomass conversion. A case study on CO₂ capture and storage options*. International Journal of Greenhouse Gas Control, 2016. 49: p. 330-342.
30. Bui, M., M. Fajardy, and N. Mac Dowell, *Bio-Energy with CCS (BECCS) performance evaluation: Efficiency enhancement and emissions reduction*. Applied Energy, 2017. 195(June): p. 289-302.
31. Lu, X. and H. Herzog, *Biomass to Liquid Fuels Pathways : A Techno-Economic Environmental Evaluation*. 2015.
32. Nassi o Di Nasso, N., et al., *Soil texture and crop management affect switchgrass (Panicum virgatum L.) productivity in the Mediterranean*. Industrial Crops and Products, 2015. 65: p. 21-26.
33. Bui, M., et al., *Carbon capture and storage (CCS): the way forward*. Energy & Environmental Science, 2018: p. 1062-1176.
34. Anderson, K. and G. Peters, *The trouble with negative emissions*. Science, 2016. 354(6309): p. 182-183.
35. Beal, C.M., et al., *Integrating Algae with Bioenergy Carbon Capture and Storage (ABECCS) Increases Sustainability*. Earth's Future, 2018. 6.
36. Hillier, J., et al., *Greenhouse gas emissions from four bioenergy crops in England and Wales: Integrating spatial estimates of yield and soil carbon balance in life cycle analyses*. GCB Bioenergy, 2009. 1(4): p. 267-281.
37. Cherubini, F. and G. Jungmeier, *LCA of a biorefinery concept producing bioethanol, bioenergy, and chemicals from switchgrass*. The International Journal of Life Cycle Assessment, 2009. 15(1): p. 53-66.
38. Daystar, J., et al., *Environmental life cycle impacts of cellulosic ethanol in the Southern U.S. produced from loblolly pine, eucalyptus, unmanaged hardwoods, forest residues, and switchgrass using a thermochemical conversion pathway*. Fuel Processing Technology, 2015. 138: p. 164-174.
39. Pacetti, T., L. Lombardi, and G. Federici, *Water-energy Nexus: A case of biogas production from energy crops evaluated by Water Footprint and Life Cycle Assessment (LCA) methods*. Journal of Cleaner Production, 2015. 101: p. 1-14.
40. Fajardy, M. and N. Mac Dowell, *Can BECCS deliver sustainable and resource efficient negative emissions?* Energy Environ. Sci., 2017. 10: p. 1389-1426.
41. Fargione, J., et al., *Land Clearing and the Biofuel Carbon Debt*. Science, 2008. 319(February): p. 1235-1237.
42. Fajardy, M. and N. Mac Dowell, *The Energy Return On Investment of negative emissions: is BECCS a threat to energy security?* Energy and Environmental Science, 2018. 11: p. 1581-1594.
43. Hall, C.A.S., Balogh, S., Murphy, D.J.R.; *What is the minimum EROI that a sustainable society must have?* Energies 2009, 2(1), 25-47
44. Fajardy, M., MacDowell, N.; *The energy return on investment of BECCS: is BECCS a threat to energy security?* Energy & Environmental Science, 2018 Issue 6
45. Humbird, D., et al., *Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol*. National Renewable Energy Laboratory Technical Report May 2011. p. 147-147.
46. Bosch, J., et al., *Aviation biofuels: strategically important, technically achievable, tough to deliver*. Grantham Institute Briefing Paper, 2017(November).
47. Smith, P., et al., *Biophysical and economic limits to negative CO₂ emissions*. Nature Climate Change, 2016. 6(1): p. 42-50.
48. Heck, V., et al., *Biomass-based negative emissions difficult to reconcile with planetary boundaries*. Nature Climate Change, 2018. 8: p. 151-155.
49. Rulli, M.C., et al., *The water-land-food nexus of first-generation biofuels*. Scientific Reports, 2016. 6(February): p. 22521-22521.
50. Hasegawa, T., et al., *Risk of increased food insecurity under stringent global climate change mitigation policy*. Nature Climate Change, 2018. 8(8): p. 699-703.
51. Milbrandt, A.R., et al., *Renewable energy potential on marginal lands in the United States*. Renewable and Sustainable Energy Reviews, 2014. 29: p. 473-481.
52. Edrisi, S.A. and P.C. Abhilash, *Exploring marginal and degraded lands for biomass and bioenergy production : An Indian scenario*. Renewable and Sustainable Energy Reviews, 2016. 54: p. 1537-1551.
53. Xue, S., et al., *Assessment of the production potentials of Miscanthus on marginal land in China*. Renewable and Sustainable Energy Reviews, 2016. 54: p. 932-943.
54. Mehmood, M.A., et al., *Biomass production for bioenergy using marginal lands*. Sustainable Production and Consumption, 2016(August): p. 1-19.
55. Smith, L.J. and M.S. Torn, *Ecological limits to terrestrial biological carbon dioxide removal*. Climatic Change, 2013. 118: p. 89-103.
56. Chapagain, A.K. and A.Y. Hoekstra, *Water footprint of nations. Volume 1 : Main report*. 2004. p. 1-80.
57. Muth, D.J. and K.M. Bryden, *An integrated model for assessment of sustainable agricultural residue removal limits for bioenergy systems*. Environmental Modelling and Software, 2013. 39: p. 50-69.

58. Welfle, A., *Balancing growing global bioenergy resource demands – Brazil's biomass potential and the availability of resource for trade*. Biomass and Bioenergy, 2017. 105: p. 83-95.
59. Portugal-Pereira, J., et al., *Agricultural and agro-industrial residues-to-energy: Techno-economic and environmental assessment in Brazil*. Biomass and bioenergy, 2015. 81: p. 521-533.
60. Alexandratos, N. and J. Bruinsma, *ESA Working Paper No. 12-03: World agriculture towards 2030-2050, in FAO Agricultural Development Economics Division*. 2016, FAO.
61. Bauen, A., et al., *Bioenergy – a Sustainable and Reliable Energy Source*. 2009, IEA Bioenergy. p. 108-108.
62. Gough, C. and P. Upham, *Biomass energy with carbon capture and storage (BECCS): a review*. Tyndall Centre for Climate Change, University of Manchester, 2010.
63. Beringer, T., W. Lucht, and S. Schaphoff, *Bioenergy production potential of global biomass plantations under environmental and agricultural constraints*. GCB Bioenergy, 2011. 3(4): p. 299-312.
64. International Energy, A., *Technology Roadmap Delivering Sustainable Bioenergy*. 2017.
65. *CCS facilities database*. 2018, Global CCS Institute: <https://www.globalccsinstitute.com/projects/large-scale-ccs-projects>.
66. *The Global Status of CCS: 2017*. 2017, Global CCS Institute. p. 43-43.
67. Kolster, C., *Economic, process and reservoir modelling for large-scale deployment of carbon capture and storage (CCS)*, in *Centre for Environmental Policy*. 2018, Imperial College London.
68. Kemper, J., *Biomass and carbon dioxide capture and storage: A review*. International Journal of Greenhouse Gas Control, 2015. 40: p. 401-430.
69. Haberl, H., et al., *Global bioenergy potentials from agricultural land in 2050: Sensitivity to climate change, diets and yields*. Biomass and Bioenergy, 2011. 35(12): p. 4753-4769.
70. Wang, M.Q., *The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model Version 1.5*. 1999.
71. DECC, *UK Bioenergy Strategy*. 2012. p. 86-86.
72. Gollakota, S. and S. McDonald, *Commercial-scale CCS project in Decatur, Illinois – Construction status and operational plans for demonstration*. Energy Procedia, 2014. 63: p. 5986-5993.

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