Can BECCS deliver immediate and efficient carbon dioxide removal?

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BECCS value chain
• Is BECCS carbon negative?
• If at all, how long does it take for BECCS to be carbon negative?
• Is BECCS a sustainable and resource efficient technology?
Miscanthus, switchgrass, willow, wheat straw
Brazil, China, Europe, India, US
Cropland, marginal land, grassland, forest, peatland

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Biomass supply chain model

Power plant model

Outputs

Annual emission balance on BECCS

500 MW BECCS power plant
BECCS project lifetime: 50 years

Annual GHG emissions balance over the lifetime

BECCS

Carbon intensity
$kg_{CO_{2}}/MWh$

Water intensity
$m^{3}/MWh$

Net efficiency
$\%_{HHV}$

Lifetime net CO$_2$ removal
$t_{CO_{2}}/ha$

CO$_2$ breakeven time
$years$

Carbon efficiency
$\%$

Biomass

Carbon footprint
$kg_{CO_{2}}/t$

Water footprint
$m^{3}/t$

Energy footprint
$GJ/t$
Data collection and curation

Range evaluation

Data series

Variation coefficient

3Q
1Q
# Model overview

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**Biomass supply chain model**

**Power plant model**

**Outputs**

- **Biomass**
  - Carbon footprint: $kg_{CO_2}/t$
  - Water footprint: $m^3/t$
  - Energy footprint: $GJ/t$

- **BECCS**
  - Carbon intensity: $kg_{CO_2}/MWh$
  - Water intensity: $m^3/MWh$
  - Net efficiency: $%_{HHV}$

- **Carbon efficiency**: $%$
- **Lifetime net CO$_2$ removal**: $t_{CO_2}/ha$
- **CO$_2$ breakeven time**: $years$

**500 MW BECCS power plant**

**BECCS project lifetime**: 50 years

Annual GHG emissions balance over the lifetime
What are the main contributions to biomass carbon footprint?

- Nitrogen application, road transport, industrial drying for high moisture biomass (willow) are key drivers.
Model overview

Biomass: Miscanthus, switchgrass, willow, wheat straw
Region: Brazil, China, Europe, India, US
Land type: Cropland, marginal land, grassland, forest, peatland
Capture rate: 90%
Co-firing proportion: 100%
Removal target: 3.3 Gt C/yr

OUTPUTS

- Carbon footprint: kg CO₂/t
- Water footprint: m³/t
- Energy footprint: GJ/t
- BECCS Carbon intensity: kg CO₂/MWh
- Water intensity: m³/MWh
- Net efficiency: % HHV
- Carbon efficiency: %
- Lifetime net CO₂ removal: t CO₂/ha
- CO₂ breakeven time: years

Biomass supply chain model

Power plant model

BECCS project lifetime: 50 years

Annual GHG emissions balance over the lifetime

500 MW BECCS power plant
How does biomass carbon footprint impact BECCS carbon intensity?

- The power plant carbon intensity decreases with biomass co-firing proportion and capture rate.
How does biomass carbon footprint impact BECCS carbon intensity?

- Adding biomass supply chain emission can offset the power plant carbon negativity,
- This increases the minimum co-firing and capture rate values for the power plant to be carbon negative, hence decreasing its flexibility.
**Model overview**

**Biomass**

- Miscanthus, switchgrass, willow, wheat straw

**Region**

- China

**Land type**

- Marginal cropland

**Capture rate**

- 90%

**Co-firing proportion**

- 100%

**Removal target**

- 3.3

**Outputs**

- Biomass
- Carbon footprint \( \text{kg CO}_2/\text{t} \)
- Water footprint \( \text{m}^3/\text{t} \)
- Energy footprint \( \text{GJ/t} \)

- BECCS
- Carbon intensity \( \text{kg CO}_2/\text{MWh} \)
- Water intensity \( \text{m}^3/\text{MWh} \)
- Net efficiency \( \%_{HHV} \)

- \( 500 \text{ MW BECCS power plant} \)

- BECCS project lifetime: 50 years

- Annual GHG emissions balance over the lifetime

- Carbon efficiency \( \% \)

- Lifetime net CO\(_2\) removal \( \text{t CO}_2/\text{ha} \)

- CO\(_2\) breakeven time \( \text{years} \)
Dynamic GHG balance

• How does the carbon balance change over the lifetime of a BECCS project?
• What are the factors affecting BECCS lifetime carbon removal and carbon breakeven time?

Alternative scenarios
- Use of biofuels
- Drying with biomass
- Use of carbon neutral electricity
- Use of organic chemicals

Decrease in electricity, fuels, chemicals carbon footprints
+ Decrease in moisture content
+ Increase in yield and carbon content

Lifetime carbon removal

Cumulative emissions ($t_{\text{CO}_2}/\text{ha}$)

Carbon breakeven time

Year
## Model overview

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### Biomass supply chain model

- \( \text{CO}_2 \rightarrow \text{H}_2\text{O} \rightarrow \text{CO}_2 \rightarrow W \)
- Power plant model
- \( \text{CO}_2 \rightarrow \text{H}_2\text{O} \rightarrow \text{CO}_2 \rightarrow W \)

### BECCS

- Carbon intensity: \( \text{kgCO}_2/\text{MWh} \)
- Water intensity: \( \text{m}^3/\text{MWh} \)
- Net efficiency: \( \%_{\text{HHV}} \)
- Carbon efficiency: %
- Lifetime net \( \text{CO}_2 \) removal: \( \text{tCO}_2/\text{ha} \)
- \( \text{CO}_2 \) breakeven time: years

### Outputs

- Carbon footprint: \( \text{kgCO}_2/\text{t} \)
- Water footprint: \( \text{m}^3/\text{t} \)
- Energy footprint: \( \text{GJ/t} \)

### BECCS project lifetime: 50 years

- Annual GHG emissions balance over the lifetime of a 500 MW BECCS power plant.
BECCS carbon efficiency
How to convert 1 EJ of bioenergy into $t_{CO2}$ removed?

• In current models:
  o 1 EJ of bioenergy $\approx 100$ Mt$_{CO2}$ on which is applied a 90% capture efficiency $\approx 90$ Mt$_{CO2}$

• 1 EJ of bioenergy = $\frac{1}{\text{HHV}_{bio}} \times \text{C\%}_{bio} \times \frac{\text{MW}_{CO2}}{\text{MW}_C} \times 10^9$

  $1/(18-20 \text{ GJ/t}_{DM}) \times 46-50\%_{DM}$

  $= 84 - 102$ Mt$_{CO2}$ biologically removed from the atmosphere

  Biomass supply chain mass loss + direct and indirect BECCS value chain CO$_2$ emissions

  $= ?$ Mt$_{CO2}$ stored in geological storage?

• Carbon efficiency = $t_{CO2}$ geologically stored/$t_{CO2}$ biologically captured
• Out of 1 t\(_{\text{CO}_2}\) stored in the biomass, how much CO\(_2\) is geologically stored?

• For efficiencies above 0\%, the system is net negative.

• 1 EJ of bioenergy = 50 Mt\(_{\text{CO}_2}\) removed

BECCS carbon efficiency
Miscanthus – Marginal land

- Inputs: 3.0%
- Farming: 1.6%
- Chopping: 2.7%
- Drying: 2.6%
- Pelleting: 4.5%
- Road transport: 6.3%
- Pellet grinding: 4.5%
- Capture: 7.7%
- CO\(_2\) T&S: 4.2%

Year 50

Biological CO\(_2\)

1.0 t\(_{\text{CO}_2}\)

Geological CO\(_2\)

0.497 t\(_{\text{CO}_2}\) 49.7%
Model overview

Biomass: Miscanthus, switchgrass, willow, wheat straw
Region: Brazil, China, Europe, India, US
Land type: Cropland, marginal land, grassland, forest, peatland

Capture rate: 90%
Co-firing proportion: 100%
Removal target: 3.3 GtC/yr

Direct (LUC) and indirect (ILUC) land use changes

60-90%
0-100%

OUTPUTS

Biomass
Carbon footprint $kg_{CO2}/t$
Water footprint $m^3/t$
Energy footprint $GJ/t$

BECCS
Carbon intensity $kg_{CO2}/MWh$
Water intensity $m^3/MWh$
Net efficiency $%_{HHV}$

Carbon efficiency $%$
Lifetime net $CO2$ removal $t_{CO2}/ha$
$CO2$ breakeven time $years$

500 MW BECCS power plant
BECCS project lifetime: 50 years
And with land use change?

- The offset effect is exacerbated with indirect land use changes.
- BECCS systems do not reach carbon negativity in the upper bound scenarios.
Dynamic GHG balance

- How is the dynamic GHG profile affected by land use change?
For efficiencies above 0%, the system is net negative.

1 EJ of bioenergy = 31 Mt$_{\text{CO}_2}$ removed
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**Outputs**

- Biomass
- Carbon footprint \(\text{kg}_{CO_2}/t\)
- Water footprint \(m^3/t\)
- Energy footprint \(GJ/t\)

**BECCS**

- Carbon intensity \(\text{kg}_{CO_2}/MWh\)
- Water intensity \(m^3/MWh\)
- Net efficiency \(\%_{HHV}\)

**Outputs**

- 500 MW BECCS power plant
- BECCS project lifetime: 50 years
- Annual GHG emissions balance over the lifetime
- Carbon efficiency \(\%\)
- Lifetime net \(CO_2\) removal \(t_{CO_2}/ha\)
- \(CO_2\) breakeven time \(\text{years}\)
The power plant water intensity increases with capture rate and co-firing proportion (efficiency drops).
BECCS water intensity

- Biomass water footprint impact on the power plant water intensity is two orders of magnitude greater than that of the power plant cooling requirement.
How much resources does BECCS need?

12 Gt CO₂/year target

- **Land**: 9,720 Mha
- **Water**: 7,980 Bm³/yr
- **Capacity**: 1.8 TW

Harvested area for world cereal production (FAOSTAT, 2014)

- Mean Miscanthus: 2.1
- Range Miscanthus: 1.6 – 2.9

World capacity of coal fired power plants (EIA, 2016)
Conclusions

• Biomass supply chain drives BECCS carbon and water intensities,
• BECCS does not remove CO\textsubscript{2} immediately: from 1 year to over 50 years,
• The CO\textsubscript{2} removed over the lifetime of a BECCS project can be very different: between 0 and 2 kt\textsubscript{CO2}/ha,
• BECCS sustainability is highly case specific,
• But in all cases relies on intelligent management of the biomass supply chain: limiting land use change, prioritizing sea/rail over road transport, using organic chemicals and alternative drying and processing.
• Important policy implications:
  • Stake holders in BECCS value chain are multiple,
  • BECCS projects can vary in “quality”,
  • Carbon breakeven time needs to be accounted for in crediting schemes.


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