Bioenergy markets in a climate-constrained world

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Abstract

Avoiding dangerous climate change requires substantial emission reductions in the energy and the land-use sector. Within the portfolio of decarbonization options bioenergy assumes a unique role because it can reduce emissions in two special ways. First, due to its versatility it can provide low-carbon energy as substitute for fossil fuels in all energy sectors. Second, due to its carbon content bioenergy combined with carbon capture and storage (CCS) can provide negative emissions that allow compensating emissions across sectors and time, which is of special interest for achieving low-stabilization targets. However, biomass cultivation requires fertile land giving rise to concerns about adverse effects, such as land-use change emissions, biodiversity loss, and competition with food production.

Scrutinizing the bioenergy assessment carried out by *The IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation* it became apparent that the available long-term scenarios assessing bioenergy as a mitigation option only cover these adverse effects to a minor degree. This thesis aims at improving the bioenergy assessment by addressing potential consequences of and requirements for bioenergy deployment in the energy sector *and* the land-use sector. Using an integrated model framework of energy-economy-climate and land-use this thesis investigates the role bioenergy can play in achieving ambitious long-term climate change mitigation targets taking into account emissions from agriculture and land-use change. It explores the global biomass potential and corresponding supply prices and investigates how pricing land-use and land-use change emissions affects the biomass potential and resulting emissions. It analyzes how mitigation strategies and costs depend on constraints on the supply and demand side of bioenergy. It investigates how bioenergy contributes to the transformation and decarbonization of the energy system in general and identifies the economic drivers behind the choice of bioenergy conversion technologies in particular.

Results show that bioenergy with CCS (BECCS) is a crucial mitigation option with paramount importance particularly for achieving stringent climate change mitigation targets. If CCS is available, bioenergy is exclusively used with CCS in mitigation scenarios and it is predominantly used to produce liquid fuels for the transportation sector. Since biomass is mainly supplied by lignocellulosic perennial grassy feedstock this requires robust gasification technologies to be available that can cope with the heterogeneous grassy feedstock. Modern bioenergy deployment increases rapidly after 2030 to around 300 EJ/yr. Mitigation costs rise sharply if bioenergy or CCS is constrained. This indicates that without bioenergy or CCS, it is difficult to achieve low stabilization targets.

Grassy biomass feedstock can be produced at prices above 5 \$/GJ. Pricing emissions in the land-use sector increases bioenergy supply prices (by 5\$/GJ in 2055 and by 10 \$/GJ in 2095) due to land exclusion of high-productive forest land and due to nitrogen-emissions from bioenergy production. Carbon taxes on land-use change emissions are found to effectively prevent deforestation and thereby significantly reduce total land-use

change emissions. However, land reduction due to GHG taxes is compensated by intensification and expansion into land that is not under emission control, the latter of which increases land-use change emissions from biomass production. This indicates that bioenergy demand *and* GHG taxes at the same time (as typical for low-stabilization scenarios) put substantial pressure on the land-use sector and could induce leakage of bioenergy or food production into land with high carbon content that is not under emission control. Average yields that would be required for large-scale bioenergy production in 2095 are roughly between 500 and 600 GJ/ha for the major producer regions. Results further indicate that the competition for water between agriculture, private households, and industry is likely to increase heavily in many regions, particularly if forests are protected and bioenergy is used for climate change mitigation.

In climate mitigation scenarios, the value of bioenergy is found to be determined by both its energy value and the value of potential negative emissions. Results show, that the availability of BECCS creates a strong link between carbon prices and bioenergy prices. This lets the carbon value of biomass exceed its pure energy value in low stabilization scenarios with BECCS availability. Rising carbon prices thus induce investments in technologies that would not be built for the purpose of energy production. Furthermore, through this price link stringent climate protection targets induce a high willingness-to-pay for bioenergy that exceeds by far bioenergy supply prices identified previously.

Bioenergy is so valuable because its negative emissions increase the amount of permissible carbon emissions from fossil fuels and therefore allow postponing emissions reductions in the short-term and the preservation of some residual emissions in the long run. For a given climate target, bioenergy thus acts as a complement to fossils rather than a substitute. However, this makes the prolonged short-term deployment of fossil fuels dependent on the long-term potential of biomass and the availability of CCS. Thus, uncertainties about the long-term developments of (i) conditions in the land-use sector (land availability, yields etc.) and (ii) CCS technology are highly relevant for short-term decisions about emission reduction.