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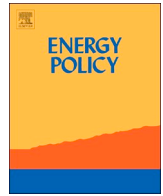
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## Transitioning towards negative CO<sub>2</sub> emissions

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### ABSTRACT

In this policy perspective we argue that mankind likely needs to achieve negative CO<sub>2</sub> emissions before 2050, describe the transition to CO<sub>2</sub>-neutrality and CO<sub>2</sub>-negativity, and illustrate the possibly critical role played herein by CO<sub>2</sub> use.

### 1. Introduction

In order to reach the 1.5 °C maximum temperature increase target of the Paris Agreement, either or not with a temporary overshoot of 2 °C during the 21<sup>st</sup> century, mankind has to achieve net zero CO<sub>2</sub> emissions in 2050 (IPCC, 2018). This conclusion by the IPCC Special Report on “Global Warming of 1.5 °C”, published in October 2018, has received ample attention in policy making circles and the media. Much less public consideration has been given to the fact that after 2050 substantial net negative CO<sub>2</sub> emissions need to be realized in order to comply with the ambition of not letting the average atmospheric temperature increase exceed 1.5 °C. A net negative balance of CO<sub>2</sub> emissions implies that more CO<sub>2</sub> has to be taken out of the atmosphere than human activities emit into it. We can think of at least six reasons why negative CO<sub>2</sub> emissions should perhaps already materialize before 2050.

First, least developed countries may not be able to achieve a net zero CO<sub>2</sub> economy by 2050, since the availability of cheap fossil fuels is today often still the fastest way to fulfill aspirations of stimulating growth and eradicating poverty. The possibly positive CO<sub>2</sub> emissions in 2050 of some developing countries need to be compensated by negative CO<sub>2</sub> emissions in developed countries, as industrialized nations are responsible for the lion's share of cumulative CO<sub>2</sub> emissions. Second, certain developed countries may fail to reach their net zero CO<sub>2</sub> emission reduction targets, e.g. as a result of a lack of internal political will to transform their economies away from fossil fuels, or because the inertia of the carbon lock-in proves too strong. Their net CO<sub>2</sub> emissions in 2050 must be counterbalanced by negative emissions from other developed countries. Third, in agriculture, forestry and land use

(AFOLU) it may be more difficult to reduce CO<sub>2</sub> emissions than in the use of fossil fuels and industry (FF&I). Net positive CO<sub>2</sub> emissions in 2050 in AFOLU need to be compensated by negative emissions in FF&I. Fourth, within FF&I, for some sectors like aviation and shipping it may be hard to achieve CO<sub>2</sub>-neutrality over the next 30 years. Their possibly remaining emissions by 2050 should be offset by negative CO<sub>2</sub> emissions in, for instance, the electricity sector where the switch to zero-CO<sub>2</sub> options is easier and less costly. Fifth, the assumption of net-zero CO<sub>2</sub> emissions strongly depends on substantial emission reductions for two other important greenhouse gases, CH<sub>4</sub> and N<sub>2</sub>O (IPCC, 2018), which are usually harder to control and more expensive to mitigate. A potential failure to achieve significant CH<sub>4</sub> and N<sub>2</sub>O emission reductions over the next few decades must be counterweighed by negative CO<sub>2</sub> emissions before 2050. Sixth, net CO<sub>2</sub>-neutrality in 2050 yields an approximately 70% probability of reaching the 1.5 °C goal of the Paris Agreement. If one wants to raise this probability to e.g. 90%, net CO<sub>2</sub> emissions need to be negative in less than 30 years.

The work by the IPCC heavily hinges on scenarios developed by integrated assessment models (IAMs; IPCC, 2018). The two main options available in most IAMs for implementing net zero or negative CO<sub>2</sub> emissions are (1) AFOLU, and (2) BECCS (biomass energy in combination with CO<sub>2</sub> capture and storage, or CCS). Thus far, IAMs have rarely accurately simulated a third category of methods for realizing net zero or negative CO<sub>2</sub> emissions, that is, processes that use CO<sub>2</sub> as main building block for the production of chemicals, hydrocarbons, materials, and plastics (often referred to as CO<sub>2</sub> capture and usage, or CCU). These alternatives can deliver a “circular carbon economy” (see, for instance, Stahel, 2016). In such an economy all carbon-based products are manufactured from renewable carbon feedstock, either via direct

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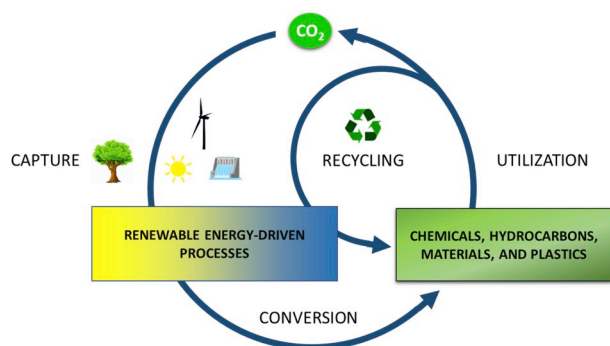


Fig. 1. An idealized circular carbon economy.

atmospheric CO<sub>2</sub> capture (also called direct air capture, or DAC; see Keith, 2009; Lackner et al., 2012), or indirectly via the conversion of waste or biomass derived from natural photosynthesis. We assume that the energy required to drive the capture, conversion, utilization, and recycling processes in an idealized circular carbon economy is provided by CO<sub>2</sub>-free renewable resources (see Fig. 1).

The use of CO<sub>2</sub> – or more generally the application of carbon circularity – for the production of chemicals, hydrocarbons, materials, and plastics is at present an activity of around 545 MtCO<sub>2</sub>/yr (mostly for the manufacturing of urea and biofuels, and the recycling of packaging; see Table 1; Aresta et al., 2013; Armstrong and Styring, 2015; Mikkelsen et al., 2010). This amount is negligible in comparison to today's level of around 38 GtCO<sub>2</sub>/yr anthropogenic CO<sub>2</sub> emissions. Based on potential average growth extrapolations drawn from the literature, we calculate that the level of CO<sub>2</sub> used in a circular carbon economy could become about 14 GtCO<sub>2</sub>/yr in 2050 (see Table 1, as well as the online appendix, in which we specify in detail all underlying assumptions). We determine this number by estimating the possible future demand of CO<sub>2</sub> for the production, in particular, of: (A) chemicals, such as alcohols (for instance methanol) and fertilizers (notably urea); (B) hydrocarbons like bitumen and tar e.g. for roads (and applications like roofing), but also fuels and lubricants e.g. for transport (such as in trucks, ships, and planes) (C) materials for construction (e.g. CaCO<sub>3</sub> and MgCO<sub>3</sub> for concrete); and inorganic salts (e.g. Na<sub>2</sub>CO<sub>3</sub>); and (D) a large variety of plastics and fibers for packaging, textiles, and construction (including e.g. machinery) part of which ends up in landfill. The (short cyclic) fabrication plus use processes behind most carbon-based products listed in Table 1 can lead to net zero CO<sub>2</sub> emissions (here called 'type I'). A share of the utilized CO<sub>2</sub> is stored in products for at least decades – usually centuries or more – and thus offers a potential for (long cyclic) negative CO<sub>2</sub> emissions (called 'type II'). We argue that the numbers listed in Table 1 ought to be accounted for in IAMs if these models are to adequately inform policy makers regarding the feasibility of reaching the Paris Agreement (cf. Gasser et al., 2015; Andersen and Peters, 2016; Kätelhön et al., 2019).

In Fig. 2 we show how the demand for CO<sub>2</sub> in a gradually more circular carbon economy could grow from 545 MtCO<sub>2</sub>/yr today to 14

GtCO<sub>2</sub>/yr in 2050 (depicted on the positive y-axis as the sum of our four categories, including both type I and II use). Four main options can supply the CO<sub>2</sub> required to meet this demand (shown on the negative y-axis): biomass, DAC, large CO<sub>2</sub> point sources (fossil fuel based or in industry), and recycling and waste streams (see the online appendix for our underlying assumptions). For each of these alternatives we assume feasible growth rates, such that supply matches demand. The first two options capture CO<sub>2</sub> from the atmosphere and yield net zero or negative CO<sub>2</sub> emissions. The third option adds CO<sub>2</sub> from fossil resources or minerals to the economy and at best involves net zero CO<sub>2</sub> emissions – although attractive for early CO<sub>2</sub> use projects, this route should ultimately be limited to nearly unavoidable emissions (e.g. from cement plants). The fourth option prevents additional release of CO<sub>2</sub> into the atmosphere by reusing, recycling, and reconverting carbon-based products before incineration, and thereby lowers the overall demand for CO<sub>2</sub>.

The circular carbon economy that we project for 2050 can yield negative CO<sub>2</sub> emissions, as demonstrated in Fig. 3 illustrating the CO<sub>2</sub> streams captured, converted, and utilized in processes driven by renewable energy. Chemicals, hydrocarbons, materials, and plastics – that can be produced via many kinds of conversion methods (Ampelli et al., 2015; Bazzanella and Ausfelder, 2017; Detz et al., 2018; GCCSI, 2011) – can jointly store CO<sub>2</sub> at a level of about 14 GtCO<sub>2</sub>/yr, either temporarily or on a longer time scale. Emissions of CO<sub>2</sub> can result from combustion, decomposition, and incineration of these products over starkly diverging timeframes. Some products can be recycled after a relatively short lifetime, while others store CO<sub>2</sub> for centuries or more. If the quantity of CO<sub>2</sub> stored annually in products exceeds the amount of CO<sub>2</sub> produced from remaining fossil fuel usage and industry, the atmospheric CO<sub>2</sub> concentration decreases, in our case by 2 GtCO<sub>2</sub>/yr. Changes in AFOLU, as well as the realization of BECCS, could further lower the ambient CO<sub>2</sub> concentration.

Different IAMs adopt broadly varying realizations of AFOLU and BECCS to achieve net negative CO<sub>2</sub> emissions, as exemplified by the four pathways (P1 to P4) described in IPCC (2018). In Fig. 4 we show how global net CO<sub>2</sub> emissions could become negative before 2050 if one gradually transitions towards the circular carbon economy described above. We assume that CO<sub>2</sub> emissions from fossil fuels and industry reduce significantly (but not down to zero) thanks to zero-carbon options like renewables and CCS, energy efficiency, and CO<sub>2</sub> use (the latter e.g. via renewable transport fuels; see pathways P2, P3 and P4 in IPCC, 2018). We also assume that as a result of sustainability practices, CO<sub>2</sub> emissions from AFOLU decline to zero by 2050 (see pathway P4 in IPCC, 2018), while BECCS by then yields negative emissions of 2 GtCO<sub>2</sub>/yr (in line with pathway P2 in IPCC, 2018). We suppose that also CO<sub>2</sub> use delivers a net effect of negative emissions in 2050 at a level of 2 GtCO<sub>2</sub>/yr, in accordance with Fig. 3. In this overall projection, net negative CO<sub>2</sub> emissions of around 2 GtCO<sub>2</sub>/yr are reached before 2050. Although the use of CO<sub>2</sub> today is small in comparison to total anthropogenic CO<sub>2</sub> emissions (Abanades et al., 2017; MacDowell et al., 2017), in our scenario a circular carbon economy would make a meaningful contribution to achieving CO<sub>2</sub>-neutrality before 2050.

Table 1  
Potential for carbon-based products with CO<sub>2</sub> (equivalents) as feedstock.

Main categories	Subcategories	CO <sub>2</sub> demand (MtCO <sub>2</sub> /yr)			References
		2015	2050 type I	2050 type II	
Chemicals	Alcohols and fertilizers	145	1200		(Alvarado, 2016; IFA, 2017; OCI, 2016)
	Hydrocarbons	Bitumen and tar	< 1	1100	
Materials	Fuels and lubricants	240	6500		(IRENA, 2018; Lindemann, 2018; Shell, 2018)
	Plastics	Concrete and salts	30	2000	
Plastics	Packaging and textiles	41	1900		(Sandalow et al., 2017; Scrivener et al., 2016; Zevenhoven et al., 2006)
	Construction and landfill	89	900		
<b>Total</b>		<b>545</b>	<b>9600</b>	<b>4000</b>	<b>13600 MtCO<sub>2</sub>/yr in 2050</b>

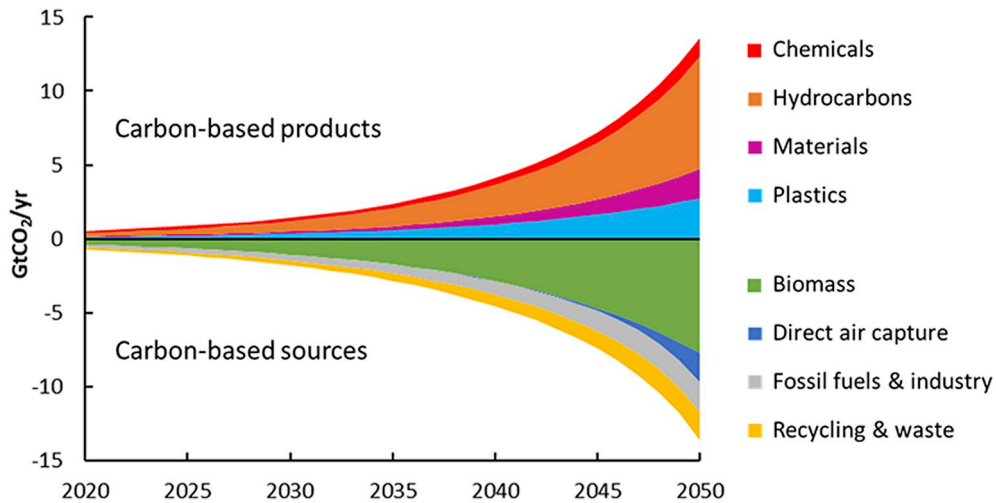


Fig. 2. Projected growth of CO<sub>2</sub> demand and supply.

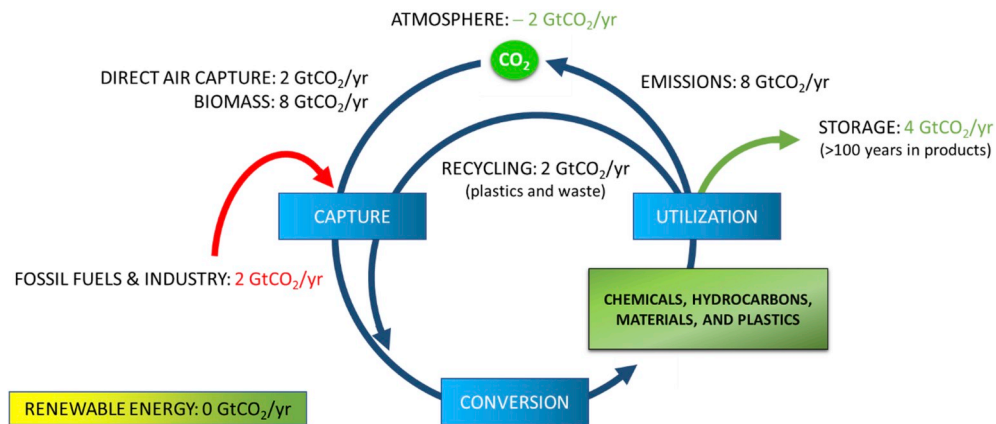


Fig. 3. Main elements of a circular carbon economy in 2050 with net negative CO<sub>2</sub> emissions.

In conclusion, we argue that mankind should prepare for achieving net negative CO<sub>2</sub> emissions before 2050. Observations that during recent years global greenhouse gas emissions have been increasing reinforces this view. We here have shown that CO<sub>2</sub> use can contribute meaningfully to achieving net negative CO<sub>2</sub> emissions before 2050. The technical means to do so, while available on the drawing board and in laboratories, cannot yet readily be scaled up to the required volumes.

We therefore recommend to step up RD&D efforts into a broad set of CO<sub>2</sub> use processes, to determine which approaches work best and can operate with the lowest possible cost, energy penalty, and environmental impact (Artz et al., 2018; Detz et al., 2018; van der Giesen and Kramer, 2014). The broader societal requirements and implications of CO<sub>2</sub> use also need to be studied in depth and from a multidisciplinary perspective. Such research may confirm that more opportunity for

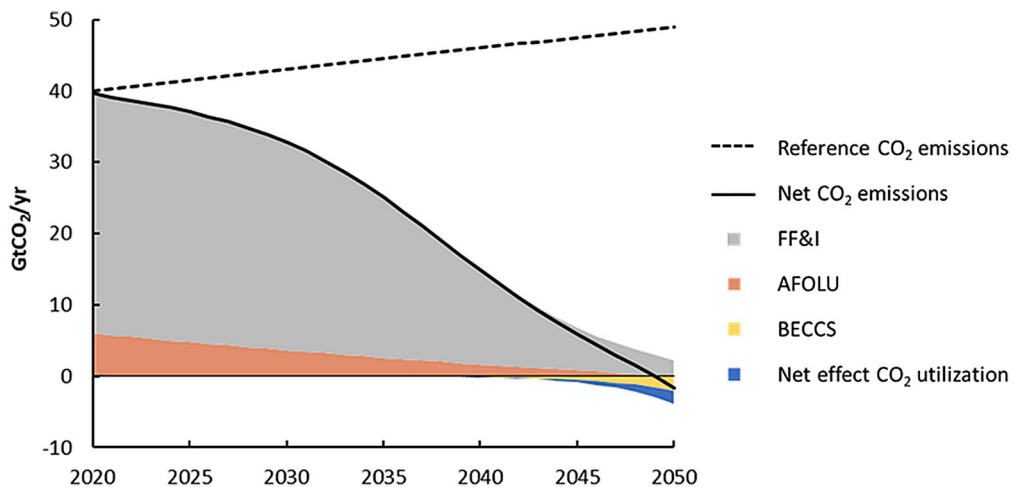


Fig. 4. Transitioning to global net negative CO<sub>2</sub> emissions with a contribution from CO<sub>2</sub> use.

reaching negative CO<sub>2</sub> emissions is available than currently assumed in IAMs if one accounts for all possible CO<sub>2</sub> use processes.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.enpol.2019.110938>.

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