



Negative emissions and international climate goals—learning from and about mitigation scenarios

Jérôme Hilaire^{1,2} · Jan C. Minx^{1,3} · Max W. Callaghan¹ · Jae Edmonds⁴ ·
Gunnar Luderer² · Gregory F. Nemet⁵ · Joeri Rogelj^{6,7,8} · Maria del Mar Zamora¹

Received: 27 December 2017 / Accepted: 8 August 2019
© The Author(s) 2019

Abstract

For aiming to keep global warming well-below 2 °C and pursue efforts to limit it to 1.5 °C, as set out in the Paris Agreement, a full-fledged assessment of negative emission technologies (NETs) that remove carbon dioxide from the atmosphere is crucial to inform science-based policy making. With the Paris Agreement in mind, we re-analyse available scenario evidence to understand the roles of NETs in 1.5 °C and 2 °C scenarios and, for the first time, link this to a systematic review of findings in the underlying literature. In line with previous research, we find that keeping warming below 1.5 °C requires a rapid large-scale deployment of NETs, while for 2 °C, we can still limit NET deployment substantially by ratcheting up near-term mitigation ambition. Most recent evidence stresses the importance of future socio-economic conditions in determining the flexibility of NET deployment and suggests opportunities for hedging technology risks by adopting portfolios of NETs. Importantly, our thematic review highlights that there is a much richer set of findings on NETs than commonly reflected upon both in scientific assessments and available reviews. In particular, beyond the common findings on NETs underpinned by dozens of studies around early scale-up, the changing shape of net emission pathways or greater flexibility in the timing of climate policies, there is a suite of “niche and emerging findings”, e.g. around innovation needs and rapid technological change, termination of NETs at the end of the twenty-first century or the impacts of climate change on the effectiveness of NETs that have not been widely appreciated. Future research needs to explore the role of climate damages on NET uptake, better understand the geophysical constraints of NET deployment (e.g. water, geological storage, climate feedbacks), and provide a more systematic assessment of NET portfolios in the context of sustainable development goals.

Keywords Negative emission · Carbon dioxide removal · Systematic evidence synthesis · Integrated assessment model · 1.5 °C · 2 °C

Electronic supplementary material The online version of this article (<https://doi.org/10.1007/s10584-019-02516-4>) contains supplementary material, which is available to authorized users.

✉ Jérôme Hilaire
hilaire@pik-potsdam.de

Extended author information available on the last page of the article

1 Introduction

Fast dwindling carbon budgets are stimulating a lively debate on the role of negative emission technologies (NETs¹) for keeping warming below 1.5 °C and 2 °C, as illustrated by a growing number of scientific and policy discussions on the subject (Fuss et al. 2014; Geden 2015; Lomax et al. 2015; Gasser et al. 2015; Anderson 2015; Lewis 2015; Williamson 2016; Anderson and Peters 2016; Lackner 2016; Field and Mach 2017; Parson 2017; Peters and Geden 2017; Geden and Löschel 2017; van Vuuren et al. 2017; Obersteiner et al. 2018; Scott and Geden 2018). At the heart of these discussions lays new evidence from long-term climate change mitigation scenarios generated with integrated assessment models (IAMs) as summarized in recent assessments by the Intergovernmental Panel on Climate Change (Bruckner et al. 2014; Clarke et al. 2014; IPCC 2014; Kunreuther et al. 2014; Smith et al. 2014; Stavins et al. 2014).

The Fifth Assessment Report (AR5) by IPCC Working Group 3 (WG3) provided a good overview of the role of NETs for stringent climate stabilization targets. It highlighted that many 2 °C scenarios entail large-scale deployment of NETs after 2050 to compensate for residual CO₂ emissions from sectors that are difficult to decarbonize, such as industry and aviation. It warned that these scenarios are mostly associated with a temporary overshoot of the climate goal and that delays in climate action and limitations in the availability of NETs can render the 2 °C goal infeasible. It also emphasized the challenges (e.g. societal concerns), risks (e.g. technological availability, biodiversity, water, food prices, inter-generational impacts) and uncertainties (e.g. geological storage, large bioenergy production) surrounding these technologies (see also [Electronic Supplementary Material \(ESM\)](#) for a complete review of NET statements in AR5).

Yet, the analysis of NETs in WG3 AR5 remained inaccessible because findings were scattered in various sections and sub-sections of the report (i.e. in Chaps. 2, 6, 7, 11, 13).

The recent IPCC Special Report on Global Warming of 1.5 °C (SR1.5) (IPCC 2018) filled this gap by drawing upon a set of recent reviews (Minx et al. 2018; Fuss et al. 2018; Nemet et al., 2018) that used formal methods of evidence synthesis. It further added a comprehensive analysis on the role of NETs in 1.5 °C scenarios based on newly emerging evidence. The report highlighted that all 1.5 °C scenarios with limited or no overshoot require NETs on the order of 100–1000 GtCO₂ over the twenty-first century but that significant near-term emissions reductions (e.g. low energy demand, low material consumption, low GHG-intensive food consumption) can limit NET deployment to a few hundred GtCO₂ without reliance on Bioenergy with Carbon Capture and Storage (BECCS). It also called attention to the lack of published pathways featuring NETs other than afforestation and reforestation (AR) and BECCS (see also [Electronic Supplementary Material \(ESM\)](#) for a complete review of NET statements in Fuss et al. 2018, IPCC 2018 and Rogelj et al. 2018b).

Despite all this progress in the understanding of NETs, the assessment practice on scenario evidence remains unsatisfactory. In particular, the imbalance in systematicity between the treatment of quantitative and qualitative findings is concerning. On the one hand, pathways are extracted from various studies, pulled together in a large database and analysed in a complete

¹ In this review, we consider NET as any human action that removes CO₂ from the atmosphere. This definition includes: afforestation and reforestation (AR), bioenergy with carbon capture and storage (BECCS), biochar, direct air capture and carbon storage (DACCS), enhanced weathering (EW), ocean alkalisation (OA), ocean fertilisation (OF), soil carbon sequestration. See ESM for more details.

systematic fashion. On the other hand, the inclusion or exclusion of qualitative findings is left to the discretion of the expert review team. While analyses based on larger scenario ensembles are more robust and generate new synthetic insights, the lack of a systematic approach for qualitative evidence is problematic for at least three reasons. First, the absence of systematic methods overall in many circumstances leads to bias (Haddaway and Macura, 2018). Second, findings in reviews and scientific assessments cannot be traced back to all relevant studies. For instance, the sentence “CDR requirements are reduced under ‘sustainability’ related assumptions.” (Rogelj et al. 2018b, p. 149) only cites Strefler et al. (2018) while studies by Bertram et al. (2018) and van Vuuren et al. (2018) are equally relevant. In a similar vain, evidence resulting from the analysis of large databases—those created specifically for reviews and assessments—can be disconnected from original findings. These problems reduce the transparency of synthetic works, a crucial element of any systematic approach. Finally, we argue and will show in this article that the lack of systematicity also runs the risk of omitting important niche and newly emerging results.

To address these shortcomings with a view on the upcoming Sixth Assessment Report (AR6), we present here the first thematic review (Boyatzis 1998; Guest et al. 2012) of the available scenario literature on NETs; provide a comprehensive, traceable and easily updatable synthetic table of all statements on NETs; and re-analyse the most important ones quantitatively. The main novelty of our approach is that it links a systematic assessment of individual findings to the literature base and evidence from scenario data. As in any systematic approach, we describe the procedures to search and select the literature, to extract evidence and to evaluate the quality of included studies in a comprehensive and transparent manner (Petticrew and McCartney 2011; Minx et al. 2017a). Such a method provides a crucial synthetic account to inform upcoming climate change assessments. In particular, we contribute to the systematic assessment literature by developing and employing a computer-assisted method to review 138 studies on the subject in a comprehensive and transparent manner, allowing us to synthesize many qualitative findings. We complement this analysis by connecting it to a summary of the available quantitative evidence. Our review includes the rapidly emerging literature on the 1.5 °C limit (Luderer et al. 2013, 2018; Rogelj et al. 2015, 2018a, b; Manoussi et al. 2017; Marcucci et al. 2017; Mintenig et al. 2017; Bauer et al. 2018; Bertram et al. 2018; Holz et al. 2018; Kriegler et al. 2018a; Rickels et al. 2018; Strefler et al. 2018; Séférián et al. 2018; van Vuuren et al. 2018; Grubler et al. 2018) that include scenarios that emphasise the role of NETs even more than the 2 °C scenarios in AR5.

Importantly, our approach provides:

- a ready-to-use method for systematically reviewing the scenario literature;
- a comprehensive, traceable and easily updatable synthetic table that maps 1360 paragraphs from 138 studies related to NETs into 66 summary statements (see Excel spreadsheet in [ESM](#));
- a focused assessment of key evidence on the distinct role of NETs for limiting climate change to 1.5 °C and 2 °C, respectively (i.e. upscaling, maximum deployment, near-term mitigation trade-offs, role of socio-economic drivers, regional NET deployment);
- an improved understanding of how deployment dynamics change as multiple NETs get deployed in small portfolios.

In the next section, we review some key findings on NETs that are important to understand scenario results and are particularly useful for the discussions of the 1.5 °C and 2 °C limits. We

support this review with quantitative evidence on the dynamics of emission pathways, climate change mitigation costs, and regional CO₂ sequestration whilst giving some special attention to small NET portfolios. Throughout the analysis, we discuss relevant key assumptions as appropriate. We close by providing a more comprehensive overview of the landscape of findings and discuss major open avenues for research.

2 Main findings from the scenario literature

The statements on NETs that we synthesized from the available literature and that are relevant to the focus of this review are organized in Table 1. We refer to them in the remainder of this article by using their unique identifier (e.g. O1, see column ID in Table 1). The methodology employed to find each statement is detailed in the [ESM](#). It should be noted that in most mitigation scenarios, BECCS is the only explicit NET available.² Unless a statement is specific to a particular NET, we therefore consider BECCS as a proxy for NETs in the following discussion and as a result interpret its deployment as total NET deployment. Towards the end of this section, we explicitly consider portfolios with multiple NETs.

The literature highlights the importance of NETs for meeting stringent climate policy targets O1. This importance is illustrated by the large amounts of carbon withdrawn from the atmosphere in most 1.5 °C and 2 °C scenarios. In 85% of 2 °C scenarios (above 15th percentile), more than 300 Gt CO₂ are removed over the twenty-first century as long as no drastic GHG emission abatement, radical changes towards sustainable lifestyles, nor constraints on technological availability and climate policy timing are imposed (see Fig. 1a1 vs Fig. 1a2–a4). This estimate increases to nearly 500 in 1.5 °C scenarios with similar assumptions (Fig. 1a5).

Differences in cumulative carbon removal reflect qualitative differences in 1.5 °C and 2 °C scenarios. Global warming cannot be limited to 1.5 °C without NETs because the overshoot of the small carbon budget associated with this goal³—resulting from socio-economic inertias—must be offset by negative emissions (Fig. 1a) (Luderer et al. 2013; Rogelj et al. 2015; Strefler et al. 2018; Rogelj et al. 2018a; Kriegler et al. 2018b). In other words, in the absence of large-scale negative emissions, scenarios without draconian near-term CO₂ emission reductions are infeasible O11 (Fig. 1a6, see Table 2 for illustration). Even in recent 1.5 °C scenarios that explore goal achievement with minimum NETs, net negative emissions during the second half of the twenty-first century are required (Bertram et al. 2018; Holz et al. 2018; van Vuuren et al. 2018; Grubler et al. 2018) (Fig. 1a6). In contrast, a variety of 2 °C scenarios exist without any explicit NET deployment, although the near-term CO₂ emission reductions envisaged in these scenarios are more severe than when NETs are deployed (Fig. 1a2) (Krey et al. 2014; Kriegler et al. 2014; Iyer et al. 2015; Eom et al. 2015). Moreover, the global economy is fully decarbonised by the second half of the twenty-first century in 1.5 °C scenarios D2 with a sustained period of net negative emissions thereafter. The scale-up of NETs between 2030 and

² This is mostly the case for scenarios prior to AR5. New scenarios increasingly feature 2 or more NETs. In addition, the new scenario data reporting template from the Integrated Assessment Modelling Consortium now separates individual NET contributions (e.g. Carbon Sequestration|CCS|Biomass, Carbon Sequestration|Land Use|Afforestation, Carbon Sequestration|Land Use|Biochar, Carbon Sequestration|Direct Air Capture, Carbon Sequestration|Enhanced Weathering...).

³ To date, no publicly available scenario considers the much larger carbon budget estimate from Millar et al. (2017).

Table 1 Thirty-one of 66 qualitative findings retrieved from 138 selected studies and supporting the focus of this review, i.e. the role of NETs for international climate goals. Findings are clustered in 5 broad categories. Studies supporting each finding are provided and tagged in blue when they contain at least one 1.5 °C scenario and in red when they do not contain any 1.5 °C scenario but at least one 2 °C scenario. The 66 qualitative findings are available in the [Electronic Supplementary Material \(Table S3\)](#)

Category	ID	Name	Statement	Supporting tables and figures	# studies	References
Mitigation pathway dynamics	D1	Upscaling	Even though net negative emissions occur later in the twenty-first century, NETs require rapid and wide-spread upscaling in the near-term (2030–2050) and must be maintained at least until 2100.	Figure 1 b2 and b3	69	Azar et al. (2001), Obersteiner et al. (2002), Azar et al. (2006), Manne and Richels (2006), Rao and Rishi (2006), Solingen and Sedjo (2006), van Vuuren et al. (2006), Rishi et al. (2007), Strengers et al. (2008), Krey and Rishi (2009), van Vliet et al. (2009), Azar et al. (2010), Luckow et al. (2010), Klein et al. (2011), Lemoine et al. (2012), Ricci (2012), Chen and Tavoni et al. (2013), Edmonds et al. (2013), Fuss et al. (2013), Tavoni and Soclow (2013), van Vuuren et al. (2013), Aboumahboub et al. (2014), Bibas and Méjean (2014), Blanford et al. (2014b), Calvin et al. (2014), Humpenöder et al. (2014), Klein et al. (2014), Kober et al. (2014), Kriegler et al. (2014), Rose et al. (2014a), Selosse and Ricci (2014), van der Zwaan et al. (2013), Yamamoto et al. (2014), Daiglou et al. (2015), Eom et al. (2015), Kriegler et al. (2015a), Rishi et al. (2015), Bauer et al. (2016), Fujimori et al. (2016), Kriegler et al. (2016), Lebowitz et al. (2016), Luderer et al. (2016a), Luderer et al. (2016b), Vaughan and Gough (2016), Favero et al. (2017), Fricko et al. (2017), Gambhir et al. (2017), Manoussi et al. (2017), Marcucci et al. (2017), Mintenig et al. (2017), Popp et al. (2017), Tavoni et al. (2017), van Vuuren et al. (2017), Akimoto et al. (2018), Bertram et al. (2018), Holz et al. (2018), Kober et al. (2018), Luderer et al. (2018), Mousavi et al. (2018), Obersteiner et al. (2018), Rickels et al. (2018), Rogelj et al. (2018a, b), Sanchez et al. (2018), Séférian et al. (2018), Srefler et al. (2018), Tanaka and O'Neill (2018), van Vuuren et al. (2018), Vaughan et al. (2018), Winning et al. (2018)
Mitigation pathway dynamics	D2		The availability and use of NETs in models strongly affect net CO ₂ emission pathways. In a typical	Figure 1a	63	Obersteiner et al. (2002), Azar et al. (2006), Rao and Rishi (2006), Solingen and Sedjo (2006), van

Table 1 (continued)

Category	ID	Name	Statement	Supporting tables and figures	# studies	References
		Shape CO ₂ pathway	2 °C scenario in AR5, including NETs increase near-term net CO ₂ emissions (e.g. 2020–2050) and the speed of decarbonisation in the long-term (e.g. 2050–2100). Net CO ₂ emissions become eventually negative in the second half of the century.			Vuuren et al. (2006), Clarke et al. (2009), Krey and Riahi (2009), Azar et al. (2010), Leimbach et al. (2010), Luckow et al. (2010), Magné et al. (2010), Lemoine et al. (2012), Azar et al. (2013), Chen and Tavoni et al. (2013), Edmonds et al. (2013), Fuss et al. (2013), Tavoni and Soclow (2013), van Vuuren et al. (2013), Bibas and Méjean (2014), Blanford et al. (2014a), Blanford et al. (2014b), Bowen et al. (2014), Humpenöder et al. (2014), Klein et al. (2014), Kober et al. (2014), Krey et al. (2014), Kriegler et al. (2014), Rose et al. (2014b), Selosse and Ricci (2014), Tavoni et al. (2013), van der Zwaan et al. (2013), van Vliet et al. (2014), Eom et al. (2015), Iyer et al. (2015), Riahi et al. (2015), Schaeffer et al. (2015), Fujimori et al. (2016), Kriegler et al. (2016), Lebowitz et al. (2016), Luderer et al. (2016a), Muratori et al. (2016), Vaughan and Gough (2016), Bauer et al. (2017), Calvin et al. (2017), Fujimori et al. (2017), Gambhir et al. (2017), Kriegler et al. (2017), Marcucci et al. (2017), Mintenig et al. (2017), van Vuuren et al. (2017), Akinoto et al. (2018), Bertram et al. (2018), Holz et al. (2018), Lehtilä and Koljonen (2018), Méjean et al. (2018), Mousavi et al. (2018), Obersteiner et al. (2018), Rickels et al. (2018), Rogelj et al. (2018a, b), Tanaka and O'Neill (2018), van Vuuren et al. (2018), Vaughan et al. (2018), Winning et al. (2018)
Mitigation pathway dynamics	D4	Compensate	NETs can compensate for past and current GHG emissions. From a sectoral viewpoint it can offset emissions that arise from sectors and activities that are difficult to decarbonize, e.g. aviation. From a regional perspective, one or several regions can offset emissions from other regions. From a GHG emission point of view, it can offset non-CO ₂ emissions (e.g. CH ₄ from agriculture).		38	Azar et al. (2006), Luckow et al. (2010), Lemoine et al. (2012), Chen and Tavoni et al. (2013), Kriegler et al. (2013a), Tavoni and Soclow (2013), Blanford et al. (2014b), Humpenöder et al. (2014), Klein et al. (2014), Kober et al. (2014), Koehler et al. (2014), Kriegler et al. (2014), Selosse and Ricci (2014), van der Zwaan et al. (2013), Bosetti et al. (2015), Eom et al. (2015), Sanchez et al. (2015), Luderer et al. (2016a), Luderer et al. (2016b), Kriegler et al. (2017), Manoussi et al. (2017), Marcucci et al.

Table 1 (continued)

Category	ID	Name	Statement	Supporting tables and figures	# studies	References
Mitigation pathway dynamics	D5	Prolong fossil_fuels_use	By redirecting investments from low-carbon technologies to fossil fuel technologies, the availability and use of NETs allow the prolonged use of fossil fuels. Conversely, reducing the availability and use of NETs increase the number of stranded assets in the fossil fuel sector and requires a greater deployment of low-carbon technologies.		30	(2017), Minnenig et al. (2017), van Vuuren et al. (2017), Akimoto et al. (2018), Heck et al. (2018), Holz et al. (2018), Keller et al. (2018), Kober et al. (2018), Luderer et al. (2018), Méjean et al. (2018), Mousavi et al. (2018), Rickels et al. (2018), Rogelj et al. (2018a, b), Séférian et al. (2018), Su et al. (2018), van Vuuren et al. (2018), Vaughan et al. (2018) Azar et al. (2006), Solingen and Sedjo (2006), Krey and Riahi (2009), van Vliet et al. (2009), Luckow et al. (2010), Lemoine et al. (2012), Ricci (2012), Chen and Tavoni et al. (2013), Fuss et al. (2013), Kriegler et al. (2013a), Bibas and Méjean (2014), Blanford et al. (2014a), Blanford et al. (2014b), Karudia et al. (2014), Klein et al. (2014), Krey et al. (2014), Kriegler et al. (2014), Rose et al. (2014a), Riahi et al. (2015), Sanchez et al. (2015), Bauer et al. (2016), Muratori et al. (2016), Calvin et al. (2017), Kriegler et al. (2017), Marcucci et al. (2017), Minnenig et al. (2017), van Vuuren et al. (2017), Luderer et al. (2018), Séférian et al. (2018), Wining et al. (2018)
Mitigation pathway dynamics	D6	Flexibility	NETs allow for a greater flexibility in the timing of mitigation policies.	Figure 1a2	25	Oberschneider et al. (2002), Azar et al. (2006), Solingen and Sedjo (2006), Krey and Riahi (2009), van Vliet et al. (2009), Azar et al. (2010), Lemoine et al. (2012), Blanford et al. (2014a), Blanford et al. (2014b), Klein et al. (2014), Krey et al. (2014), Kriegler et al. (2014), McCollum et al. (2014), Rose et al. (2014a), Selsos and Ricci (2014), Tavoni et al. (2013), Bertram et al. (2015), Bosetti et al. (2015), Eom et al. (2015), Riahi et al. (2015), Marcucci et al. (2017), Minnenig et al. (2017), van Vuuren et al. (2017), Bertram et al. (2018), Vaughan et al. (2018)
Mitigation pathway dynamics	D7	Regional_distribution	The regional distribution of NET deployment vary greatly across models, depending on modelling assumptions (e.g. regional baselines, regional abatement potentials, available technology options, techno-economic parameters) and model	Figure 3	25	Solingen and Sedjo (2006), van Vuuren et al. (2006), Tavoni et al. (2007), Strengers et al. (2008), Calvin et al. (2009), Krey and Riahi (2009), Lembach et al. (2010), Chen and Tavoni et al. (2013), Tavoni and Soclow (2013), Calvin et al.

Table 1 (continued)

Category	ID	Name	Statement	Supporting tables and figures	# studies	References
Mitigation pathway dynamics	D8	CO ₂ emission reduction	structures. Regions well-endowed with biomass and/or geological storage have a competitive advantage over others. Consequently, afforestation/reforestation is mostly carried out in tropical regions (Africa, Latin America). BECCS is mainly deployed in China, Europe, USA. DAC is mostly used in regions with large storage potentials like Middle East, North Africa, Russia. Limits on geological storage strongly affect these results.		22	(2014), Humpenöder et al. (2014), Kober et al. (2014), Popp et al. (2014), Selosse and Ricci (2014), Tavoni et al. (2013), van Sluisveld et al. (2013), Eom et al. (2015), Leibowicz et al. (2016), Mouratiadou et al. (2016), Calvin et al. (2017), Marucci et al. (2017), Tavoni et al. (2017), Sanchez et al. (2018), Séférian et al. (2018), Vaughan et al. (2018)
			Gross CO ₂ emission reductions rates have been scarcely reported in the past but remain central to climate action. Mid-term gross CO ₂ emission reduction rates envisaged in scenarios have no historical precedence. When NETs are unavailable, emission reductions must occur earlier and more rapidly over the century. Conversely, when NETs are available, emission reductions are postponed. Current national climate actions (NDCs) remain insufficient to satisfy the climate targets of the PA without a high dependency on NETs.			Luckow et al. (2010), Lemoine et al. (2012), van Vuuren et al. (2013), Kriegler et al. (2014), Eom et al. (2015), Iyer et al. (2015), Kriegler et al. (2015c, 2016), Luderer et al. (2016a), Luderer et al. (2016b), Mintenig et al. (2017), van Vuuren et al. (2017), Bertram et al. (2018), Grubler et al. (2018), Holz et al. (2018), Luderer et al. (2018), Mousavi et al. (2018), Rogelj et al. (2018a, b), Séférian et al. (2018), Streeter et al. (2018), van Vuuren et al. (2018), Winning et al. (2018)
Mitigation pathway dynamics	D9	Postpone CO ₂ abatement	The anticipated availability and use of NETs can be used as a reason to postpone near-term climate action.		18	Azar et al. (2006), Krey and Riahi (2009), van Vliet et al. (2009), Lemoine et al. (2012), Azar et al. (2013), Chen and Tavoni et al. (2013), Fuss et al. (2013), Tavoni and Socolow (2013), van Vuuren et al. (2013), Klein et al. (2014), Kriegler et al. (2014), Selosse and Ricci (2014), Luderer et al. (2016a), Marucci et al. (2017), Mintenig et al. (2017), van Vuuren et al. (2017), Holz et al. (2018), Luderer et al. (2018)
			Bioenergy is not only used in BECCS. It is a standalone low-carbon energy option that is cost-effective in ambitious climate scenarios. It is particularly attractive in the transportation sector where it provides the only cost-effective alternative to oil. Consequently, without limits on its production and irrespective of the deployment of BECCS, bioenergy is greatly used in 1.5 °C and 2 °C scenarios.			Oberschneider et al. (2002), Luckow et al. (2010), Klein et al. (2011), Kriegler et al. (2013a), Bibas and Méjean (2014), Popp et al. (2014), Selosse and Ricci (2014), Daigoul et al. (2015), Bauer et al. (2017), Mintenig et al. (2017), Popp et al. (2017), van Vuuren et al. (2017), Luderer et al. (2018), Séférian et al. (2018)

Table 1 (continued)

Category	ID	Name	Statement	Supporting tables and figures	# studies	References
Mitigation pathway dynamics	DI1	Carbon_budget	The availability and use of NETs effectively increase the available carbon budget. This is because NETs can offset CO ₂ emissions, thus allowing for a temporary overshoot of the carbon budget in the near-term and removal of excess carbon later. Under a continuation of current socio-economic trends, this offset amounts to hundreds of GtCO ₂ in 1.5C and 2C scenarios.		13	Azar et al. (2006), Klein et al. (2011), van Vuuren et al. (2013), Koelbl et al. (2014), Luderer et al. (2016b), Manoussi et al. (2017), Mintenig et al. (2017), Tavoni et al. (2017), Holz et al. (2018), Kober et al. (2018), Lehtilä and Koljonen (2018), Luderer et al. (2018), Rickels et al. (2018)
Mitigation costs	C1	Lower_costs	The availability and use of NET lower carbon prices and so decrease aggregated discounted mitigation costs. Any techno-economic limitations of NETs would result in an increase of mitigation costs (e.g. biomass limitations for BECCS)	Table 2	48	Obersteiner et al. (2002), Azar et al. (2006), Rao and Riah (2006), Tavoni et al. (2007), van Vuuren et al. (2007), Keller et al. (2008), Clarke et al. (2009), Krey and Riah (2009), van Vliet et al. (2009), Wise et al. (2009), Azar et al. (2010), Leimbach et al. (2010), Lemoine et al. (2012), Ricci (2012), Azar et al. (2013), Chen and Tavoni et al. (2013), Edmonds et al. (2013), Fuss et al. (2013), Kriegler et al. (2013a), Tavoni and Soclow (2013), Bibas and Méjean (2014), Blanford et al. (2014a), Klein et al. (2014), Koelbl et al. (2014), Krey et al. (2014), Kriegler et al. (2014), Rose et al. (2014a), Selsos and Ricci (2014), van Vliet et al. (2014), Bosetti et al. (2015), Eom et al. (2015), Iyer et al. (2015), Sanchez et al. (2015), Kreidenweis et al. (2016), Muratori et al. (2016), Vaughan and Gough (2016), Deng et al. (2017), Gambhir et al. (2017), Marucci et al. (2017), Mintenig et al. (2017), Su et al. (2017), Bertram et al. (2018), Luderer et al. (2018), Mori et al. (2018), Seferian et al. (2018), Strefler et al. (2018), van Vuuren et al. (2018), Winning et al. (2018)
Mitigation costs	C2	High_carbon_price	Compared to other mitigation technologies, BECCS is a relatively costly option. Hence it requires a high carbon price (> US\$100) for upscaling.		37	Azar et al. (2001), Obersteiner et al. (2002), Azar et al. (2003), Makihira et al. (2003), Azar et al. (2006), Keith et al. (2006), Sohngen and Sedjo (2006), van Vuuren et al. (2007), Canadell and Raupach (2008), Strengers et al. (2008), Calvin et al. (2009), Clarke et al. (2009), Krey and Riah (2009), Luckow et al. (2010), Chen and Tavoni et al. (2013), Edmonds et al. (2013), Fuss et al. (2013), Tavoni and Soclow (2013), van

Table 1 (continued)

Category	ID	Name	Statement	Supporting tables and figures	# studies	References
Technology specific	T1	Potential	Scenarios allow to explore the cost-effective potential of NETs. Studies show that AR, BECCS and DACCS can capture hundreds of GtCO ₂ over the 21st, the annual removal rate of AR is around 0–10 GtCO ₂ /yr, whereas that of BECCS and DACCS is around 0–20 GtCO ₂ /yr. However a number of environmental, governance, legal, political and social challenges could reduce these potentials.	Figure 3	50	Vuuren et al. (2013), Humpenöder et al. (2014), Klein et al. (2014), Popp et al. (2014), Selosse and Ricci (2014), van Vliet et al. (2014), Yamamoto et al. (2014), Daiglou et al. (2015), Kriegler et al. (2015a), Kreidenweis et al. (2016), Muratori et al. (2016), Vaughan and Gough (2016), Favero et al. (2017), Fricko et al. (2017), Gambhir et al. (2017), Marcucci et al. (2017), Luderer et al. (2018), Sanchez et al. (2018), Séférian et al. (2018) Schlamadinger et al. (2001), Azar et al. (2003), Makihira et al. (2003), Mame and Richels (2006), Rao and Riahi (2006), Solingen and Sedjo (2006), van Vuuren et al. (2006), van Vuuren et al. (2007), Canadell and Raupach (2008), Strengers et al. (2008), Krey and Riahi (2009), Klein et al. (2011), Chen and Tavoni et al. (2013), Edmonds et al. (2013), Fuss et al. (2013), Tavoni and Socolow (2013), van Vuuren et al. (2013), Bibas and Méjean (2014), Blanford et al. (2014a), Calvin et al. (2014), Humpenöder et al. (2014), Klein et al. (2014), Kriegler et al. (2014), Popp et al. (2014), Selosse and Ricci (2014), van der Zwaan et al. (2013), Daiglou et al. (2015), Kriegler et al. (2015a), Fujimori et al. (2016), Kreidenweis et al. (2016), Leibowicz et al. (2016), Vaughan and Gough (2016), Favero et al. (2017), Fujimori et al. (2017), Mintenig et al. (2017), Tavoni et al. (2017), van Vuuren et al. (2017), Heck et al. (2018), Holz et al. (2018), Keller et al. (2018), Kober et al. (2018), Lehtilä and Koljonen (2018), Luderer et al. (2018), Rickels et al. (2018), Sanchez et al. (2018), Séférian et al. (2018), Strefler et al. (2018), van Vuuren et al. (2018), Winning et al. (2018)
Technology specific	T3	Food price	The deployment of BECCS increases food prices due to land competition between energy and food biomass feedstocks. However food prices would still be high without BECCS because other		26	Riahi et al. (2007), Azar et al. (2010), Azar et al. (2013), Edmonds et al. (2013), Kriegler et al. (2013a), Tavoni and Socolow (2013), Bibas and Méjean (2014), Blanford et al. (2014a), Calvin

Table 1 (continued)

Category	ID	Name	Statement	Supporting tables and figures	# studies	References
Technology specific	T5	BECCS_Versatile	BECCS is a versatile technology that can generate a variety of energy types (e.g. electricity, synthetic liquid fuels, hydrogen) from diverse biomass feedstocks (e.g. crops, grass, wood).	bioenergy-based mitigation technologies would increase in importance.	13	et al. (2014), Klein et al. (2014), Popp et al. (2014), Selosse and Ricci (2014), Kreidenweis et al. (2016), Muratori et al. (2016), Vaughan and Gough (2016), Favero et al. (2017), Mintenig et al. (2017), Popp et al. (2017), Tavoni et al. (2017), van Vuuren et al. (2017), Bertan et al. (2018), Emori and Takahashi (2018), Obersteiner et al. (2018), Séfrian et al. (2018), van Vuuren et al. (2018), Yamagata et al. (2018)
						Obersteiner et al. (2002), Azar et al. (2003), Riahi et al. (2007), Azar et al. (2010), Klein et al. (2011), Humpenöder et al. (2014), Klein et al. (2014), Rose et al. (2014a), Fujimori et al. (2016), Muratori et al. (2016), Bauer et al. (2017), Mintenig et al. (2017), Vaughan et al. (2018)
Technology specific	T9	Technological_change	Technological change is crucial to any technology and will be needed to push NETs to the commercial stage. This process could take decades and could be hampered if diffusion in developing regions follows past trends.		7	Azar et al. (2001), Makihira et al. (2003), Rao and Rathi (2006), Luckow et al. (2010), Lemoine et al. (2012), Leibowicz et al. (2016), van Vuuren et al. (2017)
						Obersteiner et al. (2001), Schlamadinger et al. (2001), Sohngen and Sedjo (2006), Tavoni et al. (2007), Canadell and Raupach (2008), Keller et al. (2008), Luckow et al. (2010), Chen and Tavoni et al. (2013), Krieger et al. (2013a), Tavoni and Socolow (2013), Bibas and Méjean (2014), Blanford et al. (2014a), Calvin et al. (2014), Calvin et al. (2014), Humpenöder et al. (2014), Popp et al. (2014), Sands et al. (2014), Selosse and Ricci (2014), Fujimori et al. (2016), Kreidenweis et al. (2016), Vaughan and Gough (2016), Manoussi et al. (2017), Mintenig et al. (2017), Popp et al. (2017), Tavoni et al. (2017), van Vuuren et al. (2017), Heck et al. (2018), Holz et al. (2018), Keller et al. (2018), Lehtilä and Koljonen (2018), Luderer et al. (2018), Obersteiner et al. (2018), Rickels et al. (2018), Rogelj et al. (2018a, b), Séfrian et al. (2018), Streffer et al. (2018), van Vuuren et al. (2018),
Earth System/NET interactions	E1	Environmental_impacts	The large-scale deployment of NETs will impact the environment. This is particularly true for land-based CDR which strongly interacts with a number of environmental factors (e.g. air, natural ecosystems, soils, water bodies). The large-scale deployment of AR and BECCS could lead to biodiversity and natural ecosystems loss, increased eutrophication resulting from fertilisation with nitrogen, water shortages, and a variety of climate impacts and feedbacks.		38	

Table 1 (continued)

Category	ID	Name	Statement	Supporting tables and figures	# studies	References
Earth System/NET interactions	E3	Climate_feedbacks	CDR could lead to different climate dynamics than with GHG emission reductions because negative emissions would drive the climate system in a different direction. In addition CDR induces a number of negative feedbacks such as changes in precipitation patterns, ocean outgassing. Ocean outgassing, that is the release of CO ₂ from the oceans back to the atmosphere, would reduce the effectiveness of CDR but would decrease ocean acidification.		10	Vaughan et al. (2018) Chen and Tavoni et al. (2013), Fuss et al. (2013), Tavoni and Soclow (2013), van Vuuren et al. (2013), Blanford et al. (2014b), Manoussi et al. (2017), Tavoni et al. (2017), Keller et al. (2018), Obersteiner et al. (2018), Rickels et al. (2018)
Earth System/NET interactions	E4	Tipping_points	Temperature overshoot associated with NET deployments increasing the risks of triggering climate tipping points. High temperature overshoot decreases the probability of meeting climate targets.		8	Azar et al. (2006), Lemoine et al. (2012), Tavoni and Soclow (2013), Blanford et al. (2014b), Mintenig et al. (2017), Heck et al. (2018), Obersteiner et al. (2018), Ströfler et al. (2018)
Earth System/NET interactions	E6	Climate_impacts	Climate change could impact NETs thereby reducing their effectiveness. In a warming climate the increased risks of droughts and fires could limit the potential of land-based CDR such as afforestation and BECCS.		5	Vaughan and Gough (2016), Favero et al. (2017), Popp et al. (2017), Keller et al. (2018), Lehtilä and Koljonen (2018)
Earth System/NET interactions	E7	Carbon_cycle	The carbon cycle is a complex dynamic system that needs to be accounted for in IAMs. The lifetime of CO ₂ in the atmosphere has an effect on the optimal level of deployment of NETs.		4	Azar et al. (2006), Blanford et al. (2014b), Keller et al. (2018), Rickels et al. (2018)
Earth System/NET interactions	E10	Substitution_effect	There is a substitution effect between emission reduction and CDR, and the extra CDR required to compensate for carbon cycle feedbacks.		1	Rickels et al. (2018)
Others	O1	Important	NETs are often reported important technological options for stringent climate goals such as the temperature goals of the Paris Agreement (i.e. 1.5 °C, well-below 2 °C). The reasons are: effectiveness of reaching these targets and lower mitigation costs.		79	Azar et al. (2001), Obersteiner et al. (2002), Azar et al. (2006), Rao and Rahi (2006), Sohngen and Sedjo (2006), Rahi et al. (2007), Tavoni et al. (2007), van Vuuren et al. (2007), Blanford et al. (2009), Clarke et al. (2009), Krey and Rahi (2009), van Vliet et al. (2009), Azar et al. (2010), Edenhofer et al. (2010), Leimbach et al. (2010), Luckow et al. (2010), Klein et al. (2011), Lemoine et al. (2012), Azar et al. (2013), Chen and Tavoni et al. (2013), Edmonds et al. (2013), Fuss et al. (2013), Kriegler et al. (2013a), Luderer et al. (2013), Tavoni and Soclow

Table 1 (continued)

Category	ID	Name	Statement	Supporting tables and figures	# studies	References
Others	O2	Risk	Planning for large-scale NET deployment while postponing near-term GHG abatement, as in most 2C scenarios showed in AR5 could turn out to be an ineffective tool for reducing climate risk. The associated overshoot in GHG concentration (and perhaps temperature) would increase the risk of not meeting the PA targets and potentially lead to climate change irreversibility. This is all the more relevant given the large dependence envisaged in these scenarios. From a socio-economic perspective, NETs add another layer of risks by increasing competition for land, water, energy and financial resources.		26	(2013), Bibas and Méjean (2014), Calvin et al. (2014), Griffin et al. (2014), Humpeöder et al. (2014), Johnson et al. (2014), Klein et al. (2014), Koelbl et al. (2014), Krey et al. (2014), Krieger et al. (2014), Luderer et al. (2014), McCollum et al. (2014), Popp et al. (2014), Rose et al. (2014a), Sands et al. (2014), Selosse and Ricci (2014), van der Zwaan et al. (2013), van Sluisveld et al. (2013), van Vliet et al. (2014), Bertram et al. (2015), Bosetti et al. (2015), Daioglou et al. (2015), Eom et al. (2015), Calvin et al. (2016a), Kreidenweis et al. (2016), Leibowicz et al. (2016), Luderer et al. (2016b), Vaughan and Gough (2016), Favero et al. (2017), Manoussi et al. (2017), Marucci et al. (2017), Mintenig et al. (2017), Popp et al. (2017), Riahi et al. (2017), Selosse and Ricci (2017), Tavoni et al. (2017), van Vuuren et al. (2017), Akimoto et al. (2018), Bertram et al. (2018), Heck et al. (2018), Holz et al. (2018), Keller et al. (2018), Lehtilä and Koljonen (2018), Luderer et al. (2018), Méjean et al. (2018), Mori et al. (2018), Mousavi et al. (2018), Rickels et al. (2018), Rogelj et al. (2018a, b), Sanchez et al. (2018), Séférian et al. (2018), Streifer et al. (2018), van Vuuren et al. (2018), Vaughan et al. (2018), Winning et al. (2018) Obersteiner et al. (2002), Azar et al. (2006), Lemoine et al. (2012), Ricci (2012), Chen and Tavoni et al. (2013), Fuss et al. (2013), Tavoni and Soclow (2013), Blanford et al. (2014a), Klein et al. (2014), Krey et al. (2014), McCollum et al. (2014), Riahi et al. (2015), Vaughan and Gough (2016), Mintenig et al. (2017), van Vuuren et al. (2017), Bertram et al. (2018), Heck et al. (2018), Holz et al. (2018), Keller et al. (2018), Lehtilä and Koljonen (2018), Luderer et al. (2018), Méjean et al. (2018), Mousavi et al. (2018), Obersteiner et al. (2018), Sanchez et al. (2018), Streifer et al. (2018)

Table 1 (continued)

Category	ID	Name	Statement	Supporting tables and figures	# studies	References
Others	O3	Uncertainty	NETs are subject to many uncertainties. These include uncertainties in the climate stabilisation targets and climate sensitivity, uncertainties in CDR potentials (including storage capacity and bioenergy), costs and side-effects, uncertainties in environmental constraints, carbon-climate system feedbacks, economic impacts and legal issues.		24	Obersteiner et al. (2002), Azar et al. (2006), Fuss et al. (2013), Tavoni and Socolow (2013), van Vuuren et al. (2013), Bibas and Méjean (2014), Blanford et al. (2014a), Klein et al. (2014), Kriegler et al. (2014), Popp et al. (2014), Selosse and Ricci (2014), van der Zwaan et al. (2013), Mintenig et al. (2017), Tavoni et al. (2017), van Vuuren et al. (2017), Akimoto et al. (2018), Heck et al. (2018), Holz et al. (2018), Keller et al. (2018), Lehtilä and Koljonen (2018), Mousavi et al. (2018), Rickels et al. (2018), Sanchez et al. (2018), Streifer et al. (2018)
Others	O4	Challenges	The deployment of NETs is subject to a wide array of challenges, which can be technology specific. These include: NET upscaling, governance, political, policy, legal and finance aspects, social acceptance, food security, technological limits, reservoir leakage, environmental impacts, and climate and carbon cycle feedbacks.		23	Canadell and Raupach (2008), Strengers et al. (2008), Edmonds et al. (2013), Fuss et al. (2013), Kriegler et al. (2013a), Tavoni and Socolow (2013), Bibas and Méjean (2014), Blanford et al. (2014a), Kriegler et al. (2014), Popp et al. (2014), Selosse and Ricci (2014), Vaughan and Gough (2016), Gambhir et al. (2017), Marcucci et al. (2017), Mintenig et al. (2017), Tavoni et al. (2017), van Vuuren et al. (2017), Holz et al. (2018), Obersteiner et al. (2018), Sanchez et al. (2018), Séfrian et al. (2018), Streifer et al. (2018), Vaughan et al. (2018)
Others	O7	Sustainability	The large-scale deployment of NETs might not be compatible with the Sustainable Development Goals. Strategies for NET deployment should include sustainability criteria (e.g. sustainable production of biomass).		14	Obersteiner et al. (2001), Obersteiner et al. (2002), Rahi et al. (2007), Ricci (2012), Fuss et al. (2013), Kriegler et al. (2013a), Bibas and Méjean (2014), Calvin et al. (2014), Mintenig et al. (2017), Grubler et al. (2018), Lehtilä and Koljonen (2018), Mousavi et al. (2018), Obersteiner et al. (2018), Sanchez et al. (2018), Tavoni et al. (2013), Kriegler et al. (2013a), Tavoni and Socolow (2013), Humpenöder et al. (2014), Popp et al. (2014), Kreidenweis et al. (2016), Favero et al. (2017), Marcucci et al. (2017), Popp et al. (2017), Lehtilä and Koljonen (2018), Rogelj et al. (2018a, b), Wining et al. (2018)
Others	O8	MultiNETs	When multiple NETs are available, they are deployed by cost order, the low cost technology options coming first (e.g. afforestation, then BECCS and then DACCS). Their deployment can also be affected by: if they compete for scarce resources (e.g. land for AR and BECCS, geological storage for BECCS and DACCS).	Figure 2	12	Obersteiner et al. (2018), Sanchez et al. (2018), Chen and Tavoni et al. (2013), Kriegler et al. (2013a), Tavoni and Socolow (2013), Humpenöder et al. (2014), Popp et al. (2014), Kreidenweis et al. (2016), Favero et al. (2017), Marcucci et al. (2017), Popp et al. (2017), Lehtilä and Koljonen (2018), Rogelj et al. (2018a, b), Wining et al. (2018)
Others	O11	Discount_rate	The discount rate, which usual value is 5%, plays an important role in the timing and scale of GHG		9	Sohngen and Sedjo (2006), van Vliet et al. (2009), Lemoine et al. (2012), Chen and Tavoni et al.

Table 1 (continued)

Category	ID	Name	Statement	Supporting tables and figures	# studies	References
Others	O14	Correlation	emission abatement and NET deployment. When this value is decreased, more GHG emissions are abated in the near-term and less NETs are deployed. A few correlations between global cumulative variables have been reported in the literature. For instance, the amount of radiative forcing overshoot is correlated with cumulative CDR over the century. There is also a relationship between carbon budgets and non-Kyoto forcing. Modellers have been cautiously describing the result of introducing NETs in their models. They warn against the direction application of these scenarios which would obstruct near-term mitigation action and could turn out to be a brittle strategy.		4	(2013), Fuss et al. (2013), Tavoni and Soclow (2013), Humpenöder et al. (2014), van Vuuren et al. (2017), Obersteiner et al. (2018) van Vuuren et al. (2013), Kriegler et al. (2014), Rose et al. (2014b), Tavoni et al. (2017)
Others	O15	Warning			3	Azar et al. (2006), Blanford et al. (2014a), Holz et al. (2018)

2050 occurs faster (0.3 [0.0–0.6] GtCO₂/year versus 0.2 [0.0–0.4] GtCO₂/year expansion⁴) unless climate policy is delayed until 2030 in 2 °C scenarios (Fig. 1a3, b2) D1. In fact, once climate action is delayed until 2030, the negative emissions characteristics of 2 °C scenarios become increasingly similar to the 1.5 °C scenarios with immediate action. It is worthwhile to note that this difference in NET reliance between 1.5 and 2 °C scenarios is predicated on estimates of the climate response that remain similar to the value assessed in AR5, despite recent studies showing the potential for possible changes to climate response (Millar et al. 2017; Tokarska and Gillett 2018).

The prominence of NETs in stringent climate mitigation scenarios is the product of two factors: geophysical requirements and economic incentives, which play very different roles in 1.5 °C and 2 °C scenarios (Minx et al. 2018). As indicated earlier, while carbon dioxide removal deployment in 1.5 °C scenarios is primarily driven by geophysical requirements—for compensating for the overshoot of the allowed carbon budget (Strefler et al. 2018; Kriegler et al. 2018b; Luderer et al. 2018)—this is not the case in 2 °C scenarios. Economic incentives however are an important feature of both 1.5 °C and 2 °C scenarios as depicted by mitigation costs in Table 2. Mitigation costs are a good indicator for understanding the overall mitigation challenge in IAMs: as mitigation costs increase as models move towards their infeasibility frontier (Azar et al. 2006; Luderer et al. 2013). Moving across the columns of Table 2 shows how mitigation costs rise: (a) as long-term ambition increases and (b) as short-term emission reductions get delayed until 2030. Looking across the columns shows the decrease in mitigation costs as NETs are introduced into the models C1 and how models are driven to infeasibility in their absence, as short-term emission reductions get further delayed and long-term ambition increases O11. No single IAM study documents pathways without NETs returning warming to below 1.5 °C by 2100, or limiting warming to well below 2 °C after a delaying action until 2030.

The lowering of mitigation costs resulting from the deployment of NETs has far reaching consequences on mitigation pathways D2. Indeed, regardless of any geophysical requirement, the introduction of NETs in IAM curb emission reductions in the short run and compensates for the carbon budget overshoot towards the end century when carbon prices are high (often reaching thousands of US dollars per ton of CO₂) D2, C2. For example, Fig. 1a2 demonstrates that, until 2060, median net CO₂ emissions in 2 °C scenarios with BECCS exceeds that of the median 2 °C scenario without BECCS. Consequently, this temporal reallocation of CO₂ emissions mitigation by NETs allow for more fossil fuel consumption in the near-term, thus leaving more time for the energy system transition, and a longer utilisation of existing infrastructure in the power, industry and building sectors D5.

Temporal discounting is the main factor driving these dynamics. Indeed, by giving a lower weight to the costs of future mitigation actions, the use of a constant discount rate (generally 5%) during the twenty-first century makes the use of NETs in the second half of the century an economically attractive mitigation option that allow costly near-term emissions reductions to be postponed (van Vuuren et al. 2017; Obersteiner et al. 2018) D9. From these results, it is often concluded that NETs make the timing of climate mitigation policies more flexible D6. Aware of the potential misinterpretation of these findings, modellers described the risks, uncertainties and challenges in following such pathways O2, O3, O4, and have warned policy makers against postponing near-term abatement action O14.

⁴ Values preceding the brackets are medians while those in the brackets are minima and maxima.

By the end of the century, negative CO₂ emissions from NETs compensate for past and current residual CO₂ and non-CO₂ emissions D4. Residual CO₂ emissions can arise in the industry, buildings, transportation and land-use sectors and are a function of the ambition level of climate policy (Kriegler et al. 2018b; Luderer et al. 2018). They add to non-CO₂ greenhouse gas (GHG) emissions like CH₄, N₂O and F-Gases, which can represent a large share of total residual GHG emissions depending on the mitigation portfolio represented in models (Kober et al. 2014; Gernaat et al. 2015). When BECCS is available, the power sector is often reported to be essential for decarbonisation and to compensate for these residual emissions (van Sluisveld et al. 2013; Kriegler et al. 2013a). However, other sectors can in principle also contribute since BECCS is a versatile technology which can also be used to produce synthetic fuels, heat and hydrogen T5, O15.

Little attention has been given to portfolios of NETs in IAMs even though there is a growing number of studies that feature two or more NET options—most prominently BECCS and afforestation (AR) (Rao and Riahi 2006; Wise et al. 2009; Calvin et al. 2009a; Edmonds et al. 2013; Humpenöder et al. 2014; Bertram et al. 2018; van Vuuren et al. 2018; Grubler et al. 2018), but also BECCS and direct air capture with carbon sequestration (DACCS) (Chen and Tavoni et al. 2013; Marcucci et al. 2017) or BECCS and enhanced weathering (EW) (Strefler et al. 2015). More recently, Holz et al. (2018) produced scenarios with 6 NETs (i.e. AR, BECCS, biochar, DACCS, EW, soil carbon management). There are a few noticeable findings from these studies O8. Compared to scenarios featuring only BECCS, the availability and use of one or more additional NETs makes emission reductions in the near term even less attractive and further reduces the political costs of achieving the same climate policy objective D9, C1. Indeed, any addition of negative emission potential in scenarios results in an increase in total cumulative CO₂ removal over the twenty-first century and further exacerbates the intertemporal trade-off explained in the previous paragraphs D4, D11. This increase in carbon removal occurs at decreasing rates because of substitution effects. Competition between NETs for land and/or geological storage reduces the individual potential of these technologies. For example, Humpenöder et al. (2014) who examine two land-based NETs (i.e. competing for scarce land) find that the amount of CO₂ sequestered by BECCS over the 1995–2095 period decreases from 600 to 400 GtCO₂ when AR is added. Marcucci et al. (2017) find a lower effect of only a few gigatonnes between BECCS and DACCS, which compete for geological storage (see Fig. 2). Holz et al. (2018) also show that the contribution from AR is halved when 5 other NETs are added. These findings suggest that the availability of multiple NETs may help to better balance the various technology risks that are often scale dependent (Fuss et al. 2018). The degree to which this risk can be hedged depends however on technological competition.

Finally, while several studies have eliminated doubts that geological CO₂ storage is a major limiting factor for NET deployment in 2 °C scenarios T1, this is less clear when NET deployment with geological CO₂ storage further increase—like in 1.5 °C scenarios and with the availability of additional NET options with geological storage like DACCS (Meinshausen et al. 2011; Dooley 2013; Edmonds et al. 2013; Tavoni and Socolow 2013; Vaughan and Gough 2016). Even though sequestration rate constraints can limit the amount of CO₂ that can be stored annually, a meta-analysis concludes that 3900 GtCO₂ are “practically”⁵ available and

⁵ In the geological CO₂ storage pyramid (Bachu et al. 2007), “practical” storage capacity is a subset of the “effective” capacity. It includes storage sites that meet additional criteria (i.e. technical, legal and regulatory, infrastructure and general economic barriers to CO₂ geological storage).

13,500 GtCO₂ are “effectively”⁶ available for storing carbon in onshore and offshore saline aquifers, depleted oil and gas fields, and deep “unmineable” coal basins (Dooley 2013). In a follow-up IAM analysis, Edmonds et al. (2013) made the assumption that 7000 GtCO₂ of storage would be available globally. We compare the regional estimates of these two studies to the available 1.5 °C and 2 °C scenario data from the AMPERE (Kriegler et al. 2015b) and LIMITS (Kriegler et al. 2013b) projects (see Fig. 3). The geographical distribution of negative emissions reveals that BECCS is deployed globally (Calvin et al. 2009a; van Sluisveld et al. 2013; Edmonds et al. 2013) but particularly in regions with large biomass potential and/or large geological storage capacity such as USA, China, Former Soviet Union and Middle East D7. Interestingly, biomass trade allows regions without biomass but large geological storage like the Middle East to sequester carbon. This highlights the institutional challenges facing the large-scale deployment of BECCS. Technological change and financial requirements are also concerning particularly for developing countries⁷ T9. Nonetheless large discrepancies exist not only in quantities of geological storage but also across model results. For instance, sequestered carbon in 2 °C scenarios can differ by more than 100 GtCO₂ in Africa, Europe, Former Soviet Union, India, Latin America, Middle East, USA and up to 200 GtCO₂ in China. These differences are much smaller in 1.5 °C scenarios because the results come from a single model. Differences can be attributed to model structures (e.g. general equilibrium model vs partial equilibrium model, regional resolution, etc.) and (regional) modelling assumptions (e.g. geological storage potential, biomass potential, etc.) which can be more or less optimistic about implementable potentials given political, institutional and social acceptance-related constraints O4. It should be noted that IAMs use different estimates of geological storage. For instance, geological storage constraints in Marcucci et al. (2017) are based on Hendriks et al. (2004) whereas estimates used in GCAM are based on Dooley (2013) and Edmonds et al. (2014). In IMAGE, upper limits on geological storage are also based on Hendriks et al. (2004) with updates from Koelbl (2016).

3 Discussion and outlook

IAMs have played a central role in expanding the research frontiers of NETs and helping to discover policy-relevant findings about these technologies. Yet, qualitative evidence so far has not been adequately aggregated into a traceable and updatable body of knowledge and has been disconnected from reviews of quantitative evidence based on large scenario ensembles. In this study, we close this gap by systematically reviewing individual findings in a thematic synthesis of the underlying literature (Boyatzis 1998; Guest et al. 2012) connecting them explicitly to the quantitative ensemble evidence. We argue that such synthesis that systematically connects qualitative and quantitative evidence has been missing so far and impeded a comprehensive and transparent assessment of the role of NETs in climate change mitigation in previous IPCC reports. As such, this paper can help to establish a comprehensive and traceable account of evidence for upcoming IPCC AR6 that can be easily updated.

Table 1 provides an overview of the findings identified during our review. We emphasise that one should not interpret any statement omitted in the previous section as less significant.

⁶ Here, “effectively” refers to storage sites that satisfy a range of basic geological and engineering conditions which can be quantified with a fair degree of confidence

⁷ The financial requirements of other climate change mitigation technologies in developing countries are also of great concern. This is the case for wind and solar capacities for instance (Hirth and Steckel 2016).

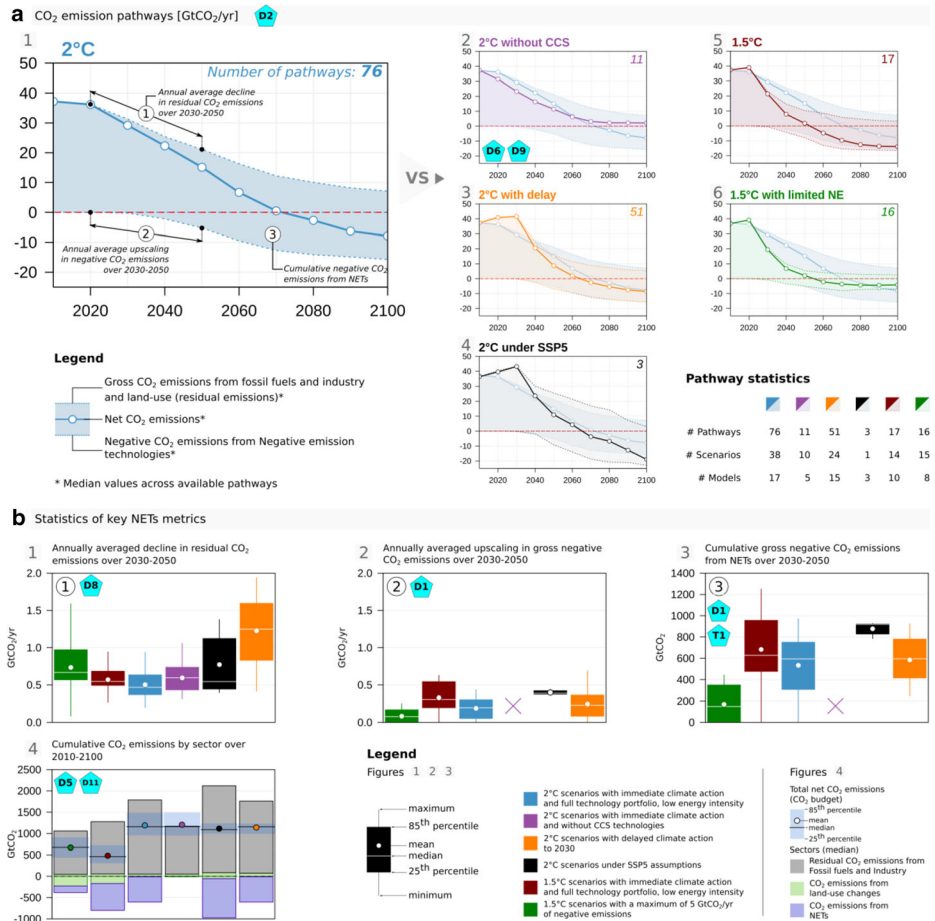


Fig. 1 The role of NETs in meeting international climate targets under various technological and policy constraints and societal choices. Part B shows key statistics. The number of pathways, models and scenarios are provided in Figure 1a. The colour scheme used to differentiate scenario categories in Figures 1a and 1b are the same that is blue for 2 °C pathways with immediate action and full technology, purple for 2 °C pathways without CCS technology, orange for 2 °C pathways with delayed action to 2030, black for 2 °C pathways under SSP5 assumptions, red for 1.5 °C pathways with immediate action and full technology and green for 1.5 °C pathways with limited CDR availability (< 5 GtCO₂/year). The cyan pentagons refer to the qualitative findings in Table 1

Instead we selected statements according to the focus of this review, i.e. the role of NETs in 1.5 °C and 2 °C scenarios, respectively. As such, it serves as a template for bridging qualitative and quantitative evidence systematically. For example, we did not discuss the role that BECCS can play in increasing food prices T3. Although the large-scale deployment of BECCS requires hundreds of millions of hectares to grow bioenergy T1, food prices would still be high in a world without BECCS because bioenergy would increase in importance as a mitigation technology⁸ D10. Similar choices will be required in upcoming climate change assessments that are inherently space constrained. The key point here is that comprehensive, traceable accounts of both quantitative and qualitative evidence are required to do make informed and transparent choices in this process (Huppmann et al. 2018).

Table 2 The role of NETs in decreasing mitigation costs. Mitigation costs are the discounted sum of all costs associated with climate mitigation action over the period 2010–2100, calculated here for a 67% confidence level of limiting warming to below 2 °C (well below 2 °C case), or a 50% confidence level of limiting end of century warming to 1.5 °C by interpolating between respective scenarios. Red crosses indicate infeasible scenarios. Costs represent discounted and aggregated consumption losses (i.e. differences in consumption between a baseline and a climate policy scenario) as a share of discounted and aggregated GDP (in the climate policy scenario). A discount rate of 5% is used. Results adapted from Luderer et al. (2013)

		Increasing long-term ambition →			
		Well below 2°C		1.5°C	
		Decreasing short-term ambition →		Decreasing short-term ambition →	
		2010	2030	2010	2030
Decreasing negative emissions potential ↓	Unconstrained	1.44%	2.16%	2.26%	3.34%
	Limited BECCS	1.90%	3.30%	4.10%	×
	No BECCS	2.30%	×	×	×

Our approach could be extended in the future. First, it does not represent the entire universe of scenarios on climate change mitigation. A more comprehensive identification and selection of qualitative evidence based on a structured search in bibliographic databases such as Web of Science or Scopus could be a first step in addressing the longstanding concern of selection bias in IPCC assessments of scenario evidence (Haddaway and Macura, 2018). Second, although we are confident that our table of statements includes the major findings of the literature, our search could be extended to capture more peripheral topics (e.g. geological storage, food price). Third, our compiled scenario database contains important data gaps as all model output is not consistently made available publicly. This selection could introduce biases in our numerical results due to model and scenario design sampling. More comprehensive reporting and data provision requirements seem crucial. The qualitative findings presented here however are in good agreement with the list of major statements from the literature. Fourth, while our assessment can robustly identify and reflect insights from the available scenario literature on NETs, it is much harder to identify whether any pervasive scenario assumptions might bias these statements in a particular direction, and whether there are specific conditions under which these insights would apply.

Despite these shortcomings, synthetic research efforts within the scientific community like this study are increasingly valuable (Kowarsch et al. 2016, 2017), particularly in times of exponentially growing scientific publications on climate change (Grieneisen and Zhang 2011;

⁰ The importance of bioenergy may decrease in future scenarios if the deployment of electric vehicles continues to gather momentum worldwide.

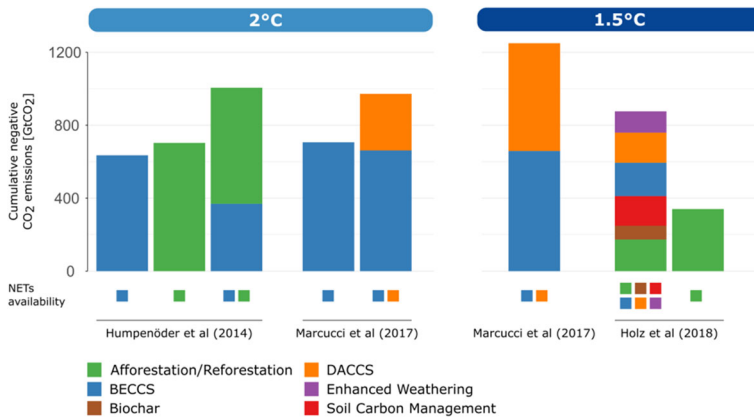


Fig. 2 The role of small NET portfolios in meeting the 1.5 °C and 2 °C climate goals. Each bar represents a scenario. NET availability is indicated by a small square below the bars. Data from Humpenöder et al. (2014) are cumulated over 1995–2095 while that of Marcucci et al. (2017) and Holz et al. (2018) are cumulated over 2010–2100

Haunschild et al. 2016; Minx et al. 2017b). Not engaging in such efforts could exacerbate the difficulty for assessment bodies like the IPCC to meet their often ambitious mandates (Minx et al. 2017a). While such computer-assisted synthetic methods (Westgate et al. 2018; Nakagawa et al. 2018; Lamb et al. 2019) still require laborious inputs from and verification by humans, it allows for a more efficient and better evaluation of the veracity of findings by linking them directly to supporting studies. It may also reduce the risk of bias and misinterpretations by policymakers, who would be in a better position to confront arguments based on cherry-picking and infrequently-made claims.

Importantly, this review allowed us to identify important research gaps, some of which have been underscored in Fuss et al. (2018) and Rogelj et al. (2018b). First, it seems

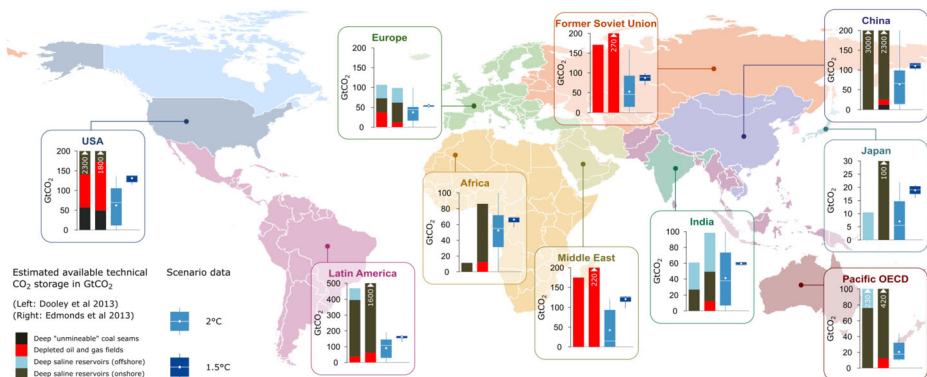


Fig. 3 Regional geological CO₂ storage capacity and CO₂ sequestered by BECCS. Geological CO₂ storage data correspond to the "practical" category from Dooley (2013) which totals 3900 GtCO₂ (left bar) and the modified version by Edmonds et al. (2013) which totals 7000 GtCO₂ (right bar). Scenario data are from AMPERE (Kriegler et al. 2015a, b, c), LIMITS (Kriegler et al. 2013a, 2013b), RoSE (Kriegler et al. 2016) and Luderer et al. (2013). Scenario data for Canada and Southeast Asia were missing and so could not be included here. Similarly 1.5 °C scenarios for the Pacific OECD region are unavailable

crucial to better understand large NET deployments frequently observed in the literature (Fuss et al. 2018; Rogelj et al. 2018b). Initial evidence suggests that this is directly related to the cost-effectiveness framework (and discount rate) underlying the models studied here, and that, even though CDR would also be large in a cost-risk analysis (Mintenig et al. 2017), a consideration of climate impacts in a cost-benefit mode would substantially decrease CDR deployments (Blanford 2013). Since climate impacts could also affect the potential of NETs, accounting for these effects in IAMs would allow identifying important trade-offs and provide additional insights on the optimal timing and levels of NETs (Rogelj et al. 2018b) E3, E4, E6, E7, E10. Second, as the wider discourse on NETs highlights that even some of the more modest deployment levels are unlikely to be reached with BECCS as a single NET, a deeper exploration of NET portfolios and their ability to hedge against some of the deployment risks are crucial O8. This would also require further exploring the adequacy of introducing NETs that have been neglected⁹ by the IAM community so far (e.g. blue carbon) as well as the synergies and trade-offs between NETs. Third, considering and understanding what benefits, risks and societal trade-offs these options could provide would be important. A number of recent studies have also highlighted the potential role of non-CO₂ GHG removal technologies (Stolaroff et al. 2012; Lomax et al. 2015; Ming et al. 2016; de Richter et al. 2016, 2017). A large fraction of residual emissions at the end of the century come from non-CO₂ GHG, some of which are stock pollutants that accumulate in the atmosphere. For these species, GHG removal appears a promising avenue for future research. Fourth, not only do large-scale deployments of NETs impact regional economies, energy systems and carbon budgets but they can also lead to food price increases (Wise et al. 2009; Calvin et al. 2009a; Reilly et al. 2012; Kreidenweis et al. 2016), local air and water pollution, water overuse and biodiversity losses (Williamson 2016) T3, E1. Consequently, NETs should be examined under a broader spectrum of societal and environmental goals. To that end, Planetary Boundaries and Sustainable Development Goals provide useful frameworks for future research E8, O7. Finally, net negative CO₂ emissions, which could amount to a few tens of gigatonnes of CO₂ by the end of century when carbon prices are high, would require substantive and sustained support from financing bodies (e.g. governments) O4. In an intertemporal optimisation framework, this can be financed by a banking and borrowing scheme. However, whether such large-scale financing product could see the light in reality is unclear at the moment. Therefore, it would be essential to investigate the role of NETs in an intergenerational modelling framework and from a political and business perspective.

Acknowledgements We would like to thank Adriana Marcucci for providing the MERGE-ETL data underlying Fig. 3, Christian Holz for providing the C-ROADS data used in Figs. 1 and 3, Detlef van Vuuren and Mathijs Hammen for providing the IMAGE data used in Fig. 1, and Ulf Weddige for his support in helping producing Fig. 2. JH has conducted the work for this article in the frame of the project “Pathways and Entry Points to limit global warming to 1.5°C” funded by the German Ministry of Research and Education (Grant reference: 01LS1610B). J.M. further contributed to this article under the Project “Strategic Scenario Analysis” (START) funded by the German Ministry of Research and Education (Grant reference: 03EK3046B).

Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

⁹ An exception is Holz et al. (2018)

References

- Aboumahboub T, Luderer G, Kriegler E et al (2014) On the regional distribution of climate mitigation costs: the impact of delayed cooperative action. *Climate Change Economics* 05:1440002–1440002. <https://doi.org/10.1142/S2010007814400028>
- Akimoto K, Sano F, Tomoda T (2018) GHG emission pathways until 2300 for the 1.5 °C temperature rise target and the mitigation costs achieving the pathways. *Mitig Adapt Strateg Glob Chang* 23:839–852. <https://doi.org/10.1007/s11027-017-9762-z>
- Anderson K (2015) Duality in climate science. *Nat Geosci* 8:ngeo2559. <https://doi.org/10.1038/ngeo2559>
- Anderson K, Peters G (2016) The trouble with negative emissions. *Science* 354:182–183. <https://doi.org/10.1126/science.aah4567>
- Azar C, Lindgren K, Persson T (2001) Carbon sequestration from fossil fuels and biomass - long-term potentials. Göteborg
- Azar C, Lindgren K, Andersson BA (2003) Global energy scenarios meeting stringent CO2 constraints—cost-effective fuel choices in the transportation sector. *Energy Policy* 31:961–976. [https://doi.org/10.1016/S0301-4215\(02\)00139-8](https://doi.org/10.1016/S0301-4215(02)00139-8)
- Azar C, Lindgren K, Larson E, Möllersten K (2006) Carbon capture and storage from fossil fuels and biomass – costs and potential role in stabilizing the atmosphere. *Clim Chang* 74:47–79. <https://doi.org/10.1007/s10584-005-3484-7>
- Azar C, Lindgren K, Obersteiner M et al (2010) The feasibility of low CO2 concentration targets and the role of bio-energy with carbon capture and storage (BECCS). *Clim Chang* 100:195–202. <https://doi.org/10.1007/s10584-010-9832-7>
- Azar C, Johansson DJA, Mattsson N (2013) Meeting global temperature targets—the role of bioenergy with carbon capture and storage. *Environ Res Lett* 8:034004. <https://doi.org/10.1088/1748-9326/8/3/034004>
- Bachu S, Bonijoly D, Bradshaw J et al (2007) CO2 storage capacity estimation: methodology and gaps. *Int J Greenh Gas Con* 1:430–443. [https://doi.org/10.1016/S1750-5836\(07\)00086-2](https://doi.org/10.1016/S1750-5836(07)00086-2)
- Bauer N, Mouratiadou I, Luderer G et al (2016) Global fossil energy markets and climate change mitigation – an analysis with REMIND. *Clim Chang* 136:69–82. <https://doi.org/10.1007/s10584-013-0901-6>
- Bauer N, Calvin K, Emmerling J et al (2017) Shared socio-economic pathways of the energy sector – quantifying the narratives. *Glob Environ Chang* 42:316–330. <https://doi.org/10.1016/j.gloenvcha.2016.07.006>
- Bauer N, Rose SK, Fujimori S et al (2018) Global energy sector emission reductions and bioenergy use: overview of the bioenergy demand phase of the EMF-33 model comparison. *Clim Chang*:1–16. <https://doi.org/10.1007/s10584-018-2226-y>
- Bertram C, Johnson N, Luderer G et al (2015) Carbon lock-in through capital stock inertia associated with weak near-term climate policies. *Technol Forecast Soc Chang* 90(Part A):62–72. <https://doi.org/10.1016/j.techfore.2013.10.001>
- Bertram C, Luderer G, Popp A et al (2018) Targeted policies can compensate most of the increased sustainability risks in 1.5 °C mitigation scenarios. *Environ Res Lett* 13:064038. <https://doi.org/10.1088/1748-9326/aac3ec>
- Bibas R, Méjean A (2014) Potential and limitations of bioenergy for low carbon transitions. *Clim Chang* 123:731–761. <https://doi.org/10.1007/s10584-013-0962-6>
- Blanford G (2013) Is overshoot optimal? Negative emissions in a cost-benefit setting. Toulouse, France
- Blanford GJ, Richels RG, Rutherford TF (2009) Feasible climate targets: the roles of economic growth, coalition development and expectations. *Energy Econ* 31(Supplement 2):S82–S93. <https://doi.org/10.1016/j.eneco.2009.06.003>
- Blanford G, Merrick J, Richels R, Rose S (2014a) Trade-offs between mitigation costs and temperature change. *Clim Chang* 1–15. doi: <https://doi.org/10.1007/s10584-013-0869-2>
- Blanford GJ, Kriegler E, Tavoni M (2014b) Harmonization vs. fragmentation: overview of climate policy scenarios in EMF27. *Clim Chang*. <https://doi.org/10.1007/s10584-013-0951-9>
- Bosetti V, Marangoni G, Borghonovo E et al (2015) Sensitivity to energy technology costs: a multi-model comparison analysis. *Energy Policy* 80:244–263. <https://doi.org/10.1016/j.enpol.2014.12.012>
- Bowen A, Campiglio E, Tavoni M (2014) A macroeconomic perspective on climate change mitigation: meeting the financing challenge. *Climate Change Economics* 05:1440005–1440005. <https://doi.org/10.1142/S2010007814400053>
- Boyatzis RE (1998) Transforming qualitative information. SAGE Publishing
- Bruckner T, Bashmakov IA, Mulugetta Y, et al (2014) Energy Systems. In: Edenhofer O, Pichs-Madruga R, Sokona Y, 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. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA
- Calvin K, Edmonds J, Bond-Lamberty B et al (2009) 2.6: limiting climate change to 450 ppm CO2 equivalent in the 21st century. *Energy Econ* 31:S107–S120. <https://doi.org/10.1016/j.eneco.2009.06.006>

- Calvin K, Pachauri S, Cien ED, Mouratiadou I (2013a) The effect of African growth on future global energy, emissions, and regional development. *Clim Chang*:1–17. <https://doi.org/10.1007/s10584-013-0964-4>
- Calvin K, Wise M, Klein D et al (2013b) A multi-model analysis of the regional and sectoral roles of bioenergy in near- and long-term CO₂ emissions reductions. *Climate Change Economics* 04:1340014–1340014. <https://doi.org/10.1142/S2010007813400149>
- Calvin K, Wise M, Kyle P et al (2014) Trade-offs of different land and bioenergy policies on the path to achieving climate targets. *Clim Chang* 123:691–704. <https://doi.org/10.1007/s10584-013-0897-y>
- Calvin K, Bond-Lamberty B, Clarke L et al (2017) The SSP4: a world of deepening inequality. *Glob Environ Chang* 42:284–296. <https://doi.org/10.1016/j.gloenvcha.2016.06.010>
- Canadell JG, Raupach M (2008) Managing forests for climate change mitigation. *Science* 320:1456–1457. <https://doi.org/10.1126/science.1155458>
- Chen C, Tavoni M (2013) Direct air capture of CO₂ and climate stabilization: a model based assessment. *Clim Chang* 118:59–72. <https://doi.org/10.1007/s10584-013-0714-7>
- Clarke L, Edmonds J, Krey V et al (2009) International climate policy architectures: overview of the EMF 22 international scenarios. *Energy Econ* 31:S64–S81. <https://doi.org/10.1016/j.eneco.2009.10.013>
- Clarke L, Jiang K, Akimoto K, et al (2014) Assessing transformation pathways. In: Edenhofer O, Pichs-Madruga R, Sokona Y, 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. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA
- Daioglou V, Wicke B, Faaij APC, van Vuuren DP (2015) Competing uses of biomass for energy and chemicals: implications for long-term global CO₂ mitigation potential. *GCB Bioenergy* 7:1321–1334. <https://doi.org/10.1111/gcbb.12228>
- de Coninck H, Revi A, Babiker M et al (2018) 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, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., 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, and T. Waterfield (eds.)]. In Press
- de Richter RK, Ming T, Caillol S, Liu W (2016) Fighting global warming by GHG removal: destroying CFCs and HFCs in solar-wind power plant hybrids producing renewable energy with no-intermittency. *International Journal of Greenhouse Gas Control* 49:449–472. <https://doi.org/10.1016/j.ijggc.2016.02.027>
- de Richter R, Ming T, Davies P et al (2017) Removal of non-CO₂ greenhouse gases by large-scale atmospheric solar photocatalysis. *Prog Energy Combust Sci* 60:68–96. <https://doi.org/10.1016/j.peccs.2017.01.001>
- Deng H, Bielicki JM, Oppenheimer M et al (2017) Leakage risks of geologic CO₂ storage and the impacts on the global energy system and climate change mitigation. *Clim Chang* 144:151–163. <https://doi.org/10.1007/s10584-017-2035-8>
- Dooley JJ (2013) Estimating the supply and demand for deep geologic CO₂ storage capacity over the course of the 21st century: a meta-analysis of the literature. *Energy Procedia* 37:5141–5150. <https://doi.org/10.1016/j.egypro.2013.06.429>
- Edenhofer O, Knopf B, Barker T et al (2010) The economics of low stabilization: model comparison of mitigation strategies and costs. *Energy J* 31:11–48. <https://doi.org/10.5547/ISSN0195-6574-EJ-Vol31-NoSI-2>
- Edmonds J, Luckow P, Calvin K et al (2013) Can radiative forcing be limited to 2.6 Wm⁻² without negative emissions from bioenergy AND CO₂ capture and storage? *Clim Chang* 118:29–43. <https://doi.org/10.1007/s10584-012-0678-z>
- Emori S, Takahashi K (2018) Integrated climate assessment: risks, uncertainties, and society. *Sustain Sci* 13:275–277. <https://doi.org/10.1007/s11625-018-0539-4>
- Eom J, Edmonds J, Krey V et al (2015) The impact of near-term climate policy choices on technology and emission transition pathways. *Technol Forecast Soc Chang* 90(Part A):73–88. <https://doi.org/10.1016/j.techfore.2013.09.017>
- Favero A, Mendelsohn R, Sohngen B (2017) Using forests for climate mitigation: sequester carbon or produce woody biomass? *Clim Chang* 144:195–206. <https://doi.org/10.1007/s10584-017-2034-9>
- Field CB, Mach KJ (2017) Rightsizing carbon dioxide removal. *Science* 356:706–707. <https://doi.org/10.1126/science.aam9726>
- Fricko O, Havlik P, Rogelj J et al (2017) The marker quantification of the shared socioeconomic pathway 2: a middle-of-the-road scenario for the 21st century. *Glob Environ Chang* 42:251–267. <https://doi.org/10.1016/j.gloenvcha.2016.06.004>
- Fujimori S, Su X, Liu J-Y et al (2016) Implication of Paris agreement in the context of long-term climate mitigation goals. *SpringerPlus* 5:1620–1620. <https://doi.org/10.1186/s40064-016-3235-9>

- Fujimori S, Hasegawa T, Masui T et al (2017) SSP3: AIM implementation of shared socioeconomic pathways. *Glob Environ Chang* 42:268–283. <https://doi.org/10.1016/j.gloenvcha.2016.06.009>
- Fuss S, Reuter WH, Szolgayová J, Obersteiner M (2013) Optimal mitigation strategies with negative emission technologies and carbon sinks under uncertainty. *Clim Chang* 118:73–87. <https://doi.org/10.1007/s10584-012-0676-1>
- Fuss S, Canadell JG, Peters GP et al (2014) Betting on negative emissions. *Nat Clim Chang* 4:850–853. <https://doi.org/10.1038/nclimate2392>
- Fuss S, Lamb WF, Callaghan MW et al (2018) Negative emissions—part 2: costs, potentials and side effects. *Environ Res Lett* 13:063002. <https://doi.org/10.1088/1748-9326/aabf9f>
- Gambhir A, Drouet L, McCollum D et al (2017) Assessing the feasibility of global long-term mitigation scenarios. *Energies* 10:89–89. <https://doi.org/10.3390/en10010089>
- Gasser T, Guivarch C, Tachiiri K et al (2015) Negative emissions physically needed to keep global warming below 2 °C. *Nat Commun* 6:ncomms8958. <https://doi.org/10.1038/ncomms8958>
- Geden O (2015) Policy: climate advisers must maintain integrity. *Nature* 521:27–28. <https://doi.org/10.1038/521027a>
- Geden O, Löschel A (2017) Define limits for temperature overshoot targets. *Nat Geosci* 10:881–882. <https://doi.org/10.1038/s41561-017-0026-z>
- Gemaat DEHJ, Calvin K, Lucas PL et al (2015) Understanding the contribution of non-carbon dioxide gases in deep mitigation scenarios. *Glob Environ Chang* 33:142–153. <https://doi.org/10.1016/j.gloenvcha.2015.04.010>
- Grieneisen ML, Zhang M (2011) The current status of climate change research. *Nat Clim Chang* 1:nclimate1093. <https://doi.org/10.1038/nclimate1093>
- Griffin B, Buisson P, Criqui P, Mima S (2014) White Knights: will wind and solar come to the rescue of a looming capacity gap from nuclear phase-out or slow CCS start-up? *Clim Chang* 123:623–635. <https://doi.org/10.1007/s10584-013-0963-5>
- Grubler A, Wilson C, Bento N et al (2018) A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nat Energy* 3:515–527. <https://doi.org/10.1038/s41560-018-0172-6>
- Guest G, MacQueen KM, Namey EE (2012) Applied thematic analysis. SAGE Publishing
- Haddaway NR, Macura B (2018) The role of reporting standards in producing robust literature reviews. *Nat Clim Chang* 8(6):444. <https://doi.org/10.1038/s41558-018-0180-3>
- Haunschild R, Bornmann L, Marx W (2016) Climate change research in view of bibliometrics. *PLoS One* 11: e0160393. <https://doi.org/10.1371/journal.pone.0160393>
- Heck V, Gerten D, Lucht W, Popp A (2018) Biomass-based negative emissions difficult to reconcile with planetary boundaries. *Nat Clim Chang* 8:151–155. <https://doi.org/10.1038/s41558-017-0064-y>
- Hendriks C, Graus W, van Bergen F (2004) Global carbon dioxide storage potential and costs. Technical Report Ecofys
- Hirth L, Steckel JC (2016) The role of capital costs in decarbonizing the electricity sector. *Environ Res Lett* 11: 114010. <https://doi.org/10.1088/1748-9326/11/11/114010>
- Hoegh-Guldberg, O, Jacob D, Taylor M et al (2018) Impacts of 1.5°C global warming on natural and human system. 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, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., 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, and T. Waterfield (eds.)]. In Press
- Holz C, Siegel LS, Johnston E et al (2018) Ratcheting ambition to limit warming to 1.5 °C—trade-offs between emission reductions and carbon dioxide removal. *Environ Res Lett* 13:064028. <https://doi.org/10.1088/1748-9326/aac0c1>
- Humpenöder F, Popp A, Dietrich JP et al (2014) Investigating afforestation and bioenergy CCS as climate change mitigation strategies. *Environ Res Lett* 9:064029–064029. <https://doi.org/10.1088/1748-9326/9/6/064029>
- Huppmann D, Rogelj J, Kriegler E et al (2018) A new scenario resource for integrated 1.5°C research. *Nat Clim Chang* 8:1027–1030. <https://doi.org/10.1038/s41558-018-0317-4>
- IPCC (2014) Summary for policymakers. In: Edenhofer O, Pichs-Madruga R, Sokona Y, 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. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA
- IPCC (2018) Summary for policymakers. 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, sustainable

- development, and efforts to eradicate poverty [Masson-Delmotte, V., 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, and T. Waterfield (eds.)]. World Meteorological Organization, Geneva, Switzerland, 32 pp.
- Iyer G, Hultman N, Eom J et al (2015) Diffusion of low-carbon technologies and the feasibility of long-term climate targets. *Technol Forecast Soc Chang* 90:103–118. <https://doi.org/10.1016/j.techfore.2013.08.025>
- 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. <https://doi.org/10.1016/j.egypro.2014.11.712>
- Kanudia A, Labriet M, Loulou R (2014) Effectiveness and efficiency of climate change mitigation in a technologically uncertain world. *Clim Chang* 123:543–558. <https://doi.org/10.1007/s10584-013-0854-9>
- Keith DW, Ha-Duong M, Stolaroff JK (2006) Climate strategy with CO₂ capture from the air. *Clim Chang* 74: 17–45. <https://doi.org/10.1007/s10584-005-9026-x>
- Keller K, McInerney D, Bradford DF (2008) Carbon dioxide sequestration: how much and when? *Clim Chang* 88:267–291. <https://doi.org/10.1007/s10584-008-9417-x>
- Keller DP, Lenton A, Scott V et al (2018) The Carbon Dioxide Removal Model Intercomparison Project (CDRMIP): rationale and experimental protocol for CMIP6. *Geosci Model Dev* 11:1133–1160. <https://doi.org/10.5194/gmd-11-1133-2018>
- Klein D, Bauer N, Bodirsky B et al (2011) Bio-IGCC with CCS as a long-term mitigation option in a coupled energy-system and land-use model. *Energy Procedia* 4:2933–2940. <https://doi.org/10.1016/j.egypro.2011.02.201>
- Klein D, Luderer G, Kriegler E et al (2014) The value of bioenergy in low stabilization scenarios: an assessment using REMIND-MAGPIE. *Clim Chang* 123:705–718. <https://doi.org/10.1007/s10584-013-0940-z>
- Kober TT, van der Zwaan B, Rösler HH (2014) Emission certificate trade and costs under regional burden-sharing regimes for a 2°C climate change control target. *Climate Change Economics* 05:1440001–1440001. <https://doi.org/10.1142/S2010007814400016>
- Kober T, Panos E, Volkart K (2018) Energy system challenges of deep global CO₂ emissions reduction under the world energy council's scenario framework. In: Giannakidis G, Karlsson K, Labriet M, Gallachóir B (eds) *Limiting global warming to well below 2 °C: energy system modelling and policy development*. Springer, Cham, pp 17–31
- Koelbl BS (2016) Deployment potential and macro-economic impacts of carbon dioxide capture and storage in the future energy system. Ph.D. thesis. ISBN: 9789086720712
- Koelbl BS, van den Broek MA, Faaij APC, van Vuuren DP (2014) Uncertainty in carbon capture and storage (CCS) deployment projections: a cross-model comparison exercise. *Clim Chang* 123:461–476. <https://doi.org/10.1007/s10584-013-1050-7>
- Kowarsch et al. (2016) Scientific assessments to facilitate deliberative policy learning. <https://www.nature.com/articles/palcomms201692>
- Kowarsch et al. (2017) A road map for global environmental assessments *Nat Clim Chang*. <https://www.nature.com/articles/nclimate3307>
- Kreidenweis U, Humpenoder F, Stevanovic M, et al (2016) Afforestation to mitigate climate change: impacts on food prices under consideration of albedo effects. *Environ Res Lett* 11:1. doi: <https://doi.org/10.1088/1748-9326/11/8/085001>
- Krey V, Riahi K (2009) Implications of delayed participation and technology failure for the feasibility, costs, and likelihood of staying below temperature targets—greenhouse gas mitigation scenarios for the 21st century. *Energy Econ* 31:S94–S106. <https://doi.org/10.1016/j.eneco.2009.07.001>
- Krey V, Luderer G, Clarke L, Kriegler E (2014) Getting from here to there - energy technology transformation pathways in the EMF27 scenarios. *Clim Chang* 123:369–382. <https://doi.org/10.1007/s10584-013-0947-5>
- Kriegler E, Edenhofer O, Reuster L et al (2013a) Is atmospheric carbon dioxide removal a game changer for climate change mitigation? *Clim Chang* 118:45–57. <https://doi.org/10.1007/s10584-012-0681-4>
- Kriegler E, Tavoni M, Riahi K, van Vuuren DP (2013b) Introducing the limits special issue. *Climate Change Economics* 04:1302002–1302002. <https://doi.org/10.1142/S2010007813020028>
- Kriegler E, Weyant JP, Blanford GJ et al (2014) The role of technology for achieving climate policy objectives : overview of the EMF 27 study on global technology and climate policy strategies. *Clim Chang*. <https://doi.org/10.1007/s10584-013-0953-7>
- Kriegler E, Petermann N, Krey V et al (2015a) Diagnostic indicators for integrated assessment models of climate policy. *Technol Forecast Soc Chang* 90:45–61. <https://doi.org/10.1016/j.techfore.2013.09.020>
- Kriegler E, Riahi K, Bauer N et al (2015b) Making or breaking climate targets: the AMPERE study on staged accession scenarios for climate policy. *Technol Forecast Soc Chang* 99:273–276. <https://doi.org/10.1016/j.techfore.2015.07.011>

- Kriegler E, Riahi K, Bosetti V et al (2015c) Introduction to the AMPERE model intercomparison studies on the economics of climate stabilization. *Technol Forecast Soc Chang* 90(part a):1–7. <https://doi.org/10.1016/j.techfore.2014.10.012>
- Kriegler E, Mouratiadou I, Luderer G, et al (2016) Will economic growth and fossil fuel scarcity help or hinder climate stabilization? *Clim Chang* 1–16. doi: <https://doi.org/10.1007/s10584-016-1668-3>
- Kriegler E, Bauer N, Popp A et al (2017) Fossil-fueled development (SSP5): an energy and resource intensive scenario for the 21st century. *Glob Environ Chang* 42:297–315. <https://doi.org/10.1016/j.gloenvcha.2016.05.015>
- Kriegler E, Bertram C, Kuramochi T et al (2018a) Short term policies to keep the door open for Paris climate goals. *Environ Res Lett* 13:074022. <https://doi.org/10.1088/1748-9326/aac4f1>
- Kriegler E, Luderer G, Bauer N et al (2018b) Pathways limiting warming to 1.5°C: a tale of turning around in no time? *Phil Trans R Soc A* 376:20160457. <https://doi.org/10.1098/rsta.2016.0457>
- Kunreuther H, Gupta S, Bosetti V, et al (2014) Integrated risk and uncertainty assessment of climate change response policies. In: Edenhofer O, Pichs-Madruga R, Sokona Y, 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*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA
- Lackner KS (2016) The promise of negative emissions. *Science* 354:714–714. <https://doi.org/10.1126/science.aal2432>
- Lamb WF, Creutzig F, Callaghan MW et al (2019) Learning about urban climate solutions from case studies. *Nat Clim Chang* 9:279–287. <https://doi.org/10.1038/s41558-019-0440-x>
- Lehtilä A, Koljonen T (2018) Pathways to post-fossil economy in a well below 2 °C world. In: Giannakidis G, Karlsson K, Labriet M, Gallachóir B (eds) *Limiting global warming to well below 2 °C: energy system modelling and policy development*. Springer, Cham, pp 33–49
- Leibowicz BD, Krey V, Grubler A (2016) Representing spatial technology diffusion in an energy system optimization model. *Technol Forecast Soc Chang* 103:350–363. <https://doi.org/10.1016/j.techfore.2015.06.001>
- Leimbach M, Bauer N, Baumstark L et al (2010) Technological change and international trade - insights from REMIND-R. *Energy J* 31:109–136. <https://doi.org/10.5547/ISSN0195-6574-EJ-Vol31-NoSI-5>
- Lemoine DM, Fuss S, Szolgayova J et al (2012) The influence of negative emission technologies and technology policies on the optimal climate mitigation portfolio. *Clim Chang* 113:141–162. <https://doi.org/10.1007/s10584-011-0269-4>
- Lewis S (2015) The dirty secret of the Paris climate Deal. *Foreign Policy*
- Lomax G, Lenton TM, Adeosun A, Workman M (2015) Investing in negative emissions. *Nat Clim Chang* 5:498–500. <https://doi.org/10.1038/nclimate2627>
- Luckow P, Wise M, Dooley J, Kim SH (2010) Large-scale utilization of biomass energy and carbon dioxide capture and storage in the transport and electricity sectors under stringent CO₂ concentration limit scenarios - ScienceDirect. *Int J Greenh Gas Con* 4. doi: <https://doi.org/10.1016/j.ijggc.2010.06.002>
- Luderer G, Pietzcker RC, Bertram C et al (2013) Economic mitigation challenges: how further delay closes the door for achieving climate targets. *Environ Res Lett* 8:034033. <https://doi.org/10.1088/1748-9326/8/3/034033>
- Luderer G, Krey V, Calvin K, et al (2014) The role of renewable energy in climate stabilization: results from the EMF27 scenarios. *Climatic Change* submitted
- Luderer G, Bertram C, Calvin K et al (2016a) Implications of weak near-term climate policies on long-term mitigation pathways. *Clim Chang* 136:127–140. <https://doi.org/10.1007/s10584-013-0899-9>
- Luderer G, Kriegler E, Delsa L, et al (2016b) Deep decarbonization towards 1.5 °C – 2 °C stabilization: policy findings from the ADVANCE project
- Luderer G, Vrontisi Z, Bertram C et al (2018) Residual fossil CO₂ emissions in 1.5–2 °C pathways. *Nat Clim Chang* 8:626–633. <https://doi.org/10.1038/s41558-018-0198-6>
- Magné B, Kypreos S, Turton H (2010) Technology options for low stabilization pathways with MERGE. *Energy J* 31:83–108
- Makihira A, Barreto L, Riahi K (2003) Assessment of alternative hydrogen pathways: natural gas and biomass. International Institute for Applied Systems Analysis (IIASA)
- Manne AS, Richels RG (2006) The role of non-CO₂ greenhouse gases and carbon sinks in meeting climate objectives. *Energy J* SI2006:. doi: <https://doi.org/10.5547/ISSN0195-6574-EJ-VolSI2006-NoSI3-20>
- Manoussi V, Shayegh S, Tavoni M (2017) Optimal carbon dioxide removal in face of ocean carbon sink feedback - FEEM working papers. Fondazione Eni Enrico Mattei, Milano, Italy
- Marcucci A, Kypreos S, Panos E (2017) The road to achieving the long-term Paris targets: energy transition and the role of direct air capture. *Clim Chang* 144:181–193. <https://doi.org/10.1007/s10584-017-2051-8>

- McCollum D, Krey V, Kolp P et al (2014) Transport electrification: a key element for energy system transformation and climate stabilization. *Clim Chang* 123:651–664. <https://doi.org/10.1007/s10584-013-0969-z>
- Meinshausen M, Smith SJ, Calvin K et al (2011) The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Clim Chang* 109:213. <https://doi.org/10.1007/s10584-011-0156-z>
- Méjean A, Guivarch C, Lefèvre J, Hamdi-Cherif M (2018) The transition in energy demand sectors to limit global warming to 1.5 °C. *Energ Effic*. <https://doi.org/10.1007/s12053-018-9682-0>
- Millar RJ, Fuglestad JS, Friedlingstein P, et al (2017) Emission budgets and pathways consistent with limiting warming to 1.5 °C. *Nat Geosci* ngeo3031. doi: <https://doi.org/10.1038/ngeo3031>
- Ming T, de Richter R, Shen S, Caillol S (2016) Fighting global warming by greenhouse gas removal: destroying atmospheric nitrous oxide thanks to synergies between two breakthrough technologies. *Environ Sci Pollut Res* 23:6119–6138. <https://doi.org/10.1007/s11356-016-6103-9>
- Mintenig J, Khabbazaan MM, Held H (2017) The role of Bioenergy and Carbon Capture and Storage (BECCS) in the case of delayed climate policy – insights from cost-risk analysis. *Earth System Dynamics Discussions In review*. doi: <https://doi.org/10.5194/esd-2017-117>
- Minx JC, Callaghan M, Lamb WF et al (2017a) Learning about climate change solutions in the IPCC and beyond. *Environ Sci Pol* 77:252–259. <https://doi.org/10.1016/j.envsci.2017.05.014>
- Minx JC, Lamb WF, Callaghan MW et al (2017b) Fast growing research on negative emissions. *Environ Res Lett* 12:035007. <https://doi.org/10.1088/1748-9326/aa5ee5>
- Minx JC, Lamb WF, Callaghan MW et al (2018) Negative emissions—part 1: research landscape and synthesis. *Environ Res Lett* 13:063001. <https://doi.org/10.1088/1748-9326/aabf9b>
- Mori S, Washida T, Kurosawa A, Masui T (2018) Assessment of mitigation strategies as tools for risk management under future uncertainties: a multi-model approach. *Sustain Sci* 13:329–349. <https://doi.org/10.1007/s11625-017-0521-6>
- Mouratiadou I, Luderer G, Bauer N, Kriegler E (2016) Emissions and their drivers: sensitivity to economic growth and fossil fuel availability across world regions. *Clim Chang* 136:23–37. <https://doi.org/10.1007/s10584-015-1368-4>
- Mousavi B, Blesl M, Giannakidis G et al (2018) Analysis of the relative roles of supply-side and demand-side measures in tackling the global 1.5 °C target. In: *Limiting global warming to well below 2 °C: energy system modelling and policy development*. Springer, Cham, pp 67–83
- Muratori M, Calvin K, Wise M et al (2016) Global economic consequences of deploying bioenergy with carbon capture and storage (BECCS). *Environ Res Lett* 11:095004–095004. <https://doi.org/10.1088/1748-9326/11/9/095004>
- Nakagawa S, Samarasinghe G, Haddaway N et al (2018) Research weaving: visualizing the future of research synthesis. *Trends Ecol Evol* 34:224–238. <https://doi.org/10.1016/j.tree.2018.11.007>
- Nemet GF, Callaghan MW, Creutzig F et al (2018) Negative emissions—part 3: Innovation and Upscaling. *Environ Res Lett* 13:063003. <https://doi.org/10.1088/1748-9326/aabff4>
- Obersteiner M, Azar C, Möllersten K, et al (2002) Biomass energy, carbon removal and permanent sequestration — a ‘real option’ for managing climate risk. International Institute for Applied Systems Analysis (IIASA)
- Obersteiner M, Bednar J, Wagner F et al (2018) How to spend a dwindling greenhouse gas budget. *Nat Clim Chang* 8:7–10. <https://doi.org/10.1038/s41558-017-0045-1>
- Parson EA (2017) Opinion: climate policymakers and assessments must get serious about climate engineering. *Proc Natl Acad Sci U S A* 114:9227–9230. <https://doi.org/10.1073/pnas.1713456114>
- Peters GP, Geden O (2017) Catalysing a political shift from low to negative carbon. *Nat Clim Chang* 7:619–621. <https://doi.org/10.1038/nclimate3369>
- Petticrew M, McCartney G (2011) Using systematic reviews to separate scientific from policy debate relevant to climate change. *Am J Prev Med* 40:576–578. <https://doi.org/10.1016/j.amepre.2010.12.022>
- Popp A, Rose SK, Calvin K et al (2014) Land-use transition for bioenergy and climate stabilization: model comparison of drivers, impacts and interactions with other land use based mitigation options. *Clim Chang* 123:495–509. <https://doi.org/10.1007/s10584-013-0926-x>
- Popp A, Calvin K, Fujimori S et al (2017) Land-use futures in the shared socio-economic pathways. *Glob Environ Chang* 42:331–345. <https://doi.org/10.1016/j.gloenvcha.2016.10.002>
- Rao S, Riahi K (2006) The role of non-CO₂ greenhouse gases in climate change mitigation: long-term scenarios for the 21st century. doi: <https://doi.org/10.5547/ISSN0195-6574-EJ-VolSI2006-NoSI3-9>
- Reilly J, Melillo J, Cai Y et al (2012) Using land to mitigate climate change: hitting the target, recognizing the trade-offs. *Environ Sci Technol* 46:5672–5679. <https://doi.org/10.1021/es2034729>
- Riahi K, Grübler A, Nakicenovic N (2007) Scenarios of long-term socio-economic and environmental development under climate stabilization. *Technol Forecast Soc Chang* 74:887–935. <https://doi.org/10.1016/j.techfore.2006.05.026>
- Riahi K, Kriegler E, Johnson N et al (2015) Locked into Copenhagen Pledges - implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technol Forecast Soc Chang*

- Riahi K, van Vuuren DP, Kriegler E et al (2017) The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. *Glob Environ Chang* 42:153–168. <https://doi.org/10.1016/j.gloenvcha.2016.05.009>
- Ricci O (2012) Providing adequate economic incentives for bioenergies with CO₂ capture and geological storage. *Energy Policy* 44:362–373. <https://doi.org/10.1016/j.enpol.2012.01.066>
- Rickels W, Reith F, Keller D et al (2018) Integrated assessment of carbon dioxide removal. *Earth's Future* 6:565–582. <https://doi.org/10.1002/2017EF000724>
- Rogelj J, Luderer G, Pietzcker RC et al (2015) Energy system transformations for limiting end-of-century warming to below 1.5 °C. *Nat Clim Chang* 5:519–527. <https://doi.org/10.1038/nclimate2572>
- Rogelj J, Popp A, Calvin KV et al (2018a) Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nat Clim Chang* 8:325–332. <https://doi.org/10.1038/s41558-018-0091-3>
- Rogelj J, Shindell K, Jiang S et al (2018b) Mitigation pathways compatible with 1.5°C in the context of sustainable development. 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, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., 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, and T. Waterfield (eds.)]. In Press
- Rose SK, Kriegler E, Bibas R et al (2014a) Bioenergy in energy transformation and climate management. *Clim Chang* 123:477–493. <https://doi.org/10.1007/s10584-013-0965-3>
- Rose SK, Richels R, Smith S et al (2014b) Non-Kyoto radiative forcing in long-run greenhouse gas emissions and climate change scenarios. *Clim Chang* 123:511–525. <https://doi.org/10.1007/s10584-013-0955-5>
- Roy J, Tschakert P, Waisman H et al (2018) Sustainable development, poverty eradication and reducing inequalities. 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, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., 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, and T. Waterfield (eds.)]. In Press
- Sanchez DL, Nelson JH, Johnston J et al (2015) Biomass enables the transition to a carbon-negative power system across western North America. *Nat Clim Chang* 5:230–234. <https://doi.org/10.1038/nclimate2488>
- Sanchez DL, Johnson N, McCoy ST, et al (2018) Near-term deployment of carbon capture and sequestration from biorefineries in the United States PNAS 201719695. doi: <https://doi.org/10.1073/pnas.1719695115>
- Sands RD, Förster H, Jones CA, Schumacher K (2014) Bio-electricity and land use in the future agricultural resources model (FARM). *Clim Chang* 123:719–730. <https://doi.org/10.1007/s10584-013-0943-9>
- Schaeffer M, Gohar L, Kriegler E et al (2015) Mid- and long-term climate projections for fragmented and delayed-action scenarios. *Technological forecasting and social change* 90(part a):257–268. <https://doi.org/10.1016/j.techfore.2013.09.013>
- Schlamadinger B, Grubb M, Azar C, et al (2001) Carbon sinks and biomass energy production: a study of linkages, options and implications 84
- Scott V, Geden O (2018) The challenge of carbon dioxide removal for EU policy-making. *Nat Energy* 3:350–352. <https://doi.org/10.1038/s41560-018-0124-1>
- Séférian R, Rocher M, Guivarch C, Colin J (2018) Constraints on biomass energy deployment in mitigation pathways: the case of water scarcity. *Environ Res Lett* 13:054011. <https://doi.org/10.1088/1748-9326/aabed7>
- Selosse S, Ricci O (2014) Achieving negative emissions with BECCS (bioenergy with carbon capture and storage) in the power sector: new insights from the TIAM-FR (TIMES Integrated Assessment Model France) model. *Energy* 76:967–975. <https://doi.org/10.1016/j.energy.2014.09.014>
- Selosse S, Ricci O (2017) Carbon capture and storage: lessons from a storage potential and localization analysis. *Appl Energy* 188:32–44. <https://doi.org/10.1016/j.apenergy.2016.11.117>
- Smith P, Bustamante M, Ahammad H, et al (2014) Agriculture, forestry and other land use (AFOLU). In: Edenhofer O, Pichs-Madruga R, Sokona Y, 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*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA
- Sohngen B, Sedjo R (2006) Carbon sequestration in global forests under different carbon price regimes. *Energy J* 27:109–126
- Stavins, Zou J, Brewer T, et al (2014) International cooperation: agreements and instruments. In: Edenhofer O, Pichs-Madruga R, Sokona Y, 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*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

- Stolaroff JK, Bhattacharyya S, Smith CA et al (2012) Review of methane mitigation technologies with application to rapid release of methane from the Arctic. *Environ Sci Technol* 46:6455–6469. <https://doi.org/10.1021/es204686w>
- Streffler J, Bauer N, Amann T, et al (2015) Enhanced weathering and BECCS - are carbon dioxide removal technologies complements or substitutes? Abu Dhabi, p 10
- Streffler J, Bauer N, Kriegler E et al (2018) Between Scylla and Charybdis: delayed mitigation narrows the passage between large-scale CDR and high costs. *Environ Res Lett* 13:044015. <https://doi.org/10.1088/1748-9326/aab2ba>
- Strengers BJ, Minnen JGV, Eickhout B (2008) The role of carbon plantations in mitigating climate change: potentials and costs. *Clim Chang* 88:343–366. <https://doi.org/10.1007/s10584-007-9334-4>
- Su X, Takahashi K, Fujimori S et al (2017) Emission pathways to achieve 2.0°C and 1.5°C climate targets. *Earth's Future* 5:592–604. <https://doi.org/10.1002/2016EF000492>
- Su X, Shiogama H, Tanaka K et al (2018) How do climate-related uncertainties influence 2 and 1.5 °C pathways? *Sustain Sci* 13:291–299. <https://doi.org/10.1007/s11625-017-0525-2>
- Tanaka K, O'Neill BC (2018) The Paris Agreement zero-emissions goal is not always consistent with the 1.5 °C and 2 °C temperature targets. *Nat Clim Chang* 8:319–324. <https://doi.org/10.1038/s41558-018-0097-x>
- Tavoni M, Soclow R (2013) Modeling meets science and technology: an introduction to a special issue on negative emissions. *Climate Change Economics* 118:1–14. <https://doi.org/10.1007/s10584-013-0757-9>
- Tavoni M, Sohngen B, Bosetti V (2007) Forestry and the carbon market response to stabilize climate 35:5346–5353. doi: <https://doi.org/10.1016/j.enpol.2006.01.036>
- Tavoni M, Kriegler E, Aboumahboub T et al (2013) The distribution of the major economies' effort in the Durban platform scenarios. *Climate Change Economics* 04:1340009–1340009. <https://doi.org/10.1142/S2010007813400095>
- Tavoni M, Bosetti V, Shayegh S et al (2017) Challenges and opportunities for integrated modeling of climate engineering. Social Science Research Network, Rochester
- Tokarska KB, Gillett NP (2018) Cumulative carbon emissions budgets consistent with 1.5 °C global warming. *Nat Clim Chang* 8:296–299. <https://doi.org/10.1038/s41558-018-0118-9>
- van der Zwaan B, Rösler H, Kober T et al (2013) A cross-model comparison of global long-term technology diffusion under a 2°C climate change control target. *Climate Change Economics* 04:1340013–1340013. <https://doi.org/10.1142/S2010007813400137>
- van Sluisveld MAE, Gernaat DEHJ, Ahina S et al (2013) A multi-model analysis of post-2020 mitigation efforts of five major economies. *Climate Change Economics* 04:1340012–1340012. <https://doi.org/10.1142/S2010007813400125>
- van Vliet J, den Elzen MGJ, van Vuuren DP (2009) Meeting radiative forcing targets under delayed participation. *Energy Econ* 31:S152–S162. <https://doi.org/10.1016/j.eneco.2009.06.010>
- van Vliet J, Hof AF, Mendoza Beltran A et al (2014) The impact of technology availability on the timing and costs of emission reductions for achieving long-term climate targets. *Clim Chang* 123:559–569. <https://doi.org/10.1007/s10584-013-0961-7>
- van Vuuren DP, Eickhout B, Lucas PL, den Elzen MGJ (2006) Long-term multi-gas scenarios to stabilise radiative forcing — exploring costs and benefits within an integrated assessment framework. *Energy J* 27: 201–233
- van Vuuren DP, den Elzen MGJ, Lucas PL et al (2007) Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. *Clim Chang* 81:119–159. <https://doi.org/10.1007/s10584-006-9172-9>
- van Vuuren DP, Deetman S, van Vliet J et al (2013) The role of negative CO₂ emissions for reaching 2 °C—insights from integrated assessment modelling. *Clim Chang* 118:15–27. <https://doi.org/10.1007/s10584-012-0680-5>
- van Vuuren DP, Hof AF, van Sluisveld MAE, Riahi K (2017) Open discussion of negative emissions is urgently needed. *Nat Energy* 2:902–904. <https://doi.org/10.1038/s41560-017-0055-2>
- van Vuuren DP, Stehfest E, Gernaat DEHJ et al (2018) Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. *Nat Clim Chang* 8:391–397. <https://doi.org/10.1038/s41558-018-0119-8>
- Vaughan NE, Gough C (2016) Expert assessment concludes negative emissions scenarios may not deliver. *Environ Res Lett* 11:095003. <https://doi.org/10.1088/1748-9326/11/9/095003>
- Vaughan NE, Gough C, Mander S et al (2018) Evaluating the use of biomass energy with carbon capture and storage in low emission scenarios. *Environ Res Lett* 13:044014. <https://doi.org/10.1088/1748-9326/aaa02>
- Westgate M, Haddaway N, Cheng SH et al (2018) Software support for environmental evidence synthesis. *Nat Ecol Evol* 2:588–590. <https://doi.org/10.1038/s41559-018-0502-x>
- Williamson P (2016) Emissions reduction: scrutinize CO₂ removal methods. *Nature News* 530:153. <https://doi.org/10.1038/530153a>

- Winning M, Pye S, Glynn J et al (2018) How low can we go? The implications of delayed ratcheting and negative emissions technologies on achieving well below 2 °C. In: Limiting global warming to well below 2 °C: energy system modelling and policy development. Springer, Cham, pp 51–65
- Wise M, Calvin K, Thomson A et al (2009) Implications of limiting CO₂ concentrations for land use and energy. *Science* 324:1183–1186. <https://doi.org/10.1126/science.1168475>
- Yamagata Y, Hanasaki N, Ito A et al (2018) Estimating water–food–ecosystem trade-offs for the global negative emission scenario (IPCC-RCP2.6). *Sustain Sci* 13:301–313. <https://doi.org/10.1007/s11625-017-0522-5>
- Yamamoto H, Sugiyama M, Tsutsui J (2014) Role of end-use technologies in long-term GHG reduction scenarios developed with the BET model. *Clim Chang* 123:583–596. <https://doi.org/10.1007/s10584-013-0938-6>

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Affiliations

Jérôme Hilaire^{1,2} • Jan C. Minx^{1,3} • Max W. Callaghan¹ • Jae Edmonds⁴ • Gunnar Luderer² • Gregory F. Nemet⁵ • Joeri Rogelj^{6,7,8} • Maria del Mar Zamora¹

Jan C. Minx
minx@mcc-berlin.net

- ¹ Mercator Research Institute on Global Commons and Climate Change, Torgauer Straße 12-15, EUREF Campus #19, 10829 Berlin, Germany
- ² Member of the Leibniz Association, Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany
- ³ School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK
- ⁴ Pacific Northwest National Laboratory – Joint Global Change Research Institute, 5825 University Research Court, College Park, MD 20740, USA
- ⁵ La Follette School of Public Affairs, University of Wisconsin–Madison, 1225 Observatory Drive, Madison, WI 53706, USA
- ⁶ ENE Program, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria
- ⁷ Grantham Institute for Climate Change and the Environment, Imperial College London, London SW7 2AZ, UK
- ⁸ Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland