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# HAMBURG CLIMATE FUTURES OUTLOOK

Assessing the plausibility of deep decarbonization by 2050

Universität Hamburg
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**CLUSTER OF EXCELLENCE**
CLIMATE, CLIMATIC CHANGE, AND SOCIETY (CLICCS)

## About CLICCS

Researchers from a wide range of disciplines have joined forces at the Cluster of Excellence CLICCS (Climate, Climatic Change, and Society) to investigate how climate and society will co-evolve. The CLICCS program is coordinated through Universität Hamburg's Center for Earth System Research and Sustainability (CEN) in close collaboration with multiple partner institutions and is funded by the Deutsche Forschungsgemeinschaft (DFG).

## About the Outlook

In the annual *Hamburg Climate Futures Outlook*, CLICCS researchers make the first systematic attempt to assess which climate futures are plausible, by combining multidisciplinary assessments of plausibility.
The inaugural 2021 *Hamburg Climate Futures Outlook* addresses the question: Is it plausible that the world will reach deep decarbonization by 2050?

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# Plausibility of model-based emissions scenarios


3.1 Climate scenarios used in the IPCC

3.2 The scenario framework of this Outlook

3.3 Plausibility of existing scenarios

3.4 Deep decarbonization by 2050

BOX II Synergies and trade-offs in the assessment of plausible climate futures

# 3

# Plausibility of model-based emissions scenarios

Scenarios help explore the future of climate by integrating many diverse aspects of the physical and social system. The goal of combining the techno-economic aspects of climate change with the physical consequences of resulting emissions has driven much of the history of model-based scenario development within the IPCC community (Section 3.1). This *Outlook* starts its assessment with the most recent generation of scenarios used in the IPCC, the SSPs (Riahi et al., 2017), and especially the high-priority subset of SSP scenarios, which are used as input for the newest generation of comprehensive climate models (O'Neill et al., 2016; see Section 3.2). Section 3.3 assesses the techno-economic plausibility of the high-priority SSP scenarios. In Section 3.4, we propose the scenario *deep decarbonization by 2050* and bridge the gap between the techno-economic and social plausibility assessments of low emissions climate futures.

## 3.1

## Climate scenarios used in the IPCC

Scenarios have long been an important structuring element in thinking about climate futures. IPCC assessments have over the last decade relied on a scenario framework that builds on two main elements: Representative Concentration Pathways (RCPs), which describe stylized forcing outcomes (van Vuuren et al., 2011), and Shared Socioeconomic Pathways (SSPs), which describe typical evolutions of the world without additional climate policies (O'Neill et al., 2014). These are complemented by Shared Policy Assumptions (SPAs) that enclose key characteristics of climate policies, concerning both mitigation and adaptation (Kriegler et al., 2014). All three were conceived as interdependent; RCPs and SSPs form a so-called *scenario matrix*, to which SPAs were to add a third dimension (van Vuuren et al., 2013). In practice, policy assumptions have been implemented as forcings that lead to change within the SSP-RCP matrix, without necessarily adding a third dimension. The rationale for this framework stems from practical considerations concerning the sequential organization of disciplinary modeling exercises for IPCC assessments, but also from reflections on the ways to ensure policy-relevance of simulations while avoiding policy prescriptiveness (Moss et al., 2008; Moss et al., 2010).

The SSP-RCP scenario framework is inscribed in a long history of scenario-building, but also departs from approaches used in earlier IPCC assessments. Previous approaches include the SA90-scenarios for the IPCC First Assessment Report (IPCC, 1990: Appendix I), the IS92 scenarios for the 1992 IPCC Supplementary Report and the Second Assessment Report (Leggett et al., 1992; Alcamo et al., 1995), and the scenario family for the Third and Fourth Assessment Reports based on the Special Report on Emissions Scenarios (SRES; Nakicenovic et al., 2000). These scenario architectures not only shape the ways in which researchers from different disciplines collaborate in the IPCC process, they also entail important yet often implicit assumptions about societal dynamics and social change (Garb et al., 2008), global politics and governance (Parikh, 1992; Dahan-Dalmedico, 2008), technological innovation (Pielke Jr et al., 2008), and possible solution spaces (Beck and Mahony, 2017).

Like its predecessors, the SSP-RCP scenario matrix also embodies specific views on the needs of the policy process in terms of prospective expertise (Cointe et al., 2019). Such views changed over the years (Girod et al., 2009). One of the most important long-standing debates concerns the inclusion of *business-as-usual* scenarios in contrast to *intervention* or *climate policy* scenarios. While the IPCC First Assessment Report included one business-as-usual scenario and three intervention scenarios, the IS92 scenarios include one business-as-usual and five non-intervention scenarios, which represent different possible evolutions of the world. The SRES scenarios are exclusively based on non-intervention baseline scenarios (six illustrative families, including three high-growth pathways, a global and a local sustainability pathway, and a regional growth pathway, making a total of 40 scenarios), which describe contrasting evolutions of the world, independent of climate policy measures. The SRES scenarios have been criticized in turn for being apolitical; they do not include explicit policy choices, although their results implicitly embed climate stabilization measures (Webster et al., 2008). This has been partly addressed in the SSP-RCP matrix. The SSPs also represent stylized evolutions in the absence of climate policy: a world of sustainability and equality (SSP1); a "middle of the road" world that perpetuates historical trends (SSP2); a fragmented world of regional rivalry (SSP3); a world of increasing inequality and low sustainability (SSP4); and a world of unconstrained growth and fossil fuel use (SSP5). However, SSPs can subsequently be combined with mitigation targets (in the form of RCPs) to test how these targets can be achieved within the context of varying assumptions about socioeconomic developments and policy choices.

A second debate concerns the transparency and usability of scenarios. Hence, the SRES scenario family is the first to include explicit narrative storylines. By making some of the assumptions behind the scenarios explicit, these storylines—which are also the foundation of the SSPs—provide a scientific foundation to scenario choice and construction. Moreover, they also increase the transparency of the scenario process and can thereby enhance the intelligibility of scenarios for users.

Overall, the history of scenarios used by the IPCC shows multiple trade-offs between scientific credibility, public salience, and political legitimacy of scenarios (Girod et al., 2009). This can be illustrated using the two debates discussed above. First, the progressive exclusion of business-as-usual, but also of explicit policy intervention scenarios increased the political legitimacy of the scenario process, because the United States and developing countries had expressed their opposition to the inclusion of both types of scenarios (albeit for different reasons). However, by excluding explicit policy choices and thereby the possibility of evaluating the effect of contrasting policy and governance options, this development also tended to reduce the public salience of scenarios. Second, the inclusion of storylines and multiple baseline scenarios in the SRES and the current SSP-RCP methodologies was seen as a way to enhance the scientific credibility of scenario construction. This came at the price of reducing public salience, because the high number of baseline scenarios and an increasingly unclear classification makes it difficult for wider publics to understand the political assumptions underlying IPCC scenarios and the reasons behind the wide range of warming outcomes.

# 3.2

# The scenario framework of this Outlook

### **3.2.1** SSP high-priority scenarios

The five high-priority SSP scenarios (O'Neill et al., 2016; Meinshausen et al., 2020) make a suitable basis for the *Outlook*, because these scenarios represent a wide range of socioeconomic narratives and emissions pathways, but are nevertheless limited in number, increasing their salience. The limited scenario selection is generic enough to withstand a multidisciplinary assessment of plausibility, which may be unable to distinguish between small differences between scenarios. The high-priority scenarios were also selected in such a way as to maximize usefulness to multiple research communities (Gidden et al., 2019). Finally, the selection encompasses a forcing level corresponding to the 1.5°C-warming target and therefore maintains political legitimacy.

### **3.2.2** Very low emissions, the 1.5°C-target, and deep decarbonization

Scenario SSP1-1.9 is the only high-priority SSP scenario that is designed to constrain warming within 1.5°C by the end of the century (O'Neill et al., 2016; van Vuuren et al., 2017; Meinshausen et al., 2020). A related set of four scenarios in the *IPCC Special Report on Global Warming of 1.5°* (SR1.5), Scenarios P1-P4, were also specifically designed to comply with the 1.5°C-target and illustrate how different balances between emissions reductions and carbon dioxide removal (CDR) could meet this target (IPCC, 2018b). All scenarios that meet the 1.5°C-target reach net $CO_2$ emissions around the year 2050 (Rogelj et al., 2018).

The SSP1 narrative is ill-suited for the social-plausibility assessment in Chapter 5, since its techno-economic focus omits descriptions of deeper social processes that create the motivation for such a socio-economic future. We therefore propose the scenario description *deep decarbonization by 2050* (see Section 3.4), which complements the techno-economic assessment in Section 3.3 and frames the most critical aspects for assessing the social plausibility of the low emissions scenario.

For the physical plausibility assessment in Chapter 6, we return to SSP1-1.9 for calculating long-term warming. Since the 1.5°C-target and deep decarbonization by 2050 are approximately commensurate with the greenhouse gas concentrations described in SSP1-1.9, both the techno-economic (Section 3.3) and social plausibility (Chapter 5) assessments can be brought to bear on this scenario and help limit the range of scenarios in the physical science framework.

### **3.2.3** Very high emissions

For the techno-economic assessment in this chapter, we examine the high-priority emissions scenario with the highest emissions, SSP5-8.5. In the physical plausibility assessment in Chapter 6, we then draw upon the results of the techno-economic plausibility assessment for very high emissions.

# 3.3

# Plausibility of existing scenarios

None of the scenarios mentioned in Sections 3.1 and 3.2 were developed with a probabilistic interpretation in mind. About twenty years ago, some discussion emerged on whether scenarios should be given a probabilistic interpretation or not (Grubler and Nakicenovic, 2001; Schneider, 2001; Schneider, 2002). Currently, the "not"-camp prevails. Nakicenovic et al. (2014) gave no probabilistic interpretation when the SPA/SSP-framework was introduced, and the later accounts and applications followed suit (e.g., O'Neill et al., 2016; Riahi et al., 2017). The question is whether there is sufficient information for providing some sort of probabilistic weighting on scenarios (Ho et al., 2019; Hausfather and Peters, 2020). We claim that such probabilistic information would be valuable in two ways. First, the range of plausible mitigation costs could be constrained. Mitigation costs are derived from contrasting a no-mitigation policy scenario (baseline scenario) and a scenario with the same set of assumptions but including a mitigation-policy goal. Baseline scenarios with lower emissions must close a smaller emissions gap in the mitigation policy scenario and therefore have lower mitigation costs. If the set of baseline assumptions could be constrained probabilistically, so could plausible mitigation costs. Second, the community dealing with centennial-scale adaptation planning could reduce the scope of global warming futures they accept as plausible. The first step in the *Outlook* methodology consists in a review of existing studies that influence the techno-economic plausibility of some future climate scenarios.

The IPCC SR1.5 (IPCC, 2018b) presents many scenarios compatible with the 1.5°C target, and all of them require net negative emissions at some point in time. We therefore assume that the plausibility of low emissions scenarios depends on the demand for negative emissions technologies, comprising bioenergy with carbon capture and storage (BECCS), afforestation and reforestation, direct air carbon capture and storage, enhanced weathering, ocean fertilization, biochar, and soil carbon sequestration. While limited evidence points to the possibility of complying with the 1.5°C target without dedicated negative emissions technologies (Holden et al., 2018), a majority of authors sees these technologies as necessary (Fuss et al., 2018b; Hilaire et al., 2019). SR1.5 specifies an interquartile range of 364 to 662 $GtCO_2$ to be removed through BECCS by 2100 (IPCC, 2018b). Concerns have been expressed regarding this scale (Boysen et al., 2017), referring to the pressure on global water use. In general, the resulting potential conflicts arising from BECCS involve fertilizer and water needs (Heck et al., 2018), competition with food production (IPCC, 2019) and biodiversity protection. Following Smith et al. (2016), the water requirements for removing one $GtCO_2$ with BECCS could be as high as 500 $km^3$, or about 10 % of current annual global water demands (Boretti and Rosa, 2019). This implies substantial trade-offs between mitigation and other SDGs (see also Box 2).

We note two further mechanisms that add to the implausibility of complying with the 1.5°C target. First, its plausibility might already be hampered by the baseline assumptions (Boysen et al., 2016). Second, mitigation costs are thought to double when raising the ambition from a 2°C to a 1.5°C target (Rogelj et al., 2015).

There are also arguments that speak against the plausibility of very high emissions scenarios. Scenario RCP8.5, the forerunner of SSP5-8.5, was constructed as a high-end emission scenario and should not be understood as a business-as-usual scenario (e.g., Hausfather and Peters, 2020). But is it at least plausible? A number of arguments against its plausibility have been articulated. Ritchie and Dowlatabadi (2017) expressed doubt as to whether the recoverable coal reserves would suffice to fuel this scenario. Hausfather and Peters (2020) argued that the falling cost of clean energy sources is a trend unlikely to be reversed, making a fivefold increase in coal use by the end of the century implausible. Furthermore, Levermann (2014) and Stern (2016) hypothesized that RCP8.5 is inconsistent because warming-induced damages would dampen economic growth to such an extent that it would be unable to drive the necessary emissions. This hypothesis has received support from modeling work that incorporates feedbacks between warming, the economy, and emissions reductions. Relative to baseline scenarios such as RCP8.5, emissions were reduced by 4.7% (Roson and van der Mensbrugghe, 2012) and 14% (Woodard et al., 2019) in year 2100. This implies that baseline assumptions would have to be even more extreme than in RCP8.5 to generate the emission levels underlying this scenario. Finally, modeling work that explicitly accounts for climate-induced economic damages in a forward-looking manner results in substantially lower economically optimal twenty-first-century emissions and global warming (e.g., Hänsel et al. 2020).

In summary, there is substantial techno-economic evidence against the plausibility of both very low emissions scenarios compatible with 1.5°C climate futures and very high emissions scenarios such as RCP8.5.

## 3.4

# Deep decarbonization by 2050

The techno-economic evidence against very low emissions scenarios speaks against the plausibility of large-scale deployment of CDR technologies. However, some very low emissions scenarios, such as P1 from the IPCC SR1.5 rely more on rapid emissions reductions than on CDR to reach net carbon zero. To complete our plausibility assessment of these very low emissions scenarios, we must therefore also consider the plausibility of rapid emissions reductions, reaching around net carbon zero by 2050 in order to meet the 1.5°C target. The plausibility of rapid emissions reductions by 2050 is inherently anchored in the plausibility of social processes, which provide the impetus to bring about such wide-reaching social change. In Chapter 4, we develop a framework to analyze the social processes that might drive such a social transformation. For this purpose, we propose a scenario that describes that social transformation—*deep decarbonization by 2050*.

Deep decarbonization describes the transition to net-zero carbon emissions, which entails very low carbon intensity in all sectors of the economy (Deep Decarbonization Pathways Project, 2015) and a reduction in energy demand and demand for carbon-intensive consumer goods (IPCC, 2018b). Such a transition also implies a radical social transformation, including changes in norms, regulations, institutions, and individual behaviors and personal values (Shove and Walker, 2010; O'Brien, 2018). The scenario must be delineated from other, less constrained futures in which decarbonization is only partially achieved by 2050. However, the scenario must also be generic enough to allow interpretation and assessment of their social plausibility.

We therefore deliberately exclude quantitative details concerning exact emission levels and different types of forcings, and focus on the approximate magnitude of change required to bring about a net-zero balance of the sources and sinks of $CO_2$ on a global scale. We assume that the social transformation required to bring about net carbon zero will contain sufficient societal momentum to reduce human-induced climate forcers other than $CO_2$ to net zero. Similarly, the techno-economic assumptions about economic growth, population growth, and carbon prices do not form part of the scenario.

We also allow for a small CDR stopgap, based on the techno-economic analysis in this chapter. This allows us to include futures in which net zero carbon is almost reached, but in which some regional economies or sectors resist complete decarbonization by 2050, since the capability of national and regional economies to decarbonize will depend on their current energy mix and respective institutional structures (Bataille et al., 2016: 8). Providing for a small CDR stopgap buys time or relieves part of the burden of socio-technical change for these resistant regions and sectors, and relieves the burden of attempting to forecast exact quantities of emissions by 2050, which is not tenable given the qualitative nature of the social plausibility assessment.

We delineate deep decarbonization from partial decarbonization in the extent and speed at which such transformation occurs. This distinction is necessarily qualitative, but some quantitative assessment can place the magnitude of this extent and speed in perspective. To reduce the approximately 36 $GtCO_2$ per year of worldwide anthropogenic $CO_2$ emissions (Friedlingstein et al., 2019) by around 90 % decarbonization by 2050, a compounding mitigation rate (Raupach et al., 2014) of over 7 % of global emissions would be required each year. This mitigation rate is equivalent to reducing year-on-year emissions every year until 2050 at the rate in reductions caused by the worldwide COVID-19 lockdown measures in 2020 (see Box 4).

Further qualities of decarbonization can place the extent and speed of such a transformation in perspective. For example, there are considerable constraints on the speed at which new zero-carbon industrial technologies will need to be developed and then deployed (Monschauer et al., 2019). The diffusion of new technologies is typically delayed by formative phases of commercial experimentation and learning, followed by optimization of design or up-scaling, which can take many decades (Wilson, 2012). There is some evidence that transitions in some markets and for some technologies are not always long, protracted affairs (Sovacool, 2016). However, even when a technology is mature enough for market penetration, there are additional delays caused by existing capital investment, which locks in particular modes of consumption (see discussion on path dependence in Chapter 4). For example, even if electric cars reach considerable technological maturity in the next decades, the lock-in effects of internal-combustion engines that have already been purchased could significantly delay decarbonization in the transport sector (Climate Transparency, 2019; Monschauer et al., 2019). We can therefore expect that the legislative and regulatory changes to promote the needed socio-technical transformation must be in place well in advance of 2050.

The nature and speed of the transition will also be determined by who drives the change. For example, decarbonization might be driven bottom-up by changes in social behavior, cultural meaning, and niche innovations that alter the existing market. Alternatively, decarbonization might be driven top-down by incumbent actors in policy and industry; in this case, practices and lifestyles may remain unchanged, but a radical technological substitution of energy sources and heavy reliance on CDR would be required. The resulting energy mix (Geels et al., 2020; Rogge et al., 2020; van Sluisveld et al., 2020) can vary dramatically, especially the relationship between solar and wind. Similarly, the reduction in energy demand, the prevalence of public transport, and the market share of battery or hybrid passenger vehicles can all depend on which strategic actors drive the change (van Sluisveld et al., 2020). Some challenges in the low-carbon transition—such as finding solutions to energy storage—will require a combination of technological, institutional, and social innovation (Eyre et al., 2018). Tracking social drivers may therefore sharpen our perspective of which actors are leading the change and sharpen our definition of the deep decarbonization scenario in future *Outlooks*.

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