False Hopes, Missed Opportunities: How Economic Models Affect the IPCC Proposals in Special Report 15 “Global Warming of 1.5 °C” (2018). An Analysis From the Scientific Advisory Board of BUND

Joachim H. Spangenberg
Scientific Committee of BUND/FoE Germany

Werner Neumann
Scientific Committee of BUND/FoE Germany

Heinz Klöser
Scientific Committee of BUND/FoE Germany

Stefan Wittig
Scientific Committee of BUND/FoE Germany

Tilmann Uhlenhaut
Scientific Committee of BUND/FoE Germany

Martha Mertens
Scientific Committee of BUND/FoE Germany

Edo Günther
Scientific Committee of BUND/FoE Germany

Ingo Valentin
Scientific Committee of BUND/FoE Germany

Markus Große Ophoff
Scientific Committee of BUND/FoE Germany

The 2018 IPCC Special Report SR15 developed four scenarios how temperature increases could either be limited to 1.5°, or, in the case of overshoot, could be brought back to that level by 2100. However, the Carbon Dioxide Removal options discussed to achieve "negative emissions" will affect not only the climate system, but also biodiversity and the ecosystem services it provides. Unfortunately, the Integrated Assessment Models, and in particular the economic models incorporated in them were capable of integrating only a selective fraction of these effects, and ignore potential tipping points triggering irreversible processes, policies beyond economic instruments and consumption changes to happen over the next 80 years. Our analysis is based on an interdisciplinary expert elicitation, analysing the options suggested by the IPCC one by one. We find that most of them are associated with biodiversity loss, hazardous chemicals dispersion, enhanced energy consumption and/or other severe other damages. We suggest which measures can be applied sustainably, which should be dropped, and which additional ones have been omitted by the report.

Keywords: IPCC SR 15, 1.5° overshoot scenarios, Carbon Dioxide Removal (CDR), biodiversity loss, risks of geoengineering

INTRODUCTION: CHALLENGE CLIMATE MODELING

The climate system is a complex, dynamic system that is not in equilibrium, but forms a dynamically changing dissipative pattern far from equilibrium, which is maintained by permanent energy and material throughput (Prigogine 1997). Because it follows physical laws, its development is in principle predictable (Bar-Yam 1997), but due to the complexity of the system with its inherent moments of uncertainty it is not exact but with ranges of ordinal probability classes.[1]

This comparatively safe situation ends when human decisions in politics, economics and consumption are taken into account. Due to the only weakly rule-based, anticipating behavior of the actors, longer-term prognoses are impossible and plausible scenarios are limited to a maximum of 20 to 30 years (Allen 1998; Bossel 2000), as evolutionary, system-dynamic or agent-based models can provide, but not the equilibrium models that are predominantly used in the Integrated Assessment Models (IAM) of climate research (Spangenberg, Polotzek 2019).

The report considers two types of development paths to be consistent with the 1.5°C target: those that limit global warming to a maximum of 1.5°C with a probability of 1/2 or 2/3 and those that exceed the target but reduce warming to 1.5°C in the second half of the century through "negative emissions".

In our opinion, the second group cannot be regarded as a suitable basis for a successful climate policy, because the ecological consequences can be fatal even with a steady development (Su et al. 2018; Wiens 2016). However, such gradual changes will not be the only ones, because exceeding the 1.5° threshold increases the probability that irreversible degradation processes will be set in motion beyond tipping points (Steffen et al. 2018, IPCC 2018). This is true for the polar regions, as recent observations of metha-ice dissolution in the coastal North Ocean show, as well as the melting of ice in Greenland (2019 as predicted by models for 2070), the forest fires north of the Arctic Circle with climate effects of burning peat soil, against which methane emissions from thawing permafrost are comparatively marginal and which cannot be stopped by further warming, the thawing permafrost in Alaska (locally in 2019 as expected for 2090), and ice losses in Antarctica (Shepherd et al. 2019)[2]. Present and near border crossings can also be seen in the ice losses of the "third pole", the Himalayas/Hindukush mountains, where a third of the ice masses are already unsustainable (endangering the drinking water supply of 2 billion people) and the rest may become unstable with further warming (Wester et al. 2019; Maurer et al. 2019). While Antarctica has already crossed the threshold of net ice loss (snowfall minus defrosting), the current best available estimate for this step for the Greenland ice sheet, for example, is 1.6°C (Ch3: 163). Further tipping points between 1.5° and 2° are not unlikely, especially if human mismanagement continues: according to recent estimates, the transition of the Amazon to bush steppe can become irreversible not only at a tipping point of about 4°C, but also if 20-25% of the total forest is lost, or more precisely: destroyed by humans, mostly by large agricultural corporations. We have already achieved a 17% loss, and if there is no fundamental change in policy, we will have to pay the 20% by the end of the right-wing government extreme Brazilian president. This would have significant consequences for the defeats and thus for agriculture in large parts of South America, but would also influence the global wind system and thus the extreme weather conditions in North America and beyond. However, such impacts cannot be estimated in IAM models (the models used in SP15 generally do not reflect the repercussions of the climate crisis on the economy and society).

Another reason to reject policy proposals that rely on exceeding the threshold of 1.5° with subsequent compensation by "negative emissions" is that they rely on the reversibility of climate impacts, i.e. assume that the status quo ante can be restored by reducing the atmospheric content of CO2 equivalents. This is not true in purely physical terms, because the climate's reaction to accumulated greenhouse gases for rising and falling atmospheric CO2 concentrations is different: inertia in the carbon cycle and in the ocean heat balance leads to a hysteresis curve. This asymmetric, path-dependent behavior is not yet well quantified and represents an important knowledge gap (Ch2: 21). Even more so, reversibility does not exist in biological and even less in socio-economic systems (Allen 1997). Instead, the sequence of first overheating and then cooling represents a double burden for biodiversity, habitat relocation, disruption of food webs, desynchronization of multi-species processes (bloom and appearance of pollinators, maturity and appearance of biocontrol populations, predators and prey, etc.), with corresponding risks for biodiversity and ecosystem services (IPBES 2019). And the assumption that economic, technical, social and other societal developments could be put back to a previous state is clearly unrealistic.

To make matters worse, even when all known "negative emissions" technologies are used, there is no guarantee that the technologies we trust in will work. The higher concentrations of CO2 equivalents accepted for them can really be reversed, because the technologies are not only risky but also uncertain (Ch2: 4). No such technology has ever been realized in the necessary scale; to reduce atmospheric CO2 concentrations by 50 ppm, 400 Gt CO2 would have to be emitted - other trace gases with a high greenhouse gas effect are not considered (Niall et al. 2012). As a result, concerns are growing about the potential, feasibility, suitability and sustainability of such technologies (Ch2: 31). It is clear to the IPCC that the technologies for CDR (Carbon Direct Removal) or "negative emissions" are neither proven effective nor generally accepted.[3] Nevertheless, they form the backbone of almost all scenarios, even if current analyses dampen quantitative hopes (Smith et al. 2016; Minx et al. 2018; Fuss et al. 2018; Conniff 2019). The fact that they nevertheless appear indispensable is partly due to the fact that almost all scenarios (all except the new "extreme sustainability" scenario) assume the continued use of nuclear and coal-fired power plants - fossil-free energy systems are recognized as feasible but are too expensive according to the econometric IAM models (whereby, as mentioned, the socio-economic consequential costs of climate change are not or only partially taken into account)(IPCC 2018). Other studies that work with other models come to completely different conclusions on this point (including UBA 2019; BfN 2018).

Also due to the fact that technologies for the recovery of CO2 from the air will only be available to a very limited extent before the middle of the century (Nemet et al. 2018), most of the scenarios described in the IPCC report are those with overshoot. The question is therefore whether limiting climate change to 1.5° requires such technologies, and whether they are suitable proposals taking into account effectiveness, efficiency and side effects.

In our opinion, hardly any of the proposed measures meet the criteria of sustainable development - some would have to be modified, but many would have to be eliminated. In part 2 we give reasons for our criticism, while in part 3 we identify the measures whose sustainably usable potential is not considered in the scenarios. Part 4 refers to the need to integrate such steps for climate protection with a broad environmental and sustainability agenda.

Mene, Mene, Tekel - Counted, Weighed and Found Too Light: The IPCC Scenarios Proposals[4]

Whether a bundle of measures can be regarded as target-oriented depends, among other things, on the assumptions made about sources and activatable sinks of greenhouse gases. In the case of the latter, in SR 15, in addition to afforestation and reforestation, BECCS in particular dominates the plan to generate energy from biomass and to capture and store underground the CO2 emissions produced during combustion. Other methods that play a role in scenario narratives, but are not yet depicted in the vast majority of models, are the introduction of pyrolysis coal into the soil (Biochar or Terra Preta), carbon fixation in the soil and carbon sequestration by rock weathering ("enhanced weathering"); the report emphasizes the substantially lower use of soil and water by these methods and hopes to achieve additional benefits (Ch3: 159).

In all cases, capturing and binding CO2 from the atmosphere or from exhaust gas streams requires energy first and foremost, because the CO2 molecule is chemically at a very low energy level. It must therefore be extracted from the air with a high energy input, bound, concentrated, bound to other molecules and finally deposited somewhere. The various processes of negative emissions differ not only in the method of capturing the CO2, but also in the source of this required energy input. In the IPCC report it is not always clear whether the capture quantities mentioned are gross or net sums and, if so, which energy mix was used to calculate the net figures. Energy input and energy mix would also influence the costs stated in $ per t CO2.

Finally, the extraction of CO2 from the atmosphere would probably lead to a release from the oceans, which have absorbed the largest part of the CO2 emissions so far; then the net effect of the extraction would only be about half as high (Rahmsdorf 2019).

Ocean Fertilization

The largest natural sink for CO2 is the oceans: they have absorbed about 30 percent of the anthropogenic carbon dioxide emitted to date (IPCC 2014). Plant marine plankton in particular, which accounts for about half of the world's photosynthesis output (Leujak et al. 2011), absorb large quantities of CO2. Via the food chain, the stored carbon dioxide reaches other marine organisms such as small crustaceans, fish or whales in organic form. If these organisms or the plankton die, they usually sink. A large part of this biomass is utilized by bacteria during transport and in the sediment, whereby the carbon dioxide stored in the organisms is released back into the surrounding water and eventually comes into contact with the atmosphere again via ocean circulation. Only a small part of the biomass sinks into the deep sea, where it is deposited deeper into the sediment at the seafloor and thus a part of the carbon dioxide originally stored in plankton is removed from the atmosphere for longer periods of time - up to 1,000 years - from exchange with the atmosphere (so-called biological pump) (DFG 2018, Salter et al. 2014).

In about one quarter of the world's oceans there is a natural deficiency of plant nutrients, especially iron (DFG 2018). Therefore, ideas for artificial iron fertilization were developed years ago. Fertilization with iron could considerably boost plankton growth, so that the uptake of carbon dioxide from the atmosphere would increase. Ultimately, more carbon dioxide could be transported into the deep sea by the dead biomass (AWI 2014, DFG 2018, Salter et al. 2014). Although iron fertilization may increase plankton growth and carbon dioxide uptake (Bakker et al. 2001; Sarmiento, Orr 1991), the potential is often significantly overestimated, since the amount of plankton that actually sinks to the deep and thus removes carbon dioxide from the atmosphere in the long term is small (Fuss et al. 2018).

Experiments have confirmed this critical assessment, e.g. the German-Indian LOHAFEX experiment, in which the German research vessel Polarstern spread 10 t of iron in the form of iron sulphate in a 300 square kilometer test area (Leujak et al. 2011). A study on natural iron fertilization in the Southern Ocean has shown that additional iron even reduces the effectiveness of the biological pump that transports carbon dioxide from the upper water layers to the deep sea (AWI 2014). In addition, iron fertilization can lead to the proliferation of phytoplankton and calcareous shell-forming marine life that feeds on algae. These animals release carbon dioxide when they build their calcareous shells. If these creatures die in a marine area with a high natural iron input, up to 30% less carbon dioxide is released into the deep sea than previously assumed (AWI 2014).

The low effectiveness is counterbalanced by considerable ecological side effects; a number of potential hazards and side effects are known for marine ecosystems (Ziebarth 2010). For example, iron fertilization has an effect on the species composition of a habitat (AWI 2014), when algae species that grow faster with a higher nutrient supply or that quickly absorb particularly large amounts of CO2 displace other algae (Ziebarth 2010). Such a species shift can affect the food webs and thus the entire ecosystem. In addition, the formation of anthropogenically forced (toxic) algal blooms can occur (German Bundestag 2009, Leujak et al. 2011), which can cause considerable disturbances in the ecosystem, as can be observed in marine areas eutrophicated by environmental pollution. These include, above all, the development of so-called "death zones", i.e. sea floor areas in which vital oxygen has been completely depleted due to the decomposition of the sedimented plankton. Currently, a threatening expansion of such zones is being observed (Jokinen et al. 2018) and this trend would be considerably intensified when fertilizing sea reservoirs. As a side effect of too much nutrients and too little oxygen, bacterial activity can also increase the formation of the stronger greenhouse gas nitrous oxide, which can rise from the sea into the atmosphere and outweigh the effects of ocean fertilization.

In addition, such experiments and research projects violate the moratorium on ocean fertilization (Decision IX/16) adopted at the 9th Conference of the Parties to the Convention on Biological Diversity (COP 9 of the CBD) in Bonn (German Bundestag 2009).

Overall, ocean fertilization cannot be applied on a large scale, nor is its potential and/or side effects sufficiently known. In particular, the interaction of the current warming and acidification of the oceans and the future effects of ocean fertilization may lead to unpredictable effects on marine ecosystems. There are therefore scientific, legal, ethical and political concerns about ocean fertilization.

Rock Weathering and Marine Alkalinization

The absorption by the oceans of carbon dioxide emitted by the burning of fossil fuels leads to the formation of carbonic acid and is responsible for the increasing acidification of the oceans (BIOACID 2019). Natural weathering counteracts ocean acidification (Albright et al. 2016, Feng et al. 2016) by washing the mineral components dissolved from the rocks during natural weathering from the land into the sea and permanently binding them in the seawater in the form of bicarbonate and carbonate ions (DFG 2018, Ziebarth 2010). As a result, marine areas become more alkaline (alkalization of the oceans), which increases their CO2 buffer capacity and allows them to absorb more carbon dioxide (DFG 2018). If the alkalization process in surface water takes place in contact with the atmosphere, the CO2 removed from the water by weathering can be replaced by atmospheric carbon dioxide.

If this natural process is to be technically enhanced, the basic substances responsible for the chemical bonding of carbon dioxide, such as silicate or carbonate rock flour, would have to be introduced directly into the surface water of the ocean. To do this, these materials would have to be mined or industrially produced on land and ground into a fine powder or chemically treated in an industrial process before they are either dissolved in seawater in plants on land and then discharged into the sea or transported out to sea in large cargo ships and distributed in the water. This treatment is necessary so that the minerals dissolve quickly in the water and do not sink to the depths before reacting with the carbon dioxide.

In order for the accelerated weathering to have a global effect, a new large-scale mining operation would have to be established for the required amount of minerals and a large industrial production facility would have to be built. According to DFG (2018), it is estimated that for a global compensation of CO2 emissions per year, minerals would have to be extracted in an amount corresponding to the amount of coal mined today. All in all, this CDR method would be expensive, energy-intensive and would also require major interventions on land (for further details, see DFG Priority Program SPP 1689).

In addition, knowledge about the effects of increased mineral concentration on marine life is practically non-existent. Some rocks contain iron, which acts as fertilizer in the sea (see below), but possibly also toxic impurities, which could lead to unintended side effects on marine ecosystems.

CO2 capture and underground storage is the technical basis of various concepts with Carbon Capture and Storage (CCS), one of the preferred solution technologies in the IPCC SR15 report (although less so than in previous reports). However, the total potential for permanent underground storage of CO2 (gas fields, aquifers) is limited; it is estimated to be 10,000 Gt CO2 (Global CCS Institute. 2018). In addition, the storage possibilities are usually far away from the CO2 emission sources, which makes a complex CO2 binding technology (capture) for transport necessary. Without exception, the different capture processes are energy-intensive, which reduces the efficiency of power plants by 30-50%, thus requiring 60-100% more energy sources for the same useful energy supply. In the case of coal-fired power plants, this means up to twice as much damage to the environment during extraction, while in the case of biomass power plants it means an increase up to twice the area needed to extract the biomass.

CCS Carbon Capture and Sequestration

The CCS technology was intensively discussed 10 years ago as a method to clean up the emissions of coal-fired power plants. It was supposed to be a "bridging technology" into the post-coal era, but even then it was criticized as unsuitable. Although the individual components are known on a small scale, all CCS technologies are technologically immature and/or commercially unavailable (Sanchez et al. 2018); to date, there is not a single large commercial CCS plant in Europe (EEA 2020), despite supportive legislation and financial support. The IPCC also does not expect to realize CCS on the scale required by climate policy until the second half of the century - CCS cannot therefore contribute to meeting the climate budget and is only relevant if an "overshoot" is to be allowed.

Moreover, CCS is energy inefficient, expensive and associated with high environmental risks (Günther 2010; Neumann 2010). CCS is inefficient because even CO2 extraction with various gas scrubbing and absorption processes costs considerable amounts of energy. With combustion power plants, the electricity efficiency is reduced by 10-15 percentage points (not percent!), e.g. from 45% to 30%, or from 30% to 15%. Power plants with CCS would consume 15-25% more primary energy, which would directly increase emissions of other pollutants, especially particulate matter and N2O (EEA 2011).

CCS is too expensive, not only because of the cost of the equipment and energy, but especially because the cost of generating electricity from wind power and photovoltaics has fallen so dramatically in the last 10 years that combustion power plants with CCS are not economically viable. Environmental risks arise when the permanent deposition of CO2 in the quantitatively and locally limited storage possibilities lead to damage in the groundwater bodies and permanent impairment of the groundwater. This applies to storage in aquifers as well as to process damage, such as the connection of previously separated groundwater layers by means of drilling; saline water can contaminate valuable usable aquifers.

For all these reasons, public acceptance and support for CCS technologies is low (Ch4: 343); the IPCC also concedes that the development paths described make "inadequate assumptions regarding the development of social support and governance structures" (Ch4: 343).

In contrast to the application of CCS to achieve a supposedly "clean coal combustion", technologies that use CO2 from biogas plants make sense.

There it has to be captured anyway and can react with hydrogen from electrolysis to form methane. This would combine the benefits of biogas/sewage gas plants and power to gas, using the storage capacity of biomass, biogas and methane for flexibility (Viessmann 2019).

Adherence to CCS on a large scale is justified by cost arguments, since without the options CCS and BECCS (see below) the costs calculated by the IAM models would rise significantly (Ch4: 343) - and since the models are programmed for cost minimization, scenarios that are contrary to the will of the public dominate (Spangenberg, Polotzek 2019). That this is a systemic characteristic of the IAM models is also shown by the fact that the current future plans of the EU Commission argue comparably on the basis of similar models: the lack of acceptance is well known, the citizens* should be involved, but their arguments are not taken into account: in the end they have to agree (European Commission 2018; 2019).

Direct Air Carbon Dioxide Capture and Storage (DACCS)

Direct air extraction for CO2 extraction (DAC, with deposition DACCS) is part of the physical methods for CO2 binding. Here, the CO2 is not extracted from the exhaust air stream but directly from the atmosphere, where it is present in a very low concentration of 400 ppm. The energy required in the absorption process is correspondingly high - an obstacle that the IPCC also discusses but is little known to the public. In fact, the energy input is immense - to capture and store 1 t CO2, 1,000-2,000 kWh of heat plus 200-2,000 kWh of electricity are required (Ausfelder, Dura 2019). This is mainly required for the operation of fans and pumping processes; heat is needed to expel the CO2 from absorbing materials, to further concentrate it and to feed it into a storage system - wherever. The same restrictions and risks apply here as for the storage of CO2 in deeper water-bearing layers.

In terms of energy, DACCS makes no sense: Because the CO2 emissions would be back to around 1 t CO2 if fossil fuels were used, the process requires the use of large quantities of renewable energy from unknown sources. On the other hand, the avoidance of emissions by using renewables to substitute fossil fuels and by increasing efficiency would be an order of magnitude more cost-effective.

BECCS Bioenergy With CO2 Capture and Storage

In contrast to the CCS attempt to reduce emissions from the combustion of fossil fuels, especially coal, by 80-95%, BECCS techniques rely in various ways on the combustion or charring of the biomass previously grown and obtained. Only the IPCC's LED scenario gets by without BECCS, in the others it increases to 3 (5) Gt CO2 yr- in 2050 after 2030, and to 6 (12) Gt CO2 yr-1 in 2100 in the scenarios without (limited) overshoot (Ch2: 43). If about 500-1,000 Gt CO2 were removed from the Earth's atmosphere over 100 years, a reduction in CO2 concentration of 60-120 ppm could be achieved, combined with the hope of reducing global warming by 0.5-1.0°C (McGlashan et al. 2012). This is far more than the potential of 0.5-5 Gt CO2 yr-1 in the recent literature (Ch4: 342-343) and underlines again that BECCS is not a solution to the climate problem. Even though the importance of BECCS has been reduced compared to the last major IPCC report, it still forms the backbone of all strategies that assume extraction from the atmosphere to return below the target concentration after exceeding the CO2 budget. The envisaged biomass sources are - similar to biofuels (see below) - residues, wood and grass plants (Ch2SM: 16). In this respect, BECCS can be seen as a combination of the "Biofuels" and "CCS" strategies; the above-mentioned criticisms of the sub-strategies also apply to BECCS. For example, the energy input for biomass production and the loss of efficiency through CO2 capture are also highly relevant for BECCS. The IPCC sees limitations for BECCS - biomass due to energy, water and nutrient requirements as well as the limited available safe disposal options and competing policy goals (Ch4: 343).

Scenarios estimating the land requirements for BECCS come to values of 25-46% of arable and permanent crops already for a limitation to 2°C (Ch4: 343). The BECCS concept often ignores the fact that the areas for biomass cultivation are not necessarily located where the CO2 can supposedly be stored. One would first have to transport the biomass to the refineries and the energy to the consumers* in order to use at least part of the energy, and one would have to transport the CO2 in pipelines or transporters to the storage sites - all this costs energy. Overall, the warning of the Science Advisory Council of the European Academies of Sciences and Humanities should be taken seriously, that "BECCS remains subject to substantial risks and uncertainties, both with respect to the resulting environmental impacts and the ability to achieve a net removal of CO2 from the atmosphere" (EASAC 2019, p. 2). They conclude that there is no reliable scientific and technological basis for a policy that would rely on BECCS and recommend that "policy makers should avoid early decisions in favor of a technology such as BECCS" (ibid).

Pyrolysis Coal/Terra Preta/Biochar

Another method of producing negative emissions by biomass use is pyrolysis, which involves charring under the exclusion of air and produces pyrolysis coal. The IPCC expects pyrolysis coal not only to store up to 35 Gt CO2 yr1, but also to increase soil fertility, have positive effects on the soil nutrient balance and reduce N2O emissions and - as a by-product - produce up to 65 EJ yr-1 (Ch3: 345). But these figures do not match: 1 billion ha of growing forest bind with 5 t CO2 ha-1 and 1.5 kWh m2 per year about 5 Gt CO2 as wood, with an energy content of 50 EJ per year, which is significantly less than 65 EJ yr-1. In addition, most studies do not take into account the considerable energy losses of the pyrolysis process; about half of the energy content is inevitably lost as conversion loss and waste heat when wood is converted into pyrolysis coal (misleadingly also called "biochar" or "Bio Char") by means of char coalification (pyrolysis). Alternatively, the energy growth of forests could have been used to substitute fossil fuels.

Not only linked to this concept, the so-called "Terra Preta", it is proposed to use this charcoal in agriculture and to bury the carbon in the soil, partly with reference to indigenous practices in the Amazon Basin (Soentgen et al. 2017). But emulating a charcoal input caused by indigenous peoples, which is minimal for the rainforest as a whole, cannot be inflated to the mega and gigatonne scale without causing significant side effects. Moreover, biochar deposits (as well as reforestation) at high latitudes could even contribute to global warming due to lower solar reflection (albedo) (Lenton 2010).

Also the soil improving properties of pyrolysis charcoal has only been partially used so far. This is due to the fact that the coal particles have a very large surface area and could therefore bind humus, nutrients and water particularly well. Therefore, yield-increasing effects of pyrolysis coal are particularly well visible in sandy soils (or even in tropical soils), which have only a low water and nutrient exchange capacity. Central European loamy soils have excellent nutrient exchange properties and therefore do not need to be improved (Flessa et al. 2018), especially since pyrolysis coal does not provide food for soil life.

Finally, pyrolysis is always associated with the formation of polycyclic hydrocarbons (PAHs) (BAuA 2016), which can be carcinogenic, mutagenic and teratogenic (UBA 2016). Some of these pollutants are very strongly bound to the vegetable carbon, so that they are hardly washed out. However, a long-term release of these very persistent substances cannot be excluded. For this reason, the introduction of pyrolysis vegetable carbon, which is inevitably contaminated with PAH, must be rejected from the point of view of a sustainable materials policy (BUND 2015; 2019).

Biofuels

The biofuels concept is also based on biomass. Renewable raw materials are to replace gasoline as alcohols (methanol, ethanol), diesel as vegetable oils and natural gas as biogas. The limited amount of land available is often overlooked: only 37.7% of the world's land area or 11% of the earth's surface, approx. 5 billion hectares, is agricultural land (UBA 2013), and this is increasingly being used for feed production. The price for the 10% of the global useful energy supply that comes from biomass today is about 40% of the worldwide "net primary production" (HANPP Human Appropriation of Net Primary Production, Haberl et al. 2004). This level of biomass use alone is partly responsible for the worldwide loss of biological diversity - this is shown by the limited bioenergy potential: more efficient use is conceivable, but a significant expansion of global cultivation areas would be ecologically irresponsible (IPBES 2019).

Biomass is therefore quantitatively insufficient as a substitute for conventional energy sources (Ulgiati 2001) and the intensification of its use well beyond the processing of residual materials (biowaste, cooking oil, etc.) has only limited potential before ecosystem services are endangered (EEA 2006). While small-scale energy from biomass is traditionally and ecologically often positive, even the current plants already pose considerable problems. For example, subsidies for biomass production make marginal sites lucrative, which are essential for the protection of biodiversity and are now being devalued; grassland biotopes and former set-aside areas are ploughed up and cultivated, destroying species-rich biotopes that are often essential for soil dwellers and breeding birds. Rape and maize monocultures are a threat to biodiversity. Particularly blatant is the EU funding of energy corn on former moor soils, which turns these soils into potent CO2 emitters. Competition with food production is unavoidable (with the exception of the use of contaminated sites) - energy crops are just as dependent on water and nutrients as food crops (Bryngelsson, Lindgren 2013; Bringezu et al. 2012; Spangenberg, Settele 2009a). If the nutrients are supplied by fertilization, additional greenhouse gas effects result from N2O emissions, and the methane slip from biogas plants makes the theoretically determined climate protection potentials even more questionable (UBA 2019). However, while current small-scale plants can be decommissioned if other plants If the use of biomass appears more lucrative and some of the damage is still reversible, this is no longer the case with the construction of large biomass refineries, which are the basis of the biomass forecasts in the IAM models (Ch2, p.43). These refineries require constantly and permanently large quantities of biomass that is as homogeneous as possible in order to generate optimal yields for the capital employed and tied up in the long term. For this purpose, short-rotation plantations of fast-growing woody plants (e.g. poplars) or grasses (e.g. Miscanthus) are usually planned (Cornwall 2017). According to the IPCC, potential consequences are a massive increase in freshwater demand, intensified competition for land, loss of biodiversity and impacts on food security (Ch2, p.43). For economic reasons, the size of the refineries would probably be comparable to modern sawmills; with a minimum production of 200,000 t methanol per year, each plant would need about 500,000 t of wood per year and an area of about 35,000 ha (equivalent to a truck load every 10 minutes). In order to reduce the transport effort as a major cost factor, such refineries would have to be located in the middle of a largely homogeneous and thus species-poor plantation zone. If the trees are fully utilized, the nutrient balance and thus the soil fertility suffers.

This also applies to refineries that do not produce methanol for the energy industry, but intermediate products for the chemical industry. For example, the new industrial biorefinery at the Leuna chemical site (planned start of production at the end of 2022) is designed for a capacity of 200,000 t/a, while hardwood will be used to produce monoethylene glycol, monopropylene glycol and industrial sugar. Fields of application for bio-monoethylene glycol include textiles, PET bottles, packaging and de-icing agents. Bio-monopropylene glycol is used in composite materials, pharmaceuticals, cosmetics and detergents, for example.

Such "second and third generation" bio-economy refineries will not solve the problems mentioned above, but rather exacerbate them (Kuchler 2014; Spangenberg, Settele 2009b; Giampietro, Mayumi 2012). The consequences of energy and biomass crop cultivation for soil degradation are currently the subject of modeling efforts; these effects have not been systematically considered in the scenarios (Ch2, p.43).

Since the production of biomass for energy supply competes with the cultivation of plants for food and animal feed, the required animal feed is mainly replaced by genetically modified soy from Brazil, which is the most important cause for the destruction of the Amazon rainforest besides livestock breeding. At the same time, the livelihoods of small farmers are being destroyed: 200 hectares of land in the tropics provide the agricultural livelihood for about 70 people, but only create four jobs in timber plantations. The cultivation of genetically modified herbicide-resistant soybean plants on currently more than 90 million hectares (in Latin America and the USA) also leads to massive use of herbicides, especially glyphosate, which not only damages the biodiversity of the growing regions (Schütte et al. 2017) but also endangers human health (Richmond 2018).

Ultimately, the majority of energy uses would have to be covered by electricity from wind and sun as well as solar heat, and this would require significantly less land. Biomass energy only makes sense because it can be stored and the high temperatures required by industry. Any combustion of this biomass destroys this high material quality and is associated with significant energy losses. Another hope of finding a new energy source is algae, especially microalgae, which carry out photosynthesis and produce biomass in water-filled containers using solar energy. According to statements by energy companies (ExxonMobile advertisement: "Algae - Generating the Fuel of the Future from Unexpected Sources") and KIT researchers*, they are "the invisible bearers of hope for a climate-neutral energy supply" because "the small unicellular organisms can be used to produce various energy sources such as biodiesel, bioethanol, and biokerosene. And this without additional competitive pressure for valuable, limited resources such as land, water, or the nutrient phosphate" (idw 2020). But hope is deceptive. In order to achieve the promised high production output, the algae need high CO2 concentrations, and this would either have to be concentrated from the air, or the exhaust gases from fossil-fired power plants, which contain a lot of CO2, would have to be fed into the tanks - the latter for cost reasons, especially if algae production was to be carried out on a large scale. In further energy-intensive steps, the algae would then have to be extracted from the water and dried. Only then follow the (also energy-intensive) steps necessary to convert the biomass into methanol and other energy sources. If one looks at the various research or demonstration projects, it is striking that information on the energy balance or efficiencies and conversion efficiencies are extremely rarely given. The result of a comprehensive analysis is sobering: Taking all factors into account, A. Weiss (2016), also at the Institute of Technology Assessment ITAS of KIT in Karlsruhe[5], found that in the overall process, the net energy expenditure for plants, pump energy, aeration, fertilization, etc. is 1.8:1 in the best case, i.e. only 1 unit of energy comes out of the production process per 1.8 units of energy used (in reality, the expenditure is rather 3-4:1). Algae fuel therefore proves to be more of an "energy destroyer" than a climate saver. Solar energy can be used far more efficiently to generate electricity and heat, and fuels can be used more efficiently than biogas from biomass waste.

In contrast to the technology-centered approaches described so far, the following ones focus on natural processes of carbon sequestration in ecosystems, which is to be intensified by management interventions. If we consider plants in general in agriculture or tree growth in forests as a kind of collector for solar energy, the "efficiency" is only about 1-2 kWh energy/m2 per year in agriculture with a CO2-bond of 2 kg/m2*a; mature forests provide about 1 kWh energy/m2*a with a CO2-bond of 1 kg /m2*a or 10 t CO2-bond/ha*a. In old-growth forests, CO2 deposition takes place in the form of large quantities of fallen leaves and dead wood, a large part of which is permanently fixed in soils. This, and CO2 sequestration through the use of wood in durable products, are in competition with the above-mentioned processes of biomass utilization.

Soil Storage

Soil storage has proven itself on site, especially in organic farming and agroforestry. However, measures such as agroforestry, remediation of contaminated and degraded soils, organic farming and nature conservation forestry can also contribute to storage (FAO 2019). Such strategies have considerable positive social and ecological effects such as increased soil fertility and stability, higher water storage capacities and more biological diversity, quite apart from their contributions to climate protection. The nutrient content of soils and food security are positively influenced.

As a side effect of the greening of agriculture, animal welfare, especially for grazing animals, made possible by a profound change in diet (reversal of current trends towards increased consumption of animal proteins), and not least by the phasing out of NPK fertilizers (due to the high energy consumption of the Haber-Bosch nitrogen fixation process) and its partial replacement by organic fertilizers, reduced emissions and increased carbon fixation occur - a welcome side effect of the greening of agriculture (FAO 2019).

After all, it cannot be a matter of putting as much dead carbon as possible into the soil and turning it into carbon deposits - if carbon storage becomes the dominant purpose of land management, it can undermine the basic ecosystem services of agriculture and impair biodiversity, as experience with REDD+ has shown (Fatheuer 2014). A positive carbon balance can only be achieved in arable farming over longer periods of time if additional humus is permanently built up. Humus formation must primarily be aimed at the development of soil life and the long-term sustainable yield. It is crucial to shift the balance of humus-degrading processes in favour of humus-building biological processes. According to current knowledge, only organic farming and permaculture and agroforestry systems in which trees are integrated into the system over the long term can achieve this on a significant scale (Idel, Beste 2018; Hülsbergen, Rahmann 2015).

Agriculture

Continued high application rates of mineral nitrogen fertilizers lead to persistent nitrous oxide (N2O) emissions (critical due to long atmospheric residence times), which require negative emissions (CCS, BECCS, Biochar, Forestry, see below) even in the scenarios that remain below 1.5°; the current IAM cannot map a reduction. A conversion to organic farming as an alternative is not considered. This is all the more true in scenarios that calculate with considerable amounts of agro energy produced with massive use of fertilizers (Ch2: 34). The same applies to methane (CH4) emissions (critical because of the high emission quantities), which the models can also only partially depict. The share of agriculture and forestry (probably mainly from wet rice cultivation and cattle farming) will increase from about half of the emissions to about 2/3 to 3/4 by 2050. A detailed analysis of the progress in rice cultivation (e.g. Kritee et al. 2018; Chirinda et al. 2018) or the consequences of a reversal of the trend towards increasing beef consumption was not carried out (Ch2: 36).

Afforestation and Reforestation

The worldwide forest fires in the summer of 2019 have once again raised public awareness of the importance of the forest as an ecological regulatory factor. Forests not only store large amounts of carbon, above ground (especially tropical rainforests like the Amazon) or underground (especially boreal forests, e.g. in Siberia), they are also home to many species and regulate the global climate. Especially in the forests of the boreal zone, which are often swampy due to the damming effect of the underlying permafrost soils and the low evaporation rates, a strong CO2-bonding takes place. The area required for processes that aim at CO2-binding through plant growth is generally very high.

Natural Forests. The first requirement for forest management is therefore a fundamental protection of all remaining natural forests and all forests whose tree populations are 150 years old or more (Luyssaert et al. 2008).

Reforestation. According to FAO (2016), 1.8 billion hectares have been deforested in the last 5000 years, which is about 50% of today's forest area. We therefore support the idea of reforesting forest-capable areas as far as possible, with tree species compositions that correspond to the species spectrum of the respective natural forests, especially because this serves to protect biodiversity (Ch3: 160; IPBES 2019). This is particularly true for the acutely threatened tropical forests, which are constantly losing forest land to agriculture, often for pasture land or the cultivation of soya, sugar cane and oil palms for exports to Europe.

Afforestation. Afforestation is a double-edged sword - afforestation of grassland ecosystems or (still) diversified agricultural landscapes with monocultures or (invasive) alien species can have significant negative impacts on biodiversity, while afforestation with site-appropriate tree species (taking climate change into account) and agroforestry systems protects biodiversity, to safeguard? of the water balance and reduce flooding as a result of heavy rainfall (which is increasing as a result of climate change) (Ch4: 343). No other form of carbon sequestration can offer these benefits. If, on the other hand, for economic reasons and to maximize carbon sequestration, fast-growing tree species are cultivated, rotation times are shortened or the residual wood is not left in the forest, negative consequences for biodiversity (Ch3: 160; IPBES 2019) and future growth potential result. Although branches, bark and leaves/needles represent only about one third of the usable biomass, their removal increases the losses of N and P threefold, and those of K, Ca and Mg three to five times (English 2007). Already today, a significant reduction of P, Mg and K can be observed in trees, which together with the N/P imbalance contribute to reduced growth rates (Flückinger, Braun 2009). The increased fertilization of the forests required for compensation would in turn contribute to greenhouse gas emissions again, through the use of energy as well as through the emission of N2O.

In addition, even large afforestation projects can only bind a part of the annual emissions - one third according to Bastin et al. (2019), who determined an additional potential for 900 million ha of forest area (current forest area worldwide approx. 4,000 million ha - decreasing). Under these assumptions 750 Gt CO2 could be stored in (re)afforested forests. This shows that forests have a high potential to act as CO2 storage. The (re)construction of natural areas is therefore a very first option for climate protection, especially since many other natural functions, biodiversity, groundwater formation and even recreational functions are involved. However, the potential should not be overestimated: taking socio-ecological conditions into account, the available areas are much smaller than often assumed (Fuss et al. 2018). In fact, the socio-economic consequences of large reforestation projects are usually ignored; if they are monitored, it is clear that they are predominantly negative (Malkamäki et al. 2018). This is particularly true for the "hidden emissions" of afforestation, i.e. emissions elsewhere as a result of agricultural intensification, of firewood substitution, and of displacement from ancestral land, which can significantly overcompensate for the positive climate effects of afforestation (Gingrich et al. 2019). Nevertheless, afforestation of forests and the prevention of deforestation and burning are - despite all restrictions and boundary conditions - a central component of climate protection strategies.

It would make more sense to burn wood only after it has been used as a material than to use wood in BECCS processes. Then wood not only acts as a storage material, but also replaces the use of concrete and cement and heating energy in the construction of buildings as a building or insulation material. Only after material use of the high material quality of biomass produced by solar energy it is no problem to burn the remainders as waste wood or biogas from wastes, naturally in highest efficiency with combined heat and power generation. The storage possibilities in wood products can be locally relevant, but are globally very limited (Johnston, Radeloff 2019). For example, the average lifespan of so-called long-lived wood products in Germany is about 50 years, a period of time (Northwest German Forest Research Institute 2017) that cannot compete with the lifespan of a living tree.

Conclusion

A closer look at the methods of negative emissions reveals that their total potential is in the range of 10-20% of annual emissions, or roughly the increase in CO2 emissions over the past 10-20 years. The proposed measures are therefore neither sufficiently effective nor socially and ecologically unproblematic. Techniques whose dangerous effects and risks are already apparent today or which show high energy inefficiency should therefore not (any longer) be a valid instrument in climate studies. At the same time, other options for action that we believe to be more compatible with sustainability are either not mentioned at all, or they are not included in the scenarios due to the weaknesses of the IAM models.

FORGOTTEN FIELDS OF ACTION: SINKS

In general, it can be said that natural processes are often useful for limiting the climate crisis, and that their increased use is always useful if it does not lead to unintended ecologically questionable effects, e.g. due to the size of the projects. This also includes the renaturation of ecosystems that have been degraded in the past. In this section we list - without claiming to be exhaustive - a number of measures that, unlike those mentioned by the IPCC, bind atmospheric CO2 without endangering the integrity of ecosystems.

Bogs

Among the land habitats, bogs are particularly potent CO2 sinks, as long as they have not lost their natural dynamics. By contrast, degraded bogs, especially those that have been converted into agricultural land, are among the most potent emitters of CO2 in the agricultural sector (Parish et al. 2008; Drösler et al. 2009; Leifeld, Menichetti 2018). Therefore, the goal must be to return any bog area that still has potential for renaturation to a natural state (Harenda et al. 2018). The regeneration of naturally growing bogs, especially raised bogs, must also have priority over the use of bog areas by paludic culture. Although paludiculture is an advance over conventional land use on peatlands, it does not usually offer the potential for permanent CO2 deposition. Furthermore, a worldwide moratorium on peat extraction is urgently needed.

Steppes

Savannas, steppes and even semi-deserts also play a significant role as CO2 sinks (Dass et al. 2018; Song et al. 2018). However, high grassland steppes with fertile black soils have now been almost completely converted into arable land that seems to be indispensable for feeding the world's population. Less fertile steppe areas must continue to be preserved as grassland (t Mannetje et al. 2008). Overgrazing and the associated degradation and reduction of CO2 fixation must be significantly reduced by restricting livestock numbers.

Organic Farming and Agroforestry

Mentioned in the discussion, but not shown in the scenarios, is organic farming; not mentioned is species-appropriate animal husbandry. This contributes to the fact that in all scenarios significant methane and ammonia emissions from animal husbandry are assumed, as well as greenhouse gas emissions from agriculture due to the use of NPK fertilizers, which increase even more if industrial biomass is to be produced in addition to food production (AgroEnergy - with a questionable energy balance due to fertilization, see above).

Achievements of organic farming that have to be taken into account are especially in the areas of significantly higher carbon storage in the higher humus content of the soil and reduced nitrous oxide emissions (Sanders, Heß 2019). Species-appropriate animal husbandry systems are characterized by more space requirement in husbandry and feeding, which in the case of ruminants is primarily based on the direct utilization of the growth of the grassland. The cultivation of fodder in arable farming with its higher nitrous oxide emissions is significantly reduced. Such (area-bound) animal husbandry in combination with the reduction of the consumption of animal food is missing as a contribution in the modeling.

Meat consumption exclusively from species-appropriate animal husbandry and domestic production also means its significant reduction - which would also be a contribution to a healthier diet and thus to the reduction of health costs, both private and public.

FORGOTTEN FIELDS OF ACTION: SOURCES

Sufficiency

Sufficiency is necessary to make efficiency effective. Although the IPCC states that demand-side measures are central elements of 1.5° compatible development paths, it largely limits itself to changes in consumer behavior without going into the conditions necessary for this in more detail. However, the conditions for changing social practices are legal and social rules, infrastructure, etc. (Shove, Walker 2010; Rijnhout, Mastini 2018). Without these, a less resource-intensive consumption of resources easily leads to a less quality of life and is difficult to realize in a consumer society (Speck, Hasselkuss 2015). Moreover, most such changes are not or only to a limited extent and indirectly expressed in the models.

Sustainable Consumption

It has long been known that the main consumption areas in which households contribute to environmental pollution are construction and housing, nutrition and mobility (Spangenberg, Lorek 2002). In this section we will, among other things, take a brief look at each of these areas and at least briefly suggest the existing potential for sufficiency. The SR15 report repeatedly points out that changes in consumer behavior can make an important contribution to reducing climate damage (in the area of land use 40% each in production (through optimized agriculture and reduced forest destruction) and consumption (through dietary changes and the avoidance of food waste, Ch2: 6) compared to the baseline scenario (Ch2: 70). Unfortunately, these sufficiency options are not considered in the models and thus not in the scenarios.

Recent studies have shown that considering consumption sufficiency in addition to production efficiency in other areas is an important prerequisite for achieving the climate goals of the Paris Convention (Mundaca et al. 2019; Wachsmuth, Duscha 2019; Wilson et al. 2019), also to offset rebound effects, and that consumption changes can be stimulated by appropriate policies (Keller et al. 2016; Hargreaves 2011).

Energy

Assuming 100% renewable energy, which does not occur in the models, and thus a complete phase-out of the combustion or industrial use of fossil materials, the remaining CO2 emissions are reduced and with them the need for negative emissions. This, in combination with general resource savings (and thus decreasing energy requirements in transport, processing, use and disposal/treatment for reuse/recycling), allows the various CCS processes to be abandoned (UBA 2018; 2019), as the IPCC's LED scenario also suggests. An accelerated transition to a completely renewable energy supply is also necessary in order to have the CO2 budget required for the conversion of the system available at all (Sers, Victor 2018).

Nutrition

As already mentioned, sustainable agriculture will produce significantly less meat, which will then be of higher quality but, like other agricultural products, more expensive, thus providing a secure livelihood for organic farmers. The highest greenhouse gas emissions are caused by intensive cattle farming - a reduction of beef consumption, but also of dairy products, to the amount produced in species-appropriate animal husbandry of grazing livestock would be an important step (grazing ungulates make an important contribution to soil quality and biodiversity, which in turn fixes CO2) - grazing means protection of grassland and thus climate protection (Idel, Beste 2018. Sheep and goats follow in order of emission-intensive farm animals, while pigs and chickens occupy the last place (Bowles et al. 2019; IPCC 2019). So meat consumption is about both, reducing overall consumption and changing the consumption spectrum (of course vegetarian and vegan diets are also helpful in this respect). Together with the avoidance of food waste, this leads to the fact that in the IPCC LED "pathway" no additional areas for energy crops are needed even if the 1.5° budget is almost met (coal burning is still assumed!) (Ch2: 71-72). However, the potential positive contributions of organic farming (Sanders, Heß 2019) are not included in the scenarios, nor is the need to strengthen the resilience of agriculture to the impacts of climate change, even if this might mean moving away from monoculture agriculture, which already leads to declining yields under climate stress today (Kahiluoto et al. 2019).

Mobility/Traffic

For us, the hierarchy of traffic avoidance before shifting (modal split) before improvement (efficiency, electrification) still applies. The energetically worst available option is the direct extraction of CO2 from the air to use the CO2 for the production of artificial fuels together with hydrogen from electrolysis powered by renewable electricity. The energetic effort is high - for 1 kWh in the form of artificial fuel (power-to-liquid) the use of 3-4 kWh electricity is required. If this fuel is used in conventional combustion engines, the result is a drive energy of only 0.25 kWh. The overall efficiency of this chain is therefore less than 10% and thus significantly lower than the use of electric drives. A conversion of the transport sector from fossil fuels to artificial fuels produced with RE electricity would require 500-1000 TWh additional electricity generation, which is not feasible in Germany. It would make more sense to implement energy efficiency of the vehicles mainly by electric drives (with recovery).

However, electrification is not a patent solution either, and a 1:1 replacement of fossil fuels by electric vehicles is neither possible nor desirable - while even with the current energy mix CO2 emissions would decrease, resource consumption would increase, and noise and accidents would remain unchanged. Priority should therefore be given to a turnaround in mobility, including the promotion of non-motorized transport and the nationwide electrification of trains and buses.

Construction and Housing

Emissions construction phase: Building for industry, commerce and housing requires large quantities of cement and concrete, which represent one of the largest material flows and whose production already generates significant emissions of greenhouse gases. This is not only due to the unavoidable energy consumption, but in particular to the fact that calcium carbonates must be converted into burnt lime, releasing the CO2 bound in the carbonates. Replacing stone and concrete with alternative (organic) building materials, on the other hand, has energetic advantages, but is associated with its own problems. In particular, land use is not only in competition with other claims for use, but especially with the goal of ending land consumption.

Emissions Utilization phase: Households account for around a quarter of final energy consumption in Europe; two thirds of this is for low-temperature heat for space heating (a good 10% for hot water, 5% for baking and cooking, and almost 20% for electrical appliances and lighting (Odyssee Database 2017). Building insulation is still not sufficiently implemented, although considerable savings in energy consumption and heating costs could be achieved. While the savings potential (and the additional qualified jobs) from optimizing the building fabric is known and there is a lack of political will to exploit it, the behavior-based contribution is usually underestimated. It can account for up to half of household energy consumption (living room temperature, ventilation times, use of hot water, etc.) and requires social innovations to be mobilized (role models, friends, colleagues, communication). The constantly increasing living space per person represents a further problem, which is due both to demographic change (increase in one-person households) and to increased demands on available living space.

Land consumption: BUND not only aims to reduce CO2 emissions to zero by 2040, but also to end land consumption by 2030 - two objectives that complement each other. This means to end the conversion of arable, forest and natural areas into settlement, residential and economic areas - construction areas are usually created as extensions of existing settlements that were originally founded in fertile, agriculturally usable areas and not in desert-like, unproductive regions. It includes the end of shopping centers "on greenfield sites", restriction of the land consumption of logistics centers, which has massively increased due to the transition to completely ground-level construction (where IT can help to manage multi-storey warehouses), dense urban construction meadows in settlement areas, improved energy efficiency of buildings in cooperation between public and private actors and real estate owners* (Trotta et al. 2018), limiting the ever-growing amount of living space per capita (Lorek, Spangenberg 2019), promoting collective learning processes and opening up spaces of opportunity instead of educational energy saving campaigns (Spangenberg, Lorek 2019).

THE IAM MODELS - OPAQUE, UNDER-COMPLEX, UNSUITABLE

The economic components of Integrated Assessment Models (IAMs) are usually global or regional (partial) equilibrium models (CGE and DSGE models) that rely on a large number of externally set assumptions (Ch2: 8; 12; Ch2 SM: 15) that cannot be influenced by the model results and are almost never explicitly stated. Since they are based on an assumed equilibrium, such models are structurally unsuitable for depicting processes of imbalance - such as the climate crisis, loss of biodiversity, etc. (Ciarli, Savona 2019).

Not only the consumption side, but also institutions, political processes, etc., are excluded despite their recognized relevance, because their integration would overtax such models (Ch2SM: 15). For this reason, they rely almost exclusively on economic instruments (Ch2: 12) and optimize the results from a cost perspective, without taking into account all the capital costs of structural investments and, above all, without giving adequate consideration to the positive aspects such as avoided damage costs, better health and diverse policy interventions (Spangenberg, Polotzek 2019). The political environment only plays a role to the extent that it influences the profitability of bioenergy through taxes or subsidies (Ch2SM: 16). In addition, an idealized form of economic impact mechanisms is assumed in that the much-cited rebound effects are not taken into account in the models (Ch2SM: 15), i.e. the effect of the instruments is clearly overestimated (Holm, Englund 2009; Santarius, Soland 2018). This economic optimization without considering climate damage has serious consequences. While the IPCC states that there is a growing number of scenarios that rely on 100% renewable energies, it states succinctly that none of the IAM projections considers 100% renewables as a cost-effective development path (and therefore ignores this option). Instead, the energy mix of the most scenarios a portion of the allegedly CO2-free nuclear energy - which does not get along without CO2 emissions, which contains well-known operating and final storage risks, requires a network, which is a handicap for decentralized renewables, ties up capital in the long term, which is urgently needed for energy saving and renewables and - even if one would leave all these problems aside - would simply come too late to slow down climate change due to the long construction times.

The result is further distorted by the fact that IAMs often assume that economic growth and increasing prosperity will lead to a reduction in environmental pollution, i.e. that one can "grow out of" an environmental crisis (Ch2SM: 15). This so-called "Environmental Kuznets Curve" hypothesis was very popular among neoclassical environmental economists in the 1990s, but can now be considered as long disproved (e.g. Ekins 1997; Fischer-Kowalski et al. 2001; Spangenberg 2001). A further weakness of economic models concerns the most basic area of economics, the estimation of future costs. Here the IPCC economists assume that in the estimation of the general public the value of future events is the lower the further away they are from each other, namely by about 5% per year (Ch2SM: 14). This results in an exponential function, which makes damage almost marginal towards the end of the century (short-term expenditures for avoiding long-term costs appear as uneconomical as, for example, Nordhaus in 2019). This in turn influences the timing of emission reductions, because a higher economic discount rate postpones the use of capital-intensive options such as renewable energies to later points in time (Ch2SM: 14). As a consequence, the proposed CO2 pricing is far too low to achieve zero emissions by 2050, and "overshoot" and "negative emissions" become a supposed economic necessity, which most scenarios derive from the assumptions made. Such a devaluation of the future is - contrary to what the mainstream of economic science assumes - not an approach appropriate to the values people hold: for certain things the value can be constant (what is the loss of value of a mountain between this year and next year?), and societal perception of values follows a hyperbolic rather than an exponential development (Gowdy et al. 2013). This is ignored by all IPCC scenarios - they differ in this respect only in the magnitude of the coefficients of the exponential function; in the scenario database they are between 2% and 8% p.a. (Ch2SM: 14), in the IIASA database with its 900 scenarios all at 5%. This is doubly absurd: on the one hand, if a discount rate is already determined as an expression of social value assessment, it should be between 0 and a maximum of 2%, as the Stern Report also emphasizes. On the other hand, the 5% does not even reflect the current market interest rates, i.e. the real economic situation while neglecting the social component, because these have been between 0 and 1.5% for years; in some cases they are even negative.

With such exponential functions, even typical properties of complex systems capable of development cannot be captured, such as uncertainty and ignorance (stochastic "smearing" in so-called "fuzzy models" represent risks that are mathematically calculable and thus deterministic, i.e. not uncertain). Modeling with continuous functions also means that the models cannot take account of tipping points - on the one hand, these are discontinuities where a marginal change in the independent variable leads to large and unpredictable changes in the dependent variable, and on the other hand, their occurrence is characterized by uncertainty and ignorance. One consequence of this situation is that the models - as the IPCC repeatedly points out - are not able to predict the consequences of a changed climate for economy, growth and society (Ch2: 12; 24). They are therefore useless as a basis for political decisions because they systematically underestimate the risks and consequences of the climate catastrophe.

Considering all these problems, the question is obvious why these models are used at all. The answer is twofold: on the one hand, they are the only models that can make predictions up to the end of the century and beyond, i.e. the appropriate counterpart to long-term climate models. Other models that allow the feedback effects of the processes to be structurally changing (system-dynamic, agent-based and evolutionary models) yield relatively consistent results for 20 to 30 years (Lamperti et al. 2018), but after that the results diverge so strongly for each model that it is safe to say that economic forecasts of more than 30 years are not even science fiction, but simply fiction (which implies that even the question of economic long-term forecasts is wrong).

On the positive side, more realistic models are available that cover the period in which the transformation to sustainability must succeed if past and future efforts are not to have been a lost cause (Ciarli, Savona 2019). The bad news is that IAMs play a dominant role and thus pure speculation without scientific value serves as the basis for policy development (macroeconomic models in Keynesian tradition share many characteristics and therefore perform only marginally better). Manski (2019) summarizes the situation precisely: "exact predictions of policy outcomes are routine, while expressions of uncertainty are rare. However, predictions and estimates often are fragile, resting on unsupported assumptions and limited data. Therefore, the expressed certitude is not credible".

Secret Matter Degrowth

Even though the authors of the IPCC report repeatedly emphasize that growth rates are a central parameter of all scenarios (e.g. Ch2: 24), information on growth rates is sought in vain in the report, the supplementary materials and the scenario database (Kurz et al. 2019). What one finds clearly described, at least in the recommended sources (a Journal Special Issue) (including Riahi et al. 2017), is the information that in SR 15 growth is measured as real, purchasing power-adjusted growth per capita, in 2005 prices - figures that are hardly comparable with other sources. More clarity is provided by the contribution of Leimbach et al. (2017), which explains that the growth of world GDP calculated according to the IPCC SR 15 method increases from US$ 48.7 trillion in 2000 to US$ 309 (SSP3) to 906 (SSP5) in 2100, depending on the scenario, i.e. by a factor of 6 to 20. This is fiction as just explained, but the comparison with the usual figures is nevertheless interesting: assuming a constant ratio of values adjusted for purchasing power and normally calculated values, the expected growth results are only about half as high (US$ 150 or 550 trillion, factor 3 to 11). So while the global economy will continue to grow strongly according to the IPCC's assumptions, the situation is different at the regional level: in the scenarios based on the Shared Socioeconomic Pathway SSP 3, GDP declines in absolute terms for almost all high income countries; under the assumptions of SSP1 and SSP4 (and thus in the majority of cases) this is true at least for Japan, Korea, Taiwan, Eastern Europe and especially China (Leimbach et al. 2017). The reason for this is the shrinking labor force combined with limited productivity gains. The impact of this development remains open - for example, a declining GDP could affect the ability to finance climate policy (or, if climate is given priority, other areas of expenditure that are important for a socio-ecological transformation).

At the same time, fears of new unemployment could prove to be unfounded if the working population shrinks at the same rate as the labor supply - in which case training for migrants and continuing education for older workers would be imperative.

According to the majority of scenarios, a shrinking of the economy can be expected in large parts of Europe (Bonaiuti 2017), but proposals for a strategy for a socio-ecologically sustainable design of the economic contraction are sought in vain. These central questions about a sustainable welfare state are not being discussed - an opportunity has thus been missed.

OUTLOOK

Limiting the climate catastrophe and transforming it into a sustainable economy and society require effective global action. Effective action requires the industrialized countries of Europe to develop strategies that recognize how fundamental changes in the form, functioning and products of business and consumption must be. It ranges from food and mobility to the future of work, from transport and chemicals to the construction industry, from local companies and networks to world trade (whose importance will probably continue to decline in the future (Wiedmann, Lenzen 2018). But global action (also) means not only enforcing standards in supply chains, but also examining policies, consumption patterns and technologies for their global compatibility – this applies in particular to all large-scale technological approaches, especially geoengineering, which influence all regions of the world via various forms of telecoupling. It is also important, out of international responsibility, to have established an economic structure in Germany and large parts of Europe by 2040 that can do without fossil fuels. This transformation must also be discussed with trading partners that have so far been dependent on exports to Europe, and their arguments must be taken into account in shaping the transformation (Biermann, Möller 2019). If these measures are implemented in an integrated manner, including carbon sequestration in healthy forests, soils and near-natural agriculture, and consumption adapted to these goals, then geoengineering is also unnecessary and (temporary) overrunning of CO2 budgets with all the risks mentioned can be avoided even without the ecologically risky approaches mentioned above (ch3: 160).

ACKNOWLEDGEMENT

Translated & edited by American Publishing Services (https://americanpublishingservices.com/).

ENDNOTES

1. The systematic estimation of error widths in scientific analysis in IPCC SR 15 illustrates this quotation: "This assessment suggests a remaining budget for limiting warming to 1.5 °C with a two-thirds chance of about 550 Gt CO2, and of about 750 Gt CO2 for an even chance […].Remaining budgets applicable to 2100, would approximately be 100 Gt CO2 lower than this to account for permafrost thawing and potential methane release from wetlands in the future. These estimates come with an additional geophysical uncertainty of at least ±50 %, related to non-CO2 response and TCRE distribution. In addition, they can vary by ±250 Gt CO2 depending on non-CO2 mitigation strategies as found in available pathways. […] Staying within a remaining carbon budget of 750 Gt CO2 implies that CO2 emissions reach carbon neutrality in about 35 years, reduced to 25 years for a 550 Gt CO2 remaining carbon budget […]. The ±50 % geophysical uncertainty range surrounding a carbon budget translates into a variation of this timing of carbon neutrality of roughly ±15-20 years." (Ch2: 5). „No pathways were available that achieve a greater than 66 % probability of limiting warming below 1.5 °C during the entire 21st die century" (Ch2: 8).
2. Der irreversible Gletschereisverlust ist inzwischen nicht nur in der Westantarktis zu beobachten (Showstack 2014; Rignot et al. 2014; Joughin et al. 2014; Feldmann, Levermann 2015) sondern auch in der Zentral- (Shepherd et al. 2019) und der Ostantarktis (Rintoul etal. 2016).
3. Most CDR technologies remain largely unproven to date and raise substantial concerns about adverse side-effects on environmental and social sustainability (Ch2: 39). "The technical, political, and social feasibility of scaling up and implementing land-intensive CDR technologies is recognised to present considerable potential barriers to future deployment" (Ch3: 160).
4. This message as a ghost writing on the wall was considered Belšazar, the son of Nebuchadnezzar, and announced the imminent collapse of his power. According to the Bible, Dan 5,8.

[5] In her doctoral thesis Annika Weiss examined the energy balances of biofuels from algae. According to documentation, very few projects had a net energy expenditure of less than 1.0, i.e. more energy came out than was used. However, all of these projects had misappropriated several energy inputs of the plant by limiting the system boundaries of the consideration. In addition, the overall efficiency decreased with increased production rate, because the operating expenses increased disproportionately and the algae "shadowed" each other.

REFERENCES

Alfredsson, E., Bengtsson, M., Brown, H.S., Isenhour, C., Lorek, S., Stevis, D., & Vergragt, P. (2018). Why achieving the Paris Agreement requires reduced overall consumption and production. *Sustainability: Science, Practice and Policy*, *14*(1), 1–5.

Allen, P.M. (1998). Evolutionary Complex Systems and Sustainable Development. In J.C.J. M. van den Bergh & M.W. Hofkes, *Theory and Implementation of Economic Models for Sustainable Development* (pp. 67–100). Dordrecht, Kluwer Academic Publishers.

Ausfelder, F., & Dura, H.E. (Ed.). (2019). *Options for a sustainable energy system with Power-to-X technologies - 1st Roadmap of the Copernicus Project Power-to-X.* Frankfurt am Main, DECHEMA.

AWI. (2014). *Carbonate counter pump stimulated by natural iron fertilization in the Polar Frontal Zone*. Nature geosciences.

Bakker, D.C.E., Watson, A.J., & Law, C.S. (2001). Southern Ocean iron enrichment promotes inorganic carbon draw-down. *Deep Sea Res., Part II: Topical Studies in Oceanography*, *48*, 2483–2507.

Bar-Yam, Y. (1997). *Dynamics of complex systems*. Reading, Massachusetts, Addison Wesley.

Bastin, J-F., Finegold, Y., Garcia, C., Mollicone, D., Rezende, M., Routh, D., . . . Crowther, T.W. (2019). The global tree restoration potential. *Science*, *365*(6448), 76.

BAuA Federal Institute for Occupational Safety and Health. (2016). *Technical rules for hazardous substances: Tar and other pyrolysis products from organic material (TRGS 551)* (version of 2.2.2016, announcement, GMBl 2016 p. 8-10 [No. 1] (from 27.1.2016). Berlin, BMAS Federal Ministry of Labour and Social Affairs.

Bélanger, J., & Pilling, D. (Eds.). (2019). *The State of the World's Biodiversity for Food and Agriculture*. FAO Food and Agriculture Organization of the United Nations. Rome, FAO Commission on Genetic Resources for Food and Agriculture, Rome.

Biermann, F., & Möller, I. (2019). Rich man's solution? Climate engineering discourses and the marginalization of the Global South. *International Environmental Agreements: Politics, Law and Economics*, *19*(2), 151–167.

BIOACID - Biological Impacts of Ocean Acidification. (nd.). *Oceans in climate change*. Retrieved June 6, 2019, from https://www.oceanacidification.de/einfuehrung/

Bonaiuti, M. (2017). Are we entering the age of involuntary degrowth? Promethean technologies and declining returns of innovation. *Journal of Cleaner Production*, *197*(2), 1800–1809.

Bossel, H. (2000). Policy assessment and simulation of actor orientation for sustainable development. *Ecological Economics*, *35*(3), 337–355.

Bowles, N., Alexander, S., & Hadjikakou, M. (2019). The livestock sector and planetary boundaries: A "limits to growth" perspective with dietary implications. *Ecological Economics*, *160*, 128–136.

Bringezu, S., O'Brien, M., & Schütz, H. (2012). Beyond biofuels: Assessing global land use for domestic consumption of biomass: A conceptual and empirical contribution to sustainable management of global resources. *Land Use Policy*, *29*(1), 224–232.

Brondizio, E.S., Díaz, S., & Settele, J. (Eds.). (2019). *The IPBES Global Assessment on Biodiversity and Ecosystem Services*. IPBES Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Bonn, Germany, Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services.

Bryngelsson, D.K., & Lindgren, K. (2013). Why large-scale bioenergy production on marginal land is unfeasible: A conceptual partial equilibrium analysis. *Energy Policy*, *55*, 454–466.

BUND: Association for Environment and Nature Conservation Germany. (2015). *Terra preta / pyrolysis coal: BUND assessment of its environmental relevance*. Berlin, BUND. Retrieved from http://www.bund.net/service/publikationen/detail/publication/terra-preta-pyrolysekohle-bund-einschaetzung-ihrer-umweltrelevanz

BUND: Association for Environment and Nature Conservation Germany. (2019). *Challenges of a sustainable materials policy - Need for transformation in a global context*. BUND Position 69. Berlin, BUND.

Chirinda, N., Arenas, L., Katto, M., Loaiza, S., Correa, F., Isthitani, M., . . . Bayer, C. (2018). Sustainable and Low Greenhouse Gas Emitting Rice Production in Latin America and the Caribbean: A Review on the Transition from Ideality to Reality. *Sustainability*, *10*(3).

Ciarli, T., & Savona, M. (2019). Modelling the Evolution of Economic Structure and Climate Change: A Review. *Ecological Economics*, *158*, 51–64.

Conniff, R. (2019). Carbon dioxide: Bury the climate gas. *Spektrum der Wissenschaft*, (6). Magazine.

Cornwall, W. (2017). The burning question. *Science*, *355*(6329), 18–21.

Dass, P., Houlton, B.Z., Wang, Y., & Warlind, D. (2018). Grasslands may be more reliable carbon sinks than forests in California. *Environmental Research Letters*, *13*(7), 074027.

Drösler, M., Adelmann, W., Augustin, J., Bergmann, L., Beyer, M., Giebels, M., . . . Werhahn, M. (2009). climate protection through moor protection. In M. Mahammadzadeh, H. Biebeler, & H. Bard (Eds.), *Climate protection and adaptation to climate impacts: Strategies, measures and examples of application* (Chapter 11, pp. 89–97). Cologne, Institute of the German Economy Köln Medien GmbH.

EASAC European Academies' Science Advisory Council. (2019). *Forest bioenergy, carbon capture and storage, and carbon dioxide removal: An update*. EASAC. Halle (Saale), Germany / Brussels, Belgium, German National Academy of Sciences / Royal Academies for Science and the Arts of Belgium.

EEA European Environment Agency. (2006). *How much bioenergy can Europe produce without harming the environment? EEA Report 7/2006*. EEA. Copenhagen, EEA.

EEA European Environment Agency. (2011). *Air pollution impacts from carbon capture and storage (CCS)*. EEA Technical Report No 14/2011. Publications Office of the European Union, Luxembourg.

EEA European Environment Agency. (2020). *Europe's Environment 2020*. State of the Environment Report. Publications Office of the European Union, Luxembourg.

Ekins, P. (1997). The Kuznets Curve for the Environment and Economic Growth: Examining the evidence, Environment and Planning. *Environment and Planning A*, *29*, 805–830.

English, M. (2007). Ecological limits of biomass use in forests. *BWF Practical Information*, *13*, 8–10.

European Commission. (2018). A Clean Planet for all. A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. *COM* , *773* final. Communication from the Commission to the European Parliament, the European Economic and Social Committee, the Committee of the Regions and the European Investment Bank. Brussels, European Commission.

European Commission. (2019). Reflection Paper: Towards a Sustainable Europe by 2030. *COM*, *22*. Brussels, European Commission.

FAO Food and Agriculture Organization of the United Nations. (2016). *State of the World's Forests 2016. Forests and agriculture: land-use challenges and opportunities*. FAO, Rome.

Fatheuer, T. (2014). A new economy of nature. *Ecological Management*, *29*(2), 19–21.

Feldmann, J., & Levermann, A. (2015). Collapse of the West Antarctic Ice Sheet after local destabilization of the Amundsen Basin. *Proceedings of the National Academy of Sciences*, *112*(46), 14191–14196.

Fischer-Kowalski, M., & Amann, C. (2001). Beyond IPAT and Kuznets Curves: Globalization as a vital factor in Analysing the Environmental Impact of Socio-Economic Metabolism. *Population and Environment*, *23*(1), 7–47.

Flessa, H., Don, A. Jacobs, A., Dechow, R., Tiemeyer, B., & Poeplau, C. (2018). *Humus in German agricultural soils. Selected results of the soil condition survey*. Thuenen-Institute for Agricultural Climate Protection, Federal Ministry of Food and Agriculture (Ed.). Bonn, BMEL. Retrieved from https://www.thuenen.de/media/institute/ak/Allgemein/news/Bodenzustandserhebung_Landwirtschaft_Kurzfassung.pdf

Flückinger, W., & Braun, S. (2009). Leave nutrients in the forest - or recycle them! *Forest and Wood*, *9*(9), 30–33.

Fuss, S., Lamb, W.F., Callaghan, M.W., Hilaire, J., Creutzig, F., Amann, T., . . . Minx, J.C. (2018). Negative emissions—Part 2: Costs, potentials and side effects. *Environmental Research Letters*, *13*(6), 063002.

German Bundestag. (2009). *The LOHAFEX experiment in the southern polar sea*. Answer of the German Federal Government to the parliamentary question of the Members of Parliament Undine Kurth (Quedlinburg), Bärbel Höhn, Cornelia Behm, other Members of Parliament and the parliamentary group BÜNDNIS 90/DIE GRÜNEN - Printed Matter 16/11860.

Giampietro, M., & Mayumi, K. (2012). *The biofuel delusion: The fallacy of large scale agro-biofuels production*. Routledge, Taylor & Francis Group, Abingdon, Oxford, UK.

Gingrich, S., Lauk, C., Niedertscheider, M., Pichler, M., Schaffartzik, A., Schmid, M., . . . Erb, K. (2019). Hidden emissions of forest transitions: A socio-ecological reading of forest change. *Current Opinion in Environmental Sustainability*, *38*, 14–21.

Global CCS Institute. (2018). *Global Status of CCS 2018*. Melbourne, Australia. Retrieved from https://www.globalccsinstitute.com/resources/global-status-report/previous-reports/

Gowdy, J., Rosser, J.B., Jr., & Roy, L. (2013). The evolution of hyperbolic discounting: Implications for truly social valuation of the future. *Journal of Economic Behavior & Organization*, *90*(Supplement), S94–S104.

Günther, J., Lehmann, H., Lorenz, U., & Purr, K. (2019). *Shaping the path to a greenhouse gas-neutral Germany in a resource-saving manner*. UBA Federal Environment Agency. Dessau-Roßlau, Federal Environment Agency.

Günther, R. (2010). Four questions, four answers. *Political Ecology*, *123*, 41–42.

Harenda, K.M., Lamentowicz, M., Samson, M., & Chojnicki, B.H. (2018). The Role of Peatlands and Their Carbon Storage Function in the Context of Climate Change. In T. Zielinski, I. Sagan, & W. Surosz, *Interdisciplinary Approaches for Sustainable Development Goals: Economic Growth, Social Inclusion and Environmental Protection* (Ch. 11, pp. 169–187). Cham, Switzerland, Springer International Publishing.

Hargreaves, T. (2011). Practicing behaviour change: Applying social practice theory to pro-environmental behaviour change. *Journal of Consumer Culture*, *11*(1), 79–99.

Holm, S-O., & Englund, G. (2009). Increased ecoefficiency and gross rebound effect: Evidence from USA and six European countries 1960–2002. *Ecological Economics*, *68*(3), 879–887.

Hülsbergen, K-J., & Rahmann, G. (Eds.). (2015). *Climate Impacts and Sustainability of Ecological and Conventional Operating Systems - Studies in a Network of Pilot Farms*. Research results 2013-2014, Thuenen Report 29th Johann Heinrich von Thuenen-Institute, Brunswick. https://doi.org/10.3220/REP_29_2015

Idel, A., & Beste, A. (2018). *The myth of climate-changing agriculture - or why less of the bad is not good*. The Greens/European Free Alliance, European Office Hessen, Wiesbaden.

Idw. (2020). Information Service Science, Karlsruhe Institute of Technology KIT 23.01.2020. Science Year 2020 - Bioeconomy. Retrieved from https://idw-online.de/de/simplesearch?words=Mikroalgen+sind+die+unsichtbaren+Hoffnungstr%C3%A4ger

+einer+klimaneutralen+Energieversorgung&_form_=InputForm&scope=press_release&scope=event

In short, R., Spangenberg, J.H., & Zahrnt, A. (2019). The missing scenario "climate protection without growth". *Ecological Economies*, *34*(2), 35–39.

Information about the locations of the 2018 IPCC report "Global Warming of 1.5°C": (Chx: y) indicate that the corresponding statement can be found on page y of chapter x. (ChzSM: y) refers to page y of the Supplementary Material to Chapter z.

IPCC Intergovernmental Panel on Climate Change. (2019). *Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse gas fluxes in Terrestrial Ecosystems*. IPCC Special Reports. WMO, Geneva, Switzerland; UNEP, Nairobi, Kenya.

IPCC. (n.d.). Geneva, Switzerland, World Meteorological Organization. Retrieved from https://www.ipcc.ch/sr15/

Johnston, C.M.T., & Radeloff, V.C. (2019). Global mitigation potential of carbon stored in harvested wood products. *Proceedings of the National Academy of Sciences*, *116*(29), 14526.

Jokinen, S.A., Virtasalo, J.J., Jilbert, T., Kaiser, J., Dellwig, O., Arz, H., . . . Saarinen, T. (2018). A 1500-year multiproxy record of coastal hypoxia from the northern Baltic Sea indicates unprecedented deoxygenation over the 20th century. *Biogeosciences*, *15*, 3975–4001.

Joughin, I., Smith, B.E., & Medley, B. (2014). Marine Ice Sheet Collapse Potentially Under Way for the Thwaites Glacier Basin, West Antarctica. *Science*, *344*(6185), 735–738.

Keller, M., Halkier, B., & Wilska, T-A. (2016). Policy and Governance for Sustainable Consumption at the Crossroads of Theories and Concepts. *Environmental Policy and Governance*, *26*(2), 75–88.

Kritee, K., Nair, D., Zavala-Araiza, D., Proville, J., Rudek, J., Adhya, T.K., . . . Hamburg, S.P. (2018). High nitrous oxide fluxes from rice indicate the need to manage water for both long- and short-term climate impacts. *Proceedings of the National Academy of Sciences*, *115*(39), 9720–9725.

Krupp, R.E. (2010). From the chimney into the earth. The CCS technology. *Political Ecology*, (123), 16–19.

Kuchler, M. (2014). Sweet dreams (are made of cellulose): Sociotechnical imaginaries of second-generation bioenergy in the global debate. *Ecological Economics*, *107*, 431–437.

Lamperti, F., Dosi, G., Napoletano, M., Roventini, A., & Sapio, A. (2018). Faraway, So Close: Coupled Climate and Economic Dynamics in an Agent-based Integrated Assessment Model. *Ecological Economics*, *150*, 315–339.

Leifeld, J., & Menichetti, L. (2018). The underappreciated potential of peatlands in global climate change mitigation strategies. *Nature Communications*, *9*, 1071.

Leimbach, M., Kriegler, E., Roming, N., & Schwanitz, J. (2017). Future growth patterns of world regions – A GDP scenario approach. *Global Environmental Change*, *42*, 215–225.

Lenton, T.M. (2010). The potential for land-based biological CO2 removal to lower future atmospheric CO2 concentration. *Carbon Management*, *1*(1), 145–160.

Leujak, W., Ginzky, H., & Claussen, U. (2011). Iron Fertilization - More CO2 Fixation by the Sea? *Warning Signals Climate - The Oceans*, pp. 348–353

Lorek S., & Spangenberg, J.H. (2019). Energy sufficiency through social innovation in housing. *Energy Policy*, *126*, 287–294.

Lovejoy, T.E., & Nobre, C. (2018). Amazon Tipping Point. *Science Advances*, *4*(2), eaat2340.

Lu, X., Cao, L., Wang, H., Peng, W., Xing, J., Wang, S., . . . McElroy, M.B. (2019). Gasification of coal and biomass as a net carbon-negative power source for environment-friendly electricity generation in China. *Proceedings of the National Academy of Sciences*, *116*(17), 8206–8213.

Luyssaert, S., Schulze, E.D., Börner, A., Knohl, A., Hessenmöller, D., Law, B.E., . . . Grace, J. (2008). Oldgrowth forests as global carbon sinks. *Nature*, *455*(7210), 213–215.

Malkamäki, A., D'Amato, D., Hogarth, N.J., Kanninen, M., Pirard, R., Toppinen, A., & Zhou, W. (2018). A systematic review of the socio-economic impacts of large-scale tree plantations, worldwide. *Global Environmental Change*, *53*, 90–103.

Mannetje, L., Amézquita, M.C., Buurman, P., & Ibrahim, M.A. (2008). *Carbon sequestration in tropical grassland ecosystem*s. Wageningen: Wageningen Academic Publishers.

Manski C.F. (2019). Communicating uncertainty in policy analysis. *Proceedings of the National Academy of Sciences*, *116*(16), 7634–7641.

Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., . . . Waterfield, T. (Eds.). (2018). *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*. IPCC Special Report 15.

Maurer, J.M., Schaefer, J.M., Rupper, S., & Corley, A. (2019). Acceleration of ice loss across the Himalayas over the past 40 years. *Science Advances*, *5*(6), eaav7266.

McGlashan, N., Workman, M., Caldecott, B., & Shah, N. (2012, October). *Negative Emissions Technologies*. Briefing paper no. 8, Grantham Institute for Climate Change, Imperial College, London.

McGlashan, N.R., Workman, M.H.W., & Shah C.N. (2012). *Negative Emissions Technologies. Grantham Institute for Climate Change Briefing* (paper No 8). London, Imperial College.

Minx, J.C., Lamb, W.F., Callaghan, M.W., Fuss, S., Hilaire, J., Creutzig, F., . . . del Mar Zamora Dominguez, M. (2018). Negative emissions—Part 1: Research landscape and synthesis. *Environmental Research Letters*, *13*(6), 063001.

Mundaca, L., Ürge-Vorsatz, D., & Wilson, C. (2019). Demand-side approaches for limiting global warming to 1.5°C. *Energy Efficiency*, *12*(2), 343–362.

Nemet, G.F., Callaghan, M.W., Creutzig, F., Fuss, S., Hartmann, J., Hilaire, J., . . . Smith, P. (2018). Negative emissions—Part 3: Innovation and upscaling. *Environmental Research Letters*, *13*(6), 063003.

Neumann, W. (2010). Crutch technology instead of bridge technology. *Political Ecology*, *123*, 56–59.

Nordhaus, W. (2019). Economics of the disintegration of the Greenland ice sheet. *Proceedings of the National Academy of Sciences*, *116*(25), 12261.

Pachauriand, R.K., & Meyer, L.A. (Eds.). (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland; https://www.ipcc.ch/report/ar5/syr/

Parish, F., Sirin, A.A., Charman, D., Joosten, H., Minayeva, T.Y.U., & Silvius, M. (2008). *Assessment on Peatlands, Biodiversity and Climate Change: Main Report*. Kuala Lumpur, Malaysia, Wageningen, Netherlands, Global Environment Centre and Wetlands International.

Prigogine, I. (1997). *The end of certainty: Time, Chaos and the new Laws of Nature*. New York, The Free Press.

Rahmstorf, P. (2019, July 16). *Can trees save the climate*. SciLogs - Klima Lounge. Retrieved from https://scilogs.spektrum.de/klimalounge/

Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., . . . Tavoni, M. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, *42*, 153–168.

Richmond, M.E. (2018). Glyphosate: A review of its global use, environmental impact, and potential health effects on humans and other species. *Journal of Environmental Studies and Sciences*. https://doi.org/10.1007/s13412-018-0517-2

Rignot, E., Mouginot, J., Morlighem, M., Seroussi, H., & Scheuchl, B. (2014). Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011. *Geophysical Research Letters*, *41*(10), 3502–3509.

Rijnhout, L., &Mastini, R. (Eds.). (2018). *Sufficiency: Moving beyond the gospel of eco-efficiency.* Brussels, Friends of the Earth Europe.

Rintoul, S.R., Silvano, A., Pena-Molino, B., van Wijk, E., Rosenberg, M., Greenbaum, J.S., & Blankenship, D.D. (2016). Ocean heat drives rapid basal melt of the Totten Ice Shelf. Sci*ence Advances*, *2*(12), e1601610.

Salter, I., Schiebel, R., Ziveri, P., Movellan, A., Lampitt, R., & Wolff, G.A. (2014). Carbonate counter pump stimulated by natural iron fertilization in the Polar Frontal Zone. *Nature Geoscience*, *7*, 885.

Sanchez, D.L., Johnson, N., McCoy, S.T., Turner, P.A., & Mach, K.J. (2018). Near-term deployment of carbon capture and sequestration from biorefineries in the United States. *Proceedings of the National Academy of Sciences*, *115*(19), 4875–4880.

Sanders, J., & Heß, J. (2019). *Services of organic farming for the environment and society*. Thuenen Report 65th Braunschweig, Johann Heinrich von Thuenen-Institute.

Santarius, T., & Soland, M. (2018). How Technological Efficiency Improvements Change Consumer Preferences: Towards a Psychological Theory of Rebound Effects. *Ecological Economics*, *146*, 414–424.

Sarmiento, J.L., & Orr, J.C. (1991). Three-dimensional simulations of the impact of Southern Ocean nutrient depletion on atmospheric CO2 and ocean chemistry. Limnol. *Oceanogr*, *36*, 1928–1950.

Schütte, G., Eckerstorfer, M., Rastelli, V., Reichenbecher, W., Restrepo-Vassalli, S., Ruohonen-Lehto, M., . . . Mertens, M. (2017). Herbicide resistance and biodiversity: Agronomic and environmental aspects of genetically modified herbicide-resistant plants. *Environ. Sci. Eur*., *29*(5). https://doi.org/10.1186/s12302-016-0100-y

Sers, M.R., & Victor, P.A. (2018). The Energy-emissions Trap. *Ecological Economics*, *151*, 10–21.

Shepherd, A., Gilbert, L., Muir, A.S., Konrad, H., McMillan, M., Slater, T., . . . Engdahl, M.E. (2019). Trends in Antarctic Ice Sheet Elevation and Mass. *Geophysical Research Letters.*

Shove, E., & Walker, G. (2010). Governing transitions in the sustainability of everyday life. *Research Policy*, *39*(4), 471–476.

Showstack, R. (2014). Sector of West Antarctic Ice Sheet in "Irreversible Retreat" Eos. *Transactions American Geophysical Union*, *95*(20), 168–168.

Smith, P., Davis, S.J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., . . . Yongsung, C. (2016). Biophysical and economic limits to negative CO2 emissions. *Nature Climate Change*, *6*(1), 42–50.

Soentgen, J., Hilbert, K., von Groote-Bidlingmaier, C., Herzog-Schröder, G., Pabst, E., & Timpf, S. (2017). Black Indian Land: Commodification and Mythification of the Amazonian Dark Earths. *GAIA – Ecological Perspectives for Science and Society*, *26*(2), 136–143.

Song, J., Wan, S., Peng, S., Piao, S., Ciais, P., Han, X., . . . Liu, L. (2018). The carbon sequestration potential of China's grasslands. *Ecosphere*, *9*(10), e02452.

Spangenberg, J.H. (2001). The Environmental Kuznets Curve – a Methodological Artefact. *Population and Environment*, *23*(2), 175–192.

Spangenberg, J.H., & Lorek, S. (2002). Environmentally sustainable household consumption: From aggregate environmental pressures to priority fields of action. *Ecological Economics*, *43*(2–3), 127–140.

Spangenberg, J.H., & Lorek, S. (2019). Sufficiency and consumer behaviour: From theory to policy. *Energy Policy*, *129*, 1070–1079.

Spangenberg, J.H., & Polotzek, L. (2019). Like blending chalk and cheese – The impact of standard economics in IPCC scenarios. *Real World Economics Review*, *87*, 196–211.

Spangenberg, J.H., & Settele, J. (2009a, December). Biofuels: Steer Clear of Degraded Land. *Science*, *326*, 1346.

Spangenberg, J.H., & Settele, J. (2009b). Neither Climate Protection nor Energy Security: Biofuels for Biofools? *Journal of International Relations*, *20*(5), 89–108.

Spangenberg, J.H., von Haaren, C., & Settele, J. (2014). The ecosystem service cascade: Further developing the metaphor. Integrating societal processes to accommodate social processes and planning, and the case of bio-energy. *Ecological Economics*, *104*, 22–32.

Speck, M., & Hasselkuss, M. (2015). Sufficiency in social practice: Searching potentials for sufficient behavior in a consumerist culture. *Sustainability: Science, Practice, & Policy*, *11*(2), 14–32.

Steffen, W., Rockström, J., Richardson, K., Lenton, T.M., Folke, C., Liverman, D., . . . Schellnhuber, H.J. (2018). Trajectories of the Earth System in the Anthropocene. *Proceedings of the National Academy of Sciences*, *115*(33), 8252–8259.

Su, B., Su, B., Huang, J., Fischer, T., Wang, Y., Kundzewicz, Z., . . . Jiang, T. (2018). Drought losses in China might double between the 1.5°C and 2.0°C warming. *Proceedings of the National Academy of Sciences*, *115*(42), 10600–10605.

Trotta, G., Lorek, S., & Spangenberg, J.H. (2018). Energy efficiency in the residential sector: Identification of promising policy instruments and private initiatives among selected European countries. *Energy Efficiency*, *11*(8), 2111–2135.

UBA Federal Environment Agency. (2013). *Using global land areas and biomass sustainably and sparingly*. Position. Dessau-Roßlau, Federal Environment Agency.

UBA Federal Environment Agency. (2016). *Chances and risks of the use of biochar and other "modified" biomass as soil additives or for C-sequestration in soils*. UBA Texte 04/16. Dessau-Roßlau, Federal Environment Agency.

UBA Federal Environment Agency. (2018). *Development of a quantitative model "Sustainable Germany"* (vol. 1-4). UBA Texte 95/2018-98/2018. Dessau-Roßlau, Federal Environment Agency.

UBA Federal Environment Agency. (2019). *Biogas plants - safety aspects and environmental impact*. Background. Dessau-Roßlau, Federal Environment Agency.

Ulgiati, S. (2001). A Comprehensive Energy and Economic Assessment of Biofuels: When “Green” Is Not Enough. *Critical Reviews in Plant Sciences*, *20*(1), 71–106.

Viessmann. (2019). *Green light for first industrial power-to-gas system in Dietikon, Switzerland*. Retrieved November 12, 2019, from https://www.viessmann-newsroom.de/unternehmen/grunes-licht-fur-erste-industrielle-power-to-gas-anlage-im-schweizerischen-dietikon

Wachsmuth, J., & Duscha, V. (2019). Achievability of the Paris targets in the EU—The role of demand-side-driven mitigation in different types of scenarios. *Energy Efficiency*, *12*(2), 403–421.

Walter, A., Wiehe, J., Schlömer, G., Hashemifarzad, A., Wenzel, T., Albert, I., . . . von Haaren, C. (2018). *Nature-compatible energy supply from 100% renewable energies 2050*. BfN Federal Agency for Nature Conservation, BfN scripts 501. Federal Agency for Nature Conservation. Bonn.

Weiss, A. (2016). *Energy balance of microalgae biofues*. Dissertation at TU Darmstadt, Project at the Institute for Technology Assessment and Systems Analysis (ITAS) of KIT. Retrieved from https://www.itas.kit.edu/projekte_weis10_emik.php or http://tuprints.ulb.tudarmstadt.de/5352/1/Weiss_Annika_Diss.pdf

Wester, P., Mishra, A., Mukherji, A., & Shrestha, A.B. (Eds.). (2019). *The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People*. Cham, Switzerland, Springer Nature Switzerland.

Wiedmann, T., & Lenzen, M. (2018). Environmental and social footprints of international trade. *Nature Geoscience*, *11*(5), 314–321.

Wiens, J.J. (2016). Climate-Related Local Extinctions Are Already Widespread among Plant and Animal Species. *PLoS Biology*, *14*(12), e2001104.

Wilson, C., Pettifor, H., Cassar, E., Kerr, L., & Wilson, M. (2019). The potential contribution of disruptive low-carbon innovations to 1.5°C climate mitigation. *Energy Efficiency*, *12*(2), 423–440.

Ziebarth, N. (2010). Technology alone will not fix it - The ecological dimensions of geoengineering. *Political Ecology*, *120*, 30–32.