

Sustainable Bio- or CO₂ economy: Chances, Risks, and Systems Perspective

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Supporting Information
available online

Abstract

To obtain a consistent view of sustainable future development, scenarios based on global balances have been derived. The world population may grow significantly faster than generally expected by many studies with up to 11.6 billion people in 2050. The climate goal of 1.5 °C can realistically not be reached any more and it is shown why it has been so difficult to realize that strong action would have been required years ago. Without change in behavior, a strong competition for land area will develop, mainly driven by human fertility and a large fraction of animal-based food. While CO₂-based econo-

my does not compete with food production for agricultural land area, its economic feasibility still needs to be demonstrated. In a bio-based economy, third-generation biomass alone will not be able to supply enough feedstock to fulfill all demands. Thus, competition with food production for land area will be unavoidable. Besides economic and ecological aspects, also ethics need to be considered. A holistic view is essential for deriving effective policies and ethical guidelines, but it also needs to influence personal decisions.

Keywords: Bioeconomy, CO₂ economy, Sustainable-energy transition, Systems view

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1 Background

A continually growing body of knowledge has been developed on a variety of aspects of sustainable economy with hundreds of books and thousands of research articles. It has been realized that fossil-based economy leads to emission of green-house gases, which cause climate change and already today induce increasing problems like more frequent extreme weather events. This insight led to the COP 21 Paris agreement, ratified by many nations, agreeing on climate goals of limiting global mean temperature to +2.0 °C and to put significant effort into trying to limit it to +1.5 °C above pre-industrial level [1]. Alternatively, utilizing biomass as a sustainable option for bio-materials production as well as bioenergy requires agricultural land area, which establishes a direct link to food scarcity and world hunger. Bioeconomy thus links very directly to several of the UN sustainable development goals including hunger, climate action, clean energy, and sustainable production. As an alternative to avoid the competition for land area, developing a CO₂ economy has been proposed. Insight is thus required into how bioeconomy competes with these upcoming as well as the already existing challenges and to relate this to a CO₂ economy.

To gain some understanding on how these different aspects of a complex system interact, a holistic view is desired, which puts the individual determining parameters into appropriate relation. Future development cannot be predicted since the trends cannot be foreseen today. Instead, only scenarios can be derived that indicate possible future development. On the other hand, if political or behavioral changes shall be resulting from the considerations, the interrelation between the main influencing parameters and the results, e.g., for the environment, have to be apparent. Thus, to derive the holistic view, simple and transparent models are used, where the influence of possible variations of assumptions can be assessed directly. It is

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believed that only if the major influences can be directly understood, the results can be a firm foundation to derive guiding principles for future development. This is especially important since the result will also hint at aspects of sustainability ethics, which may influence individual personal decisions.

The basis of the approach taken here are balances which are applied to perform an evaluation of publicly available data on resources and their utilization. Data-driven trends of the past together with demands stemming from the development goals are utilized to get detailed insight into possible future scenarios and their consequences. The key parameters are then determined that most significantly influence the overall system and which have an influence larger than any shift due to unexpected trends. The approach is described and discussed in the following, where sections with too much detail distracting from the main line of thought are collected in the Supporting Information (figures with preceding S).

Since every individual on this planet earth is responsible for his or her demands leading to resource utilization and waste production, the development of the world population is discussed first. Then the sustainable-energy transition from fossil resources to renewable energies will be considered because this will allow some characterization of the time scales on which to expect the changes to occur. The principal interaction of food production with the energetic or material use of biomass will be discussed next, which allows establishing a quantitative understanding for land area as limiting factor. Finally, the implications for material production based on carbon dioxide or bio-based materials will be analyzed, with special focus on available options to produce the major products of chemical industry, namely polymers.

2 World Population

Driving force for all anthropogenic use of resources and production of waste is the individual human, who has the desire to live his or her life in wellbeing. Aspects of that are sufficient supply of energy, food, and materials for fulfilling the everyday needs. These individual demands need to be scaled with the world population to determine the demand of humanity as a whole. Thus, world population is a key parameter for which the range of possible future development has to be realistically evaluated.

Data on past development and scenarios of future development of the world population are available from the Population Division of the Department of Economic and Social Affairs (DESA) of the UN [2] (Fig. 1). In most studies, it is assumed that the medium variant of the world population prospects (WPP) is most closely representing the development that is to be expected [3–5]. This is especially supported by the probabilistic projections included in the 2017 revision of the UN projections, indicating that the probabilities for the low and high scenario are significantly below 1% (see Fig. S2 in the Supporting Information). In some studies even slower population growth is assumed [3, 6, 7].

The data supplied by the UN are updated regularly, typically every two years. To characterize how the projected scenarios change between the publications, the projection for 2050 is

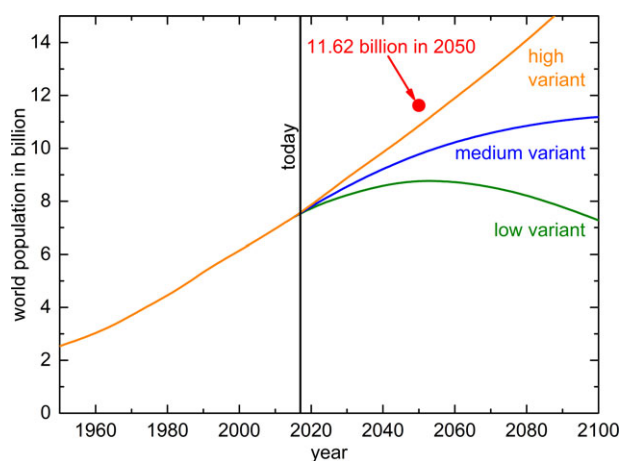


Figure 1. World population data according to the three scenarios published in the 2017 revision of the world-population prospects of the UN [2]; adapted from [8] with permission.

shown in Fig. 2 as a function of the year, in which the data were published. The low and medium projections have been essentially continually increasing. To quantify the observed trend, linear curves have been fitted to the data published since 2002 because they show a relatively systematic behavior. It has been assumed that the three projections meet in 2050, because then the projections are no longer projections, but refer to a unique estimated value of the population in that year. By minimizing the deviations, the final value at the intersection as well as the gradient of the three curves have been fitted. The projection of scenarios indicates a world population of 11.62 billion in 2050, which is even above the value projected with the high variant shown in Fig. 1.

The question arises, why the evaluation by UN-DESA indicates a probability of <1% for the high variant, even though the trend of the meta-study clearly points towards such high values. This can be understood by distinguishing between uncertainty and ignorance [20,21]. In a complex system,

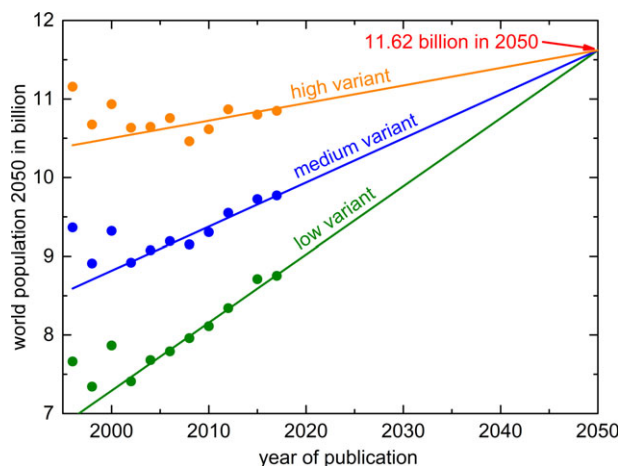


Figure 2. World population projected for 2050 as published in different years [2, 9–20]. Included are three linear fits which are assumed to meet at a single point in 2050, adapted from [8] with permission.

uncertainty may be quantified by statistical evaluations, while the lack of knowledge, technically called ignorance, which is decreasing over time, can typically not be quantified as easily. For the world population it turned out that the decrease in fertility in sub-Saharan African countries is less than expected, child survival rates increased globally more than expected, and the influence of HIV decreased [22]. It appears that while UN-DESA quantifies the uncertainty of their projections, the meta-evaluation shown above indicates an order of magnitude of variation induced by knowledge about the actual system behavior increasing over time. This lack of knowledge is not anyone's fault but rather a consequence of the openness of the future to develop.

This evaluation shows that the high variant of the population scenarios leading to more than 16.5 billion people in 2100 has to be considered as scenario for future development since it is as realistically possible as the medium variant. Considering the continually increasing knowledge about future development, which can in principle not be known in advance and may follow past trends, probable scenarios may well lie between the medium and the high variant, which are thus systematically applied here as bounding scenarios. As shown, even scenarios above the high variant may occur.

This means that all projections of future development considering only the medium variant of the population prospects or even slower population growth may draw a much too optimistic picture [3, 4, 6, 7]. Resource demands as well as waste and emissions produced may be underestimated by more than 15% for 2050 and by a factor of 1.5 for 2100, the discrepancy continually increasing. Unfortunately, population is growing exponentially until the end of century according to the high variant.

How misleading it can be to ignore the trends in Fig. 2, is exemplarily demonstrated from the latest IPCC assessment report [3, 23], in which the population projections applied in the evaluated studies are summarized. It is indicated that the 5th to 95th percentile range is relatively narrow and lies well below the medium variant of the WPP 2012 [17]. While the impossibility to use the published scenarios to quantify uncertainty is appreciated, it is nevertheless stated that "...the scenarios were generated by experts making informed judgements about how key forces might evolve in the future" [3]. Thus, the narrow range of the evaluated scenarios suggests that experts agree on the future development of the world population and that they agree that this lies well below the medium variant.

Unfortunately, the scenarios used in that evaluation, for which data sources could be found, all use the medium variant, but from WPP published between 2004 and 2010. The narrow range of scenarios thus results only from the shifts of the WPP medium variant between publication years 2004 and 2010 being small. That this range lies below the medium variant solely results from medium variants of WPP 2004 to 2010 being compared to the WPP 2012, which lies above (Fig. 2). Thus, the experts do not agree that a probable development lies below the medium variant of the UN projec-

tions. As consequence, emissions of greenhouse gases are significantly underestimated by the IPCC and other studies. Transition scenarios may turn out significantly more challenging than presented in these studies [3, 4, 6, 7, 24–26].

This unfortunately also applies for the most recent special report of the IPCC on the 1.5°C climate change [6]. The illustrative model pathways of the IPCC, which are used in this special report for illustrating possible scenarios of successful future development, are compared to the world population prospects in Fig. 3 [2, 27]. Since the population scenarios are based on the values of the 2010 edition of the WPP, those data are included for comparison [16]. Compared to these WPP 2010 data, two of the illustrative model pathways lie rather close to the medium variant, the two others towards the end of the century significantly above the low variant. Compared to the 2017 edition of the WPP, for which the low and medium variant moved significantly upward as compared to the WPP 2010, the two lower variants are partially even below the low variant and the two others are almost in the middle between the low and medium variant.

In the insert in Fig. 3, the curves are shown in close-up for a shorter time period. It becomes clear that the data of the WPP 2017 between 2010 and 2017 significantly diverge from the illustrative model pathways. This shows that the actual development during the last few years clearly indicates the inadequacy of the population projections used in the IPCC special report on 1.5°C climate change [6]. Unfortunately, also the most recent study of the Club of Rome applies a population projection which is even significantly below the low variant of the WPP 2017 [7]. Finally, also recent EU policies for sustainable energy development take only the medium variant of WPP 2015 into account [24].

Thus, the projections of some of the most prominent studies, which are currently the basis for policy development, very likely draw a much too optimistic picture. All of the mentioned studies apply population scenarios which are only on the easier side of the range of realistically possible developments as seen

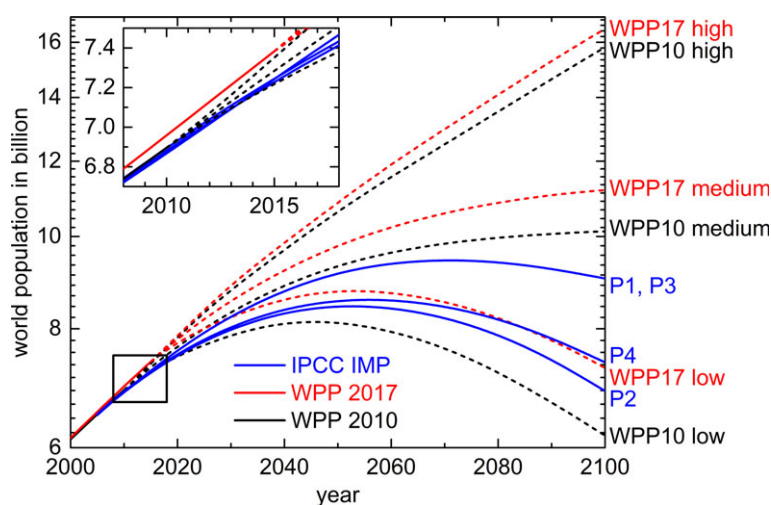


Figure 3. Population scenarios of the four IPCC illustrative model pathways P1 to P4 compared to the UN World Population Prospects of 2010 (indicated as WPP10), based on which they have been developed, and of 2017 (indicated as WPP17), the most current version [2, 6, 16, 27].

in the meta-study above and thus result in the distorted impression that we may be able to cope with climate change and world hunger with limited efforts. How mastering these challenges is influenced by the projections on world population will be shown below.

3 Sustainable-Energy Transition

To reach the climate goals of the COP 21 Paris agreement [1], the share of renewable energy has to be systematically increased. Since the maximum potentials of hydro and geothermal energy are limited, the major contribution for the sustainable-energy transition has to be realized by solar and wind energy. Their combined share in primary energy supply has increased by around 35 % a⁻¹ in 2000, a growth rate which continually decreased after that, reaching around 20 % a⁻¹ today (see Fig. S5). Based on this historic development, it is assumed that characteristic and realistic future growth rates of wind and solar energy lie between 20 % a⁻¹ and 30 % a⁻¹.

If these growth rates are projected further into the future, substitution rates develop as shown in Fig. 4. The substitution rate is the fraction of the total primary energy demand which is additionally substituted with renewable energy technology in the respective year. Nuclear energy is regarded as unsustainable, specifically because of the unsustainable waste produced, and thus also to be substituted. Three scenarios are indicated for which the growth and substitution rates are quantified. Since a constant growth rate implies exponential growth, which is not feasible beyond certain limits, the scenarios are limited between 2 % a⁻¹ and 3 % a⁻¹, with the latter being the assumed maximum that can realistically be achieved on a global scale (see Supporting Information for details).

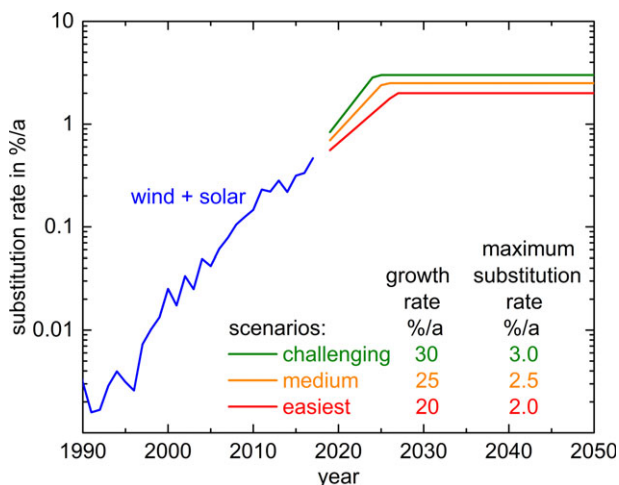


Figure 4. Historic data and projections of the substitution rate of wind and solar energy [28].

With a chosen scenario of world population and the projected per-capita energy demand, the global primary energy demand is obtained (graphs see in the Supporting Information). With the growth and substitution rates of solar and wind energy the remaining demand results, which has to be supplied

with fossil primary energy carriers. Burning these energy carriers in turn adds a defined amount of carbon dioxide to the atmosphere, which finally allows determination of the resulting global mean temperature. The result for the high UN population variant is shown in Fig. 5. These scenarios are broadly in line with the climate objectives of the COP 21 Paris agreement. The scenarios for the medium population variant yield only slightly shifted results (see Fig. S7).

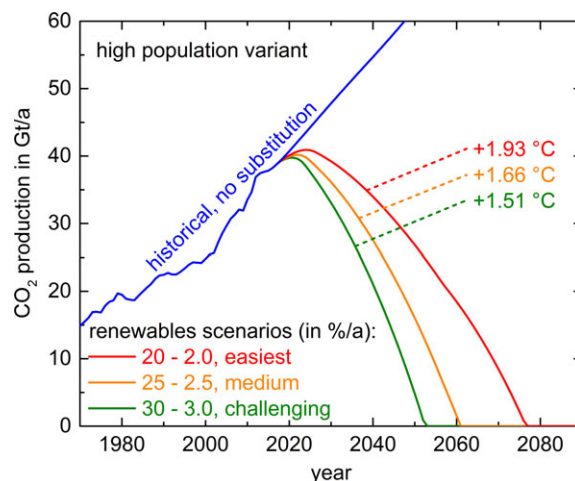


Figure 5. Reduction of CO₂ emissions according to the three investigated energy-transition scenarios for the high UN population scenario.

Fig. 5 shows that to reach the 1.5 °C climate goal, the sustainable-energy transition needs to be completed around 2050, in agreement with IPCC evaluations [6]. For the 2 °C climate goal this should be achieved around 2070. Thus, reaching the climate goals may be possible in principle but requires systematic increases in global substitution rates by a factor of 4 to 6 as compared to today's 0.5 % a⁻¹ [28]. Comparison of Figs. 4 and 5 shows that the increase of renewables drives the sustainable-energy transition. It is thus not required to formulate CO₂ goals for future decades, rather higher growth and substitution rates of renewables need to be reached today that include all energy sectors.

When the maximum annual consumption of fossil energy carriers is reached in around 5 years, the decline in demand may lead to significant price drops. Then the most expensive oil and gas extraction technologies like fracking may become uneconomical and corresponding sites may be shut down. Alternatively, they may be highly subsidized for political reasons in some countries, leading to corresponding high risks for the global economy. Additionally, in 10 to 20 years the production rates will drop below 80 % of the maximum, which may lead to problems in the downstream processes like refineries because their production rate may fall below feasible operating windows. Consequently, also downstream industries will undergo severe transitions and economical challenges. These are of course only possible aspects of future development, which could be balanced if properly managed. Nevertheless, the discussion shows that there is a high risk of strongly fluctuating supply of fossil feedstock and prices. At the same time, this implies significant challenges for the world economy

accompanying the required restructuring of major industrial sectors. Finally, the timescale of these required changes, including establishing a bio- or CO₂-based economy, is just 30 to 50 years, depending on the climate goal to be reached.

This discussion also means that bio- or CO₂ economy, which could be a sustainable basis for material production, should be on the way to be well established when the fossil feedstock prices are expected to increase, i.e., in 3 to 20 years from now at the latest. If the climate change is limited to close to 1.5 °C, these effects can be expected significantly earlier, in little more than 10 years. Depending on the scenario, bio- or CO₂ economy have to be fully established by 2050 to 2070.

Fig. 6 presents the effort required if sustainable-energy transition is intensified only after some years. Growth and substitution rates are assumed to be coupled (Fig. 6, left). The curves for the different scenarios appear to be horizontally shifted. The slope to still reach the 1.5 °C climate goal is already rather steep. Thus, independent of the population scenario, every year we miss to significantly increase the intensity of sustainable-energy transition leads to a strong increase of the required global efforts to still be able to reach 1.5 °C. Thus, continuing to negotiate boundary conditions of energy transition instead of fostering that transition itself, as at COP24 in Katowice, may not be adequate to reach the desired goals.

Comparing this globally required effort with the current status of how climate goals are tackled, it appears unrealistic that humanity can limit the climate change to 1.5 °C. We missed to realize that the system has shifted from the deceptive flat part of the curve into the steep section, where any further delay renders the goal increasingly unattainable. At the same time, it is obvious, why reaching this conclusion is so difficult. It is apparently still possible to reach that climate goal in principle, but the effort is quickly increasing according to an essentially hyperbolic function.

Keeping in mind that it is desirable to limit climate change to the lowest possible temperature increase, from Fig. 6 it can

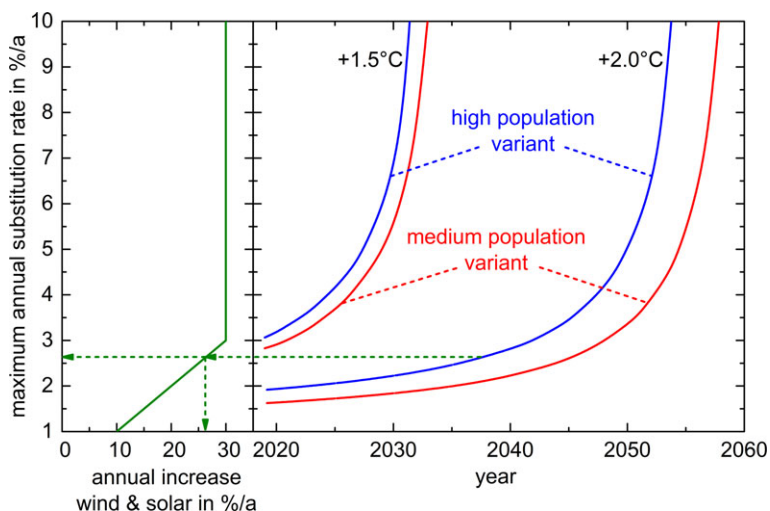


Figure 6. Effort, expressed in growth and substitution rate of solar + wind energy, required for reaching the climate goals, if prior to the start of the intensive energy transition the growth rate is only 10 % a⁻¹ and substitution rate at most 1 % a⁻¹.

be seen that any climate goal slightly above the 1.5 °C will already be in or at least close to the steep section of the curve. This in turn means that determined action is instantaneously required on a global scale to still limit the global mean temperature increase as much as possible.

What appears urgently required is a long-term perspective of how the sustainable-energy transition can be realized. Currently, major effort is focused on extending wind and solar energy on the one hand and, on the other hand, on the exit from coal and nuclear energy. It appears that these efforts are reaching a certain limit because during the last almost ten years in the EU the substitution rate stagnated below 1 % a⁻¹ (see Fig. S6). This indicates that with the current approach there may be some fundamental limitations for further progress which need to be overcome. Regarding the electricity system, e.g., in Germany, wind and solar energy indeed contribute a large fraction to electricity production. Since these sources show strong fluctuations on a daily and weekly basis, the conventional power plants are down-regulated if there is an excess of renewable energy. The capacity to do so is limited, which in turn limits further deployment of solar and wind energy. What would be required, is establishing significant capacity for energy storage. This means what would actually be urgently required is a consent on a consistent pathway of energy transition accounting for all aspects of energy transition including possibilities for energy storage. Thus, instead of promoting to switch off coal and nuclear power plants, the development of a consistent transition pathway to a sustainable energy system would be required.

Such a strategy would also need to consider the financial burden on the end consumers, who will have to replace their end-user appliances like cars or ovens, which need to be adapted to the energy carriers in a sustainable energy network. They also need to minimize end-energy demand, e.g., by house insulation. In developing a reliable transition strategy, all industrial sectors associated with a sustainable energy system would need to be included. Two major aspects that have to be addressed are the ecological goals to be reached, which may be driven by societal discourse, and the management procedures and decisions leading to industrial realization of these goals. Politics need to find a societal consent, which then acts as guard rail for the management decisions of the industrial sectors concerned. This apparently requires an iterative procedure and a systematic way of updating because insights into how the political measures affect the costs, the rate of transition as well as technological progress need to be fed back. If, as in the past, politics directly execute management decisions, like when to exit nuclear energy or coal in Germany, society will pay the extra price, not the management or the shareholders. Thus, a healthy balance between shareholders and stakeholders is required. Reaching a broad agreement about an optimal transition strategy requires a carefully monitored discourse, because it is foreseeable that lobbyists, NGOs, and religions, to a large degree via the media, will try to exert their

influence, of which the democratic legitimization is not always clear.

It should be stressed that climate change will not vanish once sustainable-energy transition is completed. Instead it will stay with us with all its consequences for centuries. Successive transfer of CO₂ from the quickly equilibrated upper ocean layers into the large reservoir of deeper ocean layers is a slow process, which has a characteristic timescale of the order of a millennium [29].

In some of the scenarios evaluated by IPCC negative-emission technologies are utilized to capture large fractions of the emitted CO₂ [3, 6]. These technologies would allow an overshoot of atmospheric CO₂ concentration and to apply suitable carbon-dioxide removal (CDR) technologies to nevertheless reach the climate goals. These CDR technologies are typically based on utilization of biomass like BECCS (bioenergy with carbon capture and storage) or AR (afforestation and reforestation), which compete with food production. In the scenarios of such studies this appears feasible, because due to assumed low population growth, competition with food production is limited. It is shown below and in the Supporting Information that these scenarios are unrealistic because population growth will not allow additional biomass utilization without significant increase in world hunger.

In the recent IPCC special report on global warming of 1.5 °C [6] three of the four illustrative model pathways assume a reduction of CO₂ emissions between 2010 and 2020 by more than 50 %. Regarding the scenarios of Figs. 5, S7, and S8 as well as the current slow increase in renewable energies, these goals appear too challenging to be realistically reachable. Only one illustrative pathway realized a slower decline in CO₂ emissions, but unfortunately that scenario relies most strongly on negative-emission technologies, which do not appear feasible at the assumed rate as mentioned above and shown in more detail below. Thus, with respect to the sustainable-energy transition this IPCC report draws a possibly much too optimistic picture.

4 Food Versus Fuel and Materials

Today more than 800 million people are undernourished, i.e., more than every tenth person is starving [30]. Thus, production of biomass, which is used for non-food applications like biofuels and biomaterials, is already putting excessive pressure on agricultural land area today. In order to quantify this competition for agricultural land area, corresponding scenarios until 2100 have been developed.

Based on detailed evaluation of the FAOSTAT database [30], all required trends have been projected mostly linearly into the future, some with a slight quadratic contribution accounting for corresponding expected development (see Supporting Information for details). Caloric food supply is assumed to slightly increase until toward the middle of the century sufficient calories are supplied on average to be able to overcome undernourishment. It has also been assumed that the land-area specific agricultural productivity will continue to increase linearly until 2100 as it did in the past. Also, for the production of animal-based food it has been assumed that intensification continues as in the past. Finally, it is assumed that 10 % of the

primary-energy demand is realized via biocombustibles produced from dedicated biomass. Of this, 2.5 % alone will be required as jet fuel, the rest accounting for processes, e.g., in steel and chemical industry, which require carbon input or reducing atmosphere in chemical reactions.

Three resulting characteristic scenarios of land area requirement are shown in Fig. 7. In the left part of each diagram the historical development of per-capita land area is shown, where only those contributions are considered that can be used agriculturally with reasonable effort [30]. In the right part of each diagram the required land area for fulfilling the different demands is presented. The white lines indicate how the limits between arable land, pasture & meadows as well as forest area would develop considering only population growth.

As a basis for discussing the individual scenarios, it should be mentioned that every individual assumption can be debated. Variation of individual parameters within reasonable limits leads to changes in the results, which are typically smaller than the changes induced by the main parameters that are varied between the three scenarios shown. Also, variation of individual parameters affects the three shown scenarios in a comparable way, so that the differences between the scenarios are maintained. Analysis thus allows identifying the major parameters and determining their influence.

For the high population variant, even with the continued increase of agricultural productivity which is assumed to continue at maximum rate, conversion of forests into agricultural land is unavoidable if the number of undernourished people shall not increase (Fig. 7 a). If instead the population develops according to the medium variant, the pressure on the natural resources is still at an upper limit until around 2060 (Fig. 7 b). Only for the longer-term perspective the situation relaxes. If additionally, together with the sustainable-energy transition, the nutritional basis is shifted to solely vegetal nutrition, the pressure on natural resources relaxes significantly and instantaneously (Fig. 7 c). The latter strong effect is caused by the large mismatch between food supply and land-area demand for animal-based food. Today, 80 % of the land area on which food is produced, are used to generate animal-based food, e.g., as pasture and for feed production, which supply only 17.5 % of the food calories [30]. Thus, the production of animal-based food is highly land-area inefficient.

Comparing the different scenarios, it is apparent that population growth has a significant influence on the available area per capita. Only if the medium population variant is realized, the curves tend to stabilize towards 2100. For the high variant, the available land area per capita in 2100 will be less than half of that of today.

Reduction of animal-based food supply relaxes the situation quite considerably. Only the scenario shown in Fig. 7 c would allow for significant use of bioenergy and bio-based negative-emission technologies like BECCS without the risk to increase world hunger. In all cases, the biocombustibles, which cover only 10 % of the primary-energy demand, have a significant contribution. Thus, as long as people are starving, the fraction of bio-based energy and utilization of bio-based negative-emission technologies should be minimized. Thus, if nutritional habits do not change, negative-emission technologies like BECCS or AR, which require fertile land area, can only have

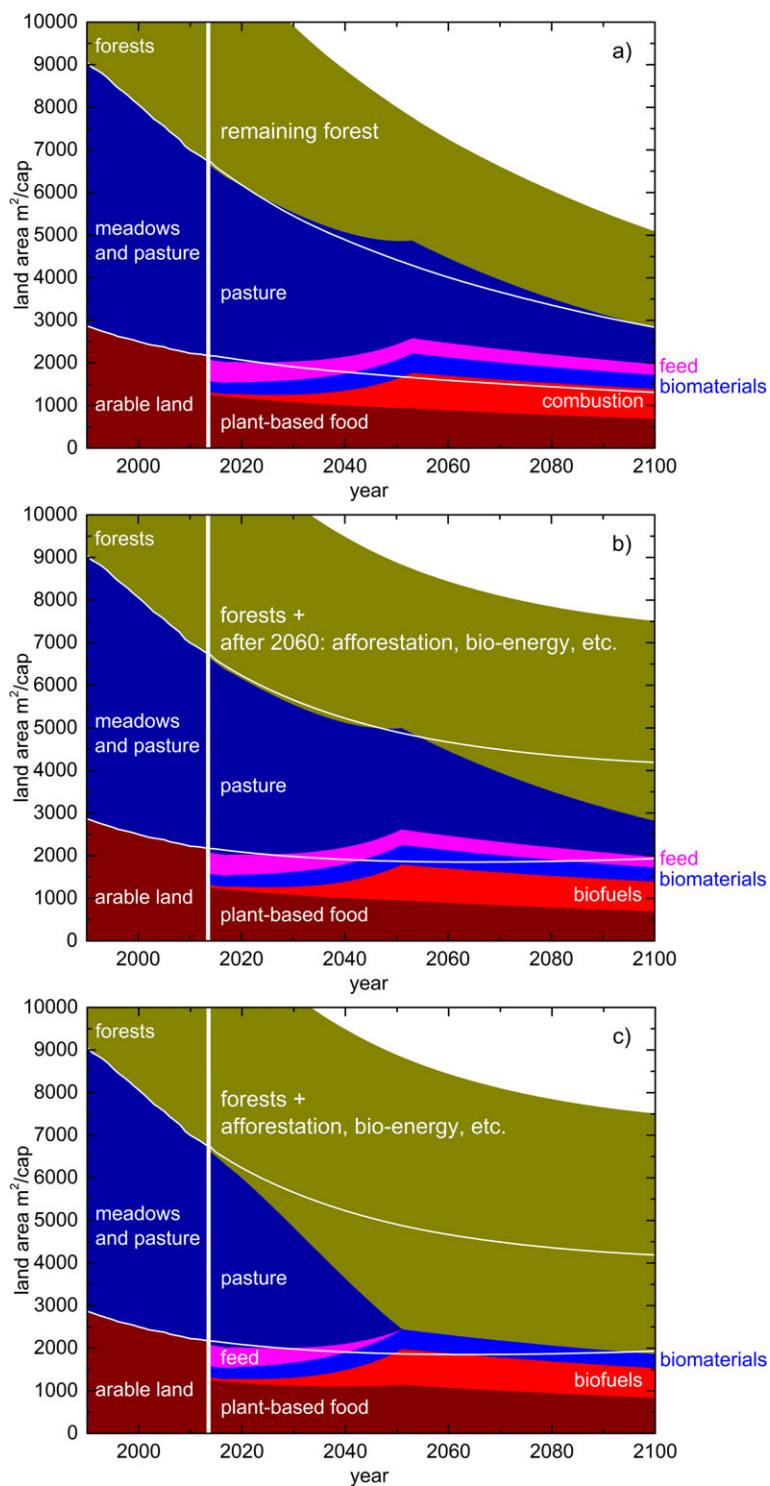


Figure 7. Three scenarios of land-area utilization for the challenging energy scenario: a) high population variant, b) medium population variant and shift to solely vegetal food supply parallel to sustainable-energy transition; adapted from [8] with permission.

limited impact on an ethically acceptable sustainable-energy transition.

Fig. 7 shows that the required land area can be reduced by a factor of around 1.5 until 2100 by shifting from the high to the medium population variant while the choice of nutrition induces a factor of around 2. Since it has already been assumed that agricultural productivity will continue to increase at the high rate observed in the past, there is no other parameter influencing land area utilization to a similarly large degree. Even, if materials and combustibles are solely produced from CO₂ instead of biomass, the reduction in required agricultural land area would be less than 40 (Fig. 7 a).

Systematic utilization of genetically modified (GM) crops is sometimes proposed as another influencing parameter and workaround. It is shown in the Supporting Information, where also a variety of other options are discussed, that at least until now these GM crops do not show any advantage over conventionally bred crops, neither with respect to overall productivity nor concerning the fluctuations between years.

This comparison shows that the situation with respect to land area is rather different from that for energy. While the available technology is fully sufficient to establish sustainability, but only has to be realized on larger scale, behavioral aspects have a major influence on sustainable utilization of land area. The pressure on the land area mainly depends on fertility, i.e., on the number of children per women in her lifetime, and on the food choices. If the behavior is not changed, agricultural intensity has to continually increase at the highest rate to avoid an increasing number of undernourished people or more forests need to be converted into agricultural land. If instead the behavior is changed, existing agricultural intensity is fully sufficient to supply enough food for everyone and to fulfill additional demands, e.g., for biomaterials, biofuels, and stabilizing biodiversity. In the context of world hunger, behavioral changes are significantly more important than any foreseeable additional technological advancement. Thus, behavior change is unavoidable to reach the sustainability goals. This insight also establishes a direct link between bioeconomy and ethics.

Feeding a growing world population will require to convert a significant area of meadows and pasture into arable land (Fig. 7). For the high population variant with unchanged nutritional habits, roughly half of the area of the meadows and pasture will need to be rededicated. Only with behavioral changes the required shift can be limited.

Fig. 7 already hints that the competition for land area between food, biofuels, and biomaterials production is unavoidable, which will be discussed in more detail below. The land area for producing the feedstock even for biomaterials is small, but de-

pending on the feedstock, can be significant. Thus, feedstock and technologies used for biomaterial production need to consider not only the energy demand but also the land area requirement.

5 Sustainable Chemicals and Fuels Production

As seen above, a dramatic change of market situation for fossil carbon sources is to be expected in 30 to 50 years. Since today only around 4 % of these resources are utilized as feedstock for chemical processes, the chemical industry is strongly dependent on this future development. Chemicals and fuels can be produced in a sustainable way by either utilizing biomass or CO₂ from the atmosphere [33]. Also, bioeconomy can lead to point-sources for CO₂ as (side-)product, which can be further utilized. Finally, an additional carbon source to be utilized in successive process steps can stem from increased recycling, e.g., by recycling separated individual components, via pyrolysis, or gasification. Alternatively, complete combustion can supply energy and the generated CO₂ can further be used chemically. All of these options would finally allow reaching a fully circular economy. Nevertheless, the question needs to be answered if and how it will be possible to fulfill the feedstock demands of the chemical industry as well as for combustibles along both possible routes, i.e., in a bio- or in a CO₂-based economy. As already mentioned above, for the chemical industry the focus is on the major products, i.e., large-scale polymers.

5.1 CO₂ in Chemical Industry

The utilization of CO₂ from the atmosphere has been proposed as an urgent requirement for meeting the climate goals [31] and it has been shown that it may lead to reasonable costs for CO₂ [32]. The economic viability on a large scale nevertheless still has to be proven. This is quite demanding since the liquid or solid absorbents proposed under optimal conditions typically have a capacity of 2 ma % of CO₂ [34,35]. Under realistic conditions, which due to variable weather, i.e. humidity and temperature, are suboptimal as compared to the lab situation, at least 100 t of absorbent have to be moved and regenerated for each ton of CO₂ recovered from the atmosphere. Since the absorbents typically degrade over time, the corresponding makeup streams further worsen the economic performance. In cases where CO₂ can be obtained from point sources, this limitation does not apply.

The CO₂ can then be transformed into liquid hydrocarbon as feedstock for the chemical industry or as biocombustible. Alternatively, the CO₂ can directly be utilized in processes leading to the final product. Examples for such processes are the conversion of CO₂ with hydrogen to methanol with a CO₂ efficiency above 95 %, which is already realized on a scale of 5500 t a⁻¹, and incorporation of CO₂ into polymers, which is already commercialized [36–38]. Such processes are attractive, because the land area required for collection of sustainable energy like photovoltaics for activating the zero-exergy CO₂ is not competing with agricultural land area. Thus, especially

available point-sources of CO₂ should be utilized as feedstock for such processes. Nevertheless, it has to be shown that these processes are economically feasible on a large scale for each individual application.

The challenges become clear if the required energy for the process steps are considered. For the sorption of CO₂ from the air, between 50 and 200 kJ mol⁻¹ CO₂ have been reported [35], with the highest values referring to amine-based sorbents and the lowest to a moisture-swing process proposed by Lackner and coworkers. After CO₂ has been captured, the conversion with hydrogen, e.g., to methanol, requires at least the chemical exergy of hydrogen, namely 734 kJ mol⁻¹ CO₂. Actually, both processes will show inefficiencies leading to actually higher energy demands. Comparing these values to the electricity currently obtained from fossil resources, from around 120 kJ mol⁻¹ CO₂ for coal-fired power plants to 400 kJ mol⁻¹ CO₂ for power plants with a gas turbine, it is obvious that overall, a significant multiple of the end-user energy gained today by burning fossil resources has to be supplied to convert carbon dioxide from the air as well as from point sources into hydrocarbons. Based on current electricity generation cost, this will lead to costs of at least around 2000 US\$ t⁻¹ of hydrocarbon feedstock produced from carbon dioxide. Since these considerations are only intended to give a first impression of the challenges, actual process inefficiencies as well as taking into account the overall carbon footprint of each technology will lead to results that are even more challenging.

This directly shows why recycling of carbon-based materials will be so essential in a future sustainable economy. At the same time, the high energetic effort for the hydrogen supply means that structural recycling would be highly beneficial, which could also directly be inferred from exergetic considerations. If, on the other hand, remaining carbon-containing waste would be incinerated, the carbon dioxide recovered from this point source, and converted into chemicals feedstock, the large energy demand for hydrogen production could not be avoided. Thus, significant effort will need to be invested into the design of products and recycling pathways to allow recycling of individual components at least for large fractions of the major polymers. This applies not only for a CO₂-based but equally for a bio-based economy. In any case, recycling large fractions of the products would allow minimizing the remaining make-up-streams.

It should be stressed that this route is currently not an efficient means to reduce the greenhouse-gas emissions. The exergy required to convert CO₂ to a liquid hydrocarbon, e.g., by reaction with hydrogen obtained via electrolysis from sustainable electricity, corresponds to the energy which is released when burning exactly that liquid. The latter process is realized today to produce electricity with an efficiency of typically less than 40 %. As long as we are using fossil primary energy carriers to generate electricity, it is more efficient by at least a factor of 2.5 to feed any excess electricity directly into the electricity grid and to reduce the amount of fossil resources burnt than to utilize it for conversion of CO₂ into a liquid. This applies analogously for solid or gaseous fuel-like components produced from CO₂ and is also relevant for all carbon capture and sequestration efforts that rely on such a conversion for safer storage of the carbon.

As alternative to the chemical route, the conversion of CO₂ into lipids produced with algae cultivated in open-ponds or closed systems has been proposed. Since the lipid content in the algae is at most 70 % of the dry matter, and in the process up to several 10 % of carbon dioxide fed into the system are lost, the carbon efficiency is around 50 % at most [39]. This lies significantly below the carbon efficiencies reported for the chemical routes, which are well above 90 %. Thus, algae cannot compete with the chemical conversion described above.

5.2 Bio-Based Chemical Industry

The use of biomass for energy supply and for bio-based chemicals production has extensively been discussed and also modelled with significant detail, especially considering efficiencies and energetic requirements [6, 33, 40]. Bioenergy already being used today indicates that bioeconomy would be economically viable on large scale. As seen above, the production of biomass as feedstock for the chemical industry may compete with food production for essentially the same land area. Here the question is to be answered, which options for a bio-based economy are feasible, taking land area requirement into account. As a boundary condition, energetic evaluation of bio-based production routes shows that it is expected that oxygen-containing intermediates and products will be more favored than today, based on fossil feedstock [41] (see Supporting Information).

The land area required to fulfill the demand for bio-based chemicals has been determined for a variety of options linking crops and major process routes (Fig. 8). On the one hand, the bars span the range obtained for the world average land-area specific productivity and, on the other hand, for average productivity of a major producing nation with the highest land-area specific yields for the respective crop [30]. The bars thus indicate characteristic land area demands. Up to the intermediate(s) mentioned, the processes indicated in lighter green are currently only realized on pilot-plant scale. Since these options are identical for the production of biocombustibles, the same considerations apply for bioenergy. If 10 % of the primary energy demand are to be realized via bioenergy as assumed above, the additional area demand is roughly twice that for biomaterials. The total area shown is the arable land area according to the high population variant. The indicated goal corresponds to the area for biomaterials shown in Fig. 7 a. If world population would develop according to the

medium variant instead of the high variant, in 2050 1870 m² per capita would be available instead of the 1685 m²cap⁻¹ shown.

The routes are grouped according to the generation of biomass used. For first-generation biomass edible components are directly utilized, and as second generation biomass the crops are grown on comparable land. With third-generation biomass the competition with food production is entirely avoided because, e.g., only byproducts like straw or dung from the food production are used.

In Fig. 8 also the radius is specified, in which a crop has to be grown to feed a chemical plant with 250 000 t a⁻¹ production rate, where proper crop rotation has been accounted for [42]. The radii assume that the entire land area is solely agriculturally utilized, which applies approximately for regions like the corn belt in the US. To account for agricultural land area being typically interspersed with settlement and forest area, e.g., in Europe, a factor of roughly 3 would need to be applied [43]. If feedstock for the largest world-scale chemical processes with up to 3 Mt a⁻¹ shall be supplied, another factor of 3 needs to be added. In many cases this would lead to radii significantly exceeding 50 km, which appears a limit typically found for many bio-based plants like sugar plants. Therefore, for such

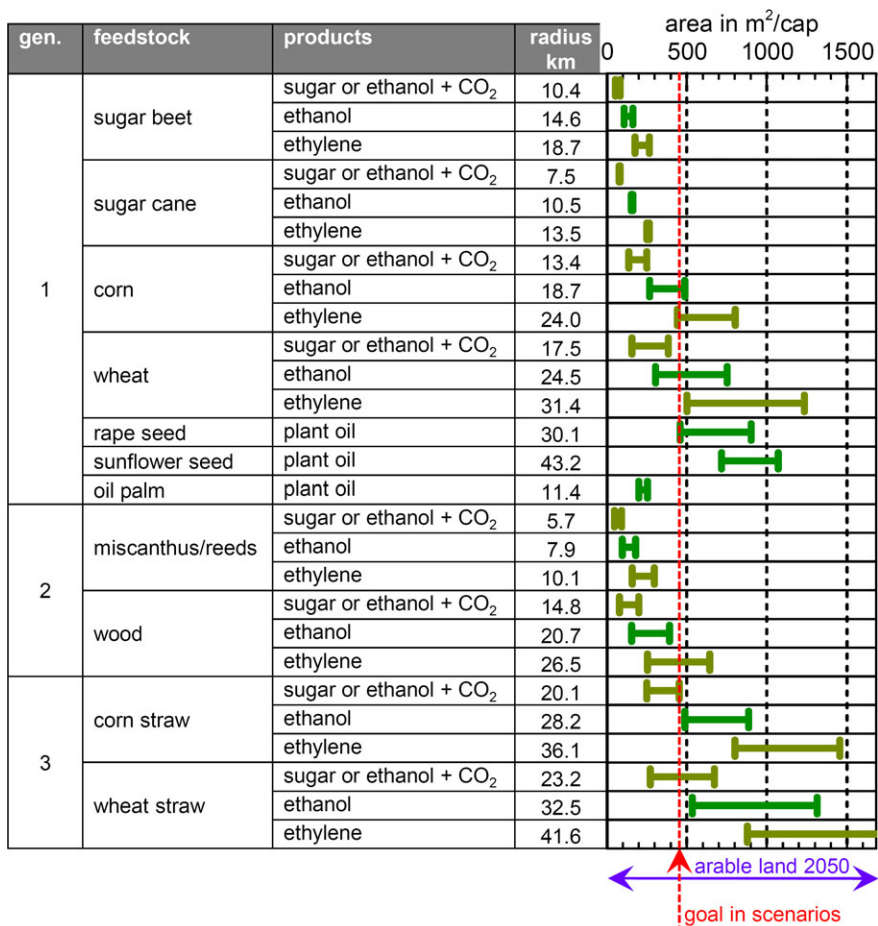


Figure 8. Evaluation of area demand in 2050 for various combinations of crops and intermediates as chemical feedstock, assuming that each individually supplies the total demand.

large chemical-industry complexes a decentralized supply needs to be realized, where the raw material is transferred between the sites producing the bio-based feedstock and the chemical industry complex, in which the end products like polymers are obtained.

For crops containing sugar, starch, or cellulose as major component, three exemplary options have been compared, which characterize different mass efficiencies, with which the major biocomponent ends up in the feedstock for successive steps. As first option, after depolymerization and fermentation only the ethanol is used while the CO₂ is released into the atmosphere. Alternatively, all atoms from the sugar can be utilized, either via sugar chemistry or by also utilizing the CO₂ from fermentation, e.g., via methanol, as described above. Finally, ethylene as direct drop-in for conventional processes can be obtained by dehydration of ethanol [44, 45]. While this last option is minimizing the changes required in existing chemical processes, it maximizes required land area, because CO₂ and water are lost from the product molecule. On the other hand, for ethanol and methanol as feedstock, the successive chemical steps would need adjustment because large processes typically use ethylene and propylene as major feedstock. These three alternative routes have exemplary character, being realized already at least on pilot-plant scale. Other options are possible, e.g., via lactic acid. Since the different routes for each crop are distinguished only by mass efficiency, interpolating land-area demand between the options for any alternative route is directly possible based on mass efficiency.

The land area required to supply biomaterials and bio-combustibles solely from third-generation biomass would be so large that essentially all rest biomass would need to be collected from all fields, in some options even exceeding the available rest biomass. The reason for this large area demand is the low efficiency of only around 50% for the biochemical route to depolymerize cellulose used today on an industrial level. This can in part be understood as nature having successfully evolved cellulose and lignin such that they are difficult to be disaggregated as structural element in crops while as feedstock to bioeconomy they have to be depolymerized. The land area demand may decrease if more efficient chemical or biochemical routes are developed. On the other hand, a good alternative for utilizing this rest-biomass is to work it into the soil for humus formation, thus enhancing soil fertility. Only roughly one third of the rest biomass should be utilized to ensure sustainable soil fertility and agriculture [46]. Thus, the sustainable land area requirement for third-generation biomass is a factor of roughly 3 higher than the technical limit shown in Fig. 3. Taking these factors into account, third-generation biomass thus cannot be a major contribution in bioeconomy, it can only be an add-on where feasible. This in turn means that first and second-generation biomass will be essential for a bio-based economy, at the same time inducing the direct but unavoidable competition for land area with food production in a sustainable economy.

Fig. 8 shows that several options of first and second-generation biomass demand sufficiently small agricultural land area, a significant number of options even for world-average productivities. Possibly even a slight reduction of required agricultural land area as compared to Fig. 7 may be possible if the highest

productivities are realized. This shows that the scenarios of Fig. 7 can realistically be matched with appropriate routes.

In evaluating the options, aspects other than land area need to be accounted for. To plant oil palms, primeval forests are often cleared, which is detrimental for climate. Regarding reaction kinetics, mass efficiency, and process complexity, sugar- and starch-based processes are favored over cellulose-based routes, which in turn are less complex than those based on wood.

The most promising options use sugar cane, sugar beets, corn, miscanthus, or other reeds. The options are presented as if they would individually supply the complete feedstock to chemical industry, but depending on the local climate and soil situation, globally an appropriate mix of different options will be applied. Regarding required land area, it turns out that rapeseed oil needs a large area, which implies that using it as basis for biodiesel production today competes excessively with human nutrition. Overall, sugar-based options appear somewhat advantageous compared to oil-based processes.

Figs. 7 and 8 now also allow to discuss the IPCC scenarios, several of which rely on negative-emission technologies to reach the climate goals [3, 6]. Fig. 7 shows that first- and second-generation biomass contributing as little as 10% to the primary-energy demand is significantly competing with food production for agricultural land area. Without change in behavior, BECCS can only be realized in an ethically acceptable way from third-generation biomass. The discussion of Fig. 8, on the other hand, shows that the amount of sustainable third-generation biomass in that case is very limited. This in turn means that the extra time which the utilization of BECCS can buy until a carbon-neutral economy is established, can also only be a fraction of the remaining time, i.e., some few years. Thus, in an ethically acceptable way BECCS cannot be deployed at the large scales assumed in many scenarios, including two of the four illustrative model pathways of the IPCC special report on 1.5 °C climate change [6]. Similar considerations limit the realization of AR. The higher contributions of BECCS and AR, e.g., in the IPCC illustrative model pathways, only appear feasible because they consider an unrealistically low population growth, as discussed above.

In the context of bio-based feedstock, algae are sometimes proposed as option with very high productivities. These high efficiencies are unfortunately only possible if CO₂ is fed to the cultures. The CO₂ is then utilized with lower efficiency as would be possible along the chemical routes discussed above. Without the supply of CO₂, the net-productivity accounting for the energy required to operate, e.g., the open-pond systems, is less than that of optimal land-based crops. Thus, algae cannot be an optimal solution. They can only be a sensible option, if they are grown without CO₂ supply on land area not used agriculturally. Unfortunately, under such conditions the efficiency is typically decreased additionally, e.g., because light intensity and temperature are higher than would be optimal for the algae, and by excessive evaporation of water in open-pond systems [39].

Finally, a fundamental advantage of the bio-based route should be mentioned: As a side stream from several bio-based routes food components like proteins can also be obtained. This means that bio-based economy and food production may be synergistically interlinked at least to a certain degree and not as strictly competing as usually discussed.

6 Conclusions

If past trends continue, world population may grow much faster than predicted by many scenarios currently used to support policy makers, reaching a factor of 1.5 until 2100. Use of bioenergy and BECCS to limit net CO₂ emissions cannot be realized to the degree required by these scenarios to limit climate change. The sustainable energy transition may thus be significantly more challenging than currently expected. Implementation of sustainable energy technology should be fostered to limit climate change as much as possible, even though we presumably already missed the 1.5 °C climate goal. This is especially important since the economic situation may become challenging in the near future due to all simultaneous transitions lying ahead. Overall, a quick increase by a factor of 6 in substitution rate as compared to today would be required to limit climate change to 1.5 °C. These as well as the following conclusions have been drawn assuming that the world population will at most grow according to the high variant published by the UN. The meta-study shown in Figs. 1 and 2 indicates that the world population may realistically grow even faster leading to an even more challenging future.

The fight against world hunger is strongly governed by behavioral aspects. Only two children per woman and shifting to solely plant-based food would ensure sustainability instantaneously, removing the pressure on land area and agricultural productivity. This would free land area to such a degree that bioenergy could significantly contribute to the future energy mix, more land area could be left unused to support biodiversity, and also negative-emission technologies based on biomass could be established on large scale.

If these behavioral changes are not realized, agriculture will need to continually increase productivity at the highest possible rate for the foreseeable future and would still not be able to avoid an increasing number of undernourished people. In less developed regions such worsening of the food situation on top of the increasing climate challenges slows down development and consequently also leads to a slower decline in fertility. At a certain point a situation may be reached, where the more developed countries will no longer be able to support the global system to a degree required for an overall positive development. This constitutes a global developmental tipping point.

Even, if such a tipping point is avoided, a further increase in at least the perceived difference in living conditions between developed and least developed countries may significantly increase migration, putting further stress on the global system. It has to be kept in mind that exceeding certain limits of a driving force inducing a flux in chemical engineering very generally leads to an unforeseeable disruptive change in behavior, like the onset of Rayleigh-Bénard or Marangoni convection. It is to be expected that exceeding comparable limits of driving force for migration, which is also just a flux, will lead to corresponding behavior. The mobilization of migrants from Honduras and El Salvador passing through Mexico starting in October 2018 as well as the migrants walking through Europe starting at the end of August 2015 may be seen as early onsets of such disruptive change in system behavior. If such transitions are to be avoided, significant effort needs to be put into reducing the driving force, i.e., to support the development in less developed

regions. Here a systems view needs to be taken, because it is clear that if we fail to achieve this goal, the negative consequences will be globally realized.

The options for a sustainable economy can be viewed in this context. Since third-generation biomass alone cannot supply sufficient feedstock for the chemical industry and for the production of fuels, an economy based mainly on biomass cannot avoid putting additional pressure on agricultural land area. As long as the mentioned behavioral changes are not realized on sufficiently large scale, the production of biofuels or biomaterials in a sustainable economy is ethically questionable because it fosters undernourishment. This applies already today for the current use of any first- or second-generation bioenergy like biodiesel from rapeseed or palm oil. In the EU policies this has already been realized to a certain degree and is accounted for in their policies on biofuels and indirect land use change [47]. Only if behavioral changes lead to a significant decrease of pressure on land area, bioeconomy can be realized without this ethical conflict. Sufficiently far-reaching behavioral changes could even allow large scale implementation of bio-based negative-emission technologies, which would ease the sustainable energy transition. It has been shown that the technological aspects of bioeconomy can be realized with various process routes that are available today at least on pilot-plant scale.

At the same time, it has to be clear that there will be no immediate business case for CO₂ removal technologies, especially not in the economically challenging times induced by the major transitions and current trends towards “my nation first”. Only fostering policies of cap&trade emission rights may induce increased investment into carbon-saving or even negative-emission technologies. All nations would need to adhere to such a policy even in the economically difficult times lying ahead.

A sustainable economy based on atmospheric CO₂ as major feedstock can avoid the ethical conflict with undernourishment but suffers from high energy demand and the challenging CO₂ capture. Until now, CO₂ capture from the atmosphere and conversion has not been shown to work economically feasible on large scale despite around the two decades of research and strong political statements [31, 48]. If on the other hand CO₂ is obtained from point sources, this carbon source should be utilized.

While CO₂ economy would avoid the competition with food production, it may simply be economically so unattractive that bioeconomy wins the race. Thus, world hunger may significantly increase. To a certain degree this can be avoided if food components like proteins are obtained from side streams of the bio-based processes. At the same time, such a synergistic linking of food production and bioeconomy would increase the flexibility of the entire system to react appropriately, e.g., in cases of bad harvest, which can be expected to be more frequent in the future due to climate change. This discussion shows, that our individual behavior determines if a relatively easy to realize bio- instead of the today still demanding CO₂ economy would be ethically acceptable, with a bioeconomy also significantly enhancing viability of the overall system.

It should be stressed again that the routes and the options discussed are regarded as if each would individually contribute the total feedstock for chemicals production. Of course, it is to be expected that a network of processes will be established,

which is finally fed from a variety of sources. This may include carbon dioxide, especially all CO₂ from point sources, as well as biomass. Recycling may be increased and incorporated materially into the circular economy concept, e.g., by chemically utilizing the CO₂ generated in waste incineration plants. Of course, direct material recycling would be highly desired because it minimizes the energy demand. Also, waste streams from food production will presumably be more systematically utilized, e.g., for the generation of biogas, which is then introduced into the gas net. The routes discussed here are thus to be understood as exemplary cases characterizing certain material efficiency during conversion of primary feedstock into the final product. Second-generation has no benefit over first-generation biomass based on land area productivity. Due to the simplicity of the processes and typically higher efficiency, first-generation biomass has the advantage of lower energy and equipment demand. Thus, if the ethical aspects are solved, first-generation is to be preferred over second-generation biomass. Third-generation biomass should be utilized as far as possible without impeding soil fertility.

The results presented show that major transitions for a sustainable economy are required within few decades if sustainable wellbeing is to be achieved globally. At the same time, it has to be recognized that a major factor for reaching the sustainability goals is the change of individual behavior. Thus, some thoughts are required on how this can be achieved. For politicians in a democracy the desire to be re-elected is a major driving force. The managers of companies, on the other hand, will be driven by maximizing the profit for shareholders and themselves. Finally, the consumer would like to minimize expenses for living well. Thus, none of these individual drivers, which in public discourse agree on the rules according to which society develops, has a direct interest in enhancing sustainability of the system as a whole. The goal of sustainability only entered recently because the consequences of the failure to establish a sustainable economy will arrive so soon that we ourselves will experience them. While it is positive that everyone now actually needs to account for these effects in his or her personal decisions, it is negative that we had to wait so long before the driving force became strong enough for us to finally act. Unfortunately, meanwhile the challenge to master the required changes in time has grown immensely. On the other hand, since the citizen/consumer decides on his or her behavior, elects the politicians in a democracy, and decides what to buy from which company, it is the only individual citizen who can actively change his or her behavior and thus influence the behavior of the system as a whole. Politicians will not be successful in establishing politics that the citizens do not support and managers will not be able to establish products that the consumers do not buy, even if they were beneficial or even required to achieve a sustainable economy. Thus, indeed we individually determine with our behavior the success of establishing a sustainable economy and how difficult it will be to get there.

Finally, also the existing chances should be stressed. If the challenges are mastered and, especially, if sustainability becomes a major aspect in our personal decisions, we can reach full sustainability of the human society within roughly 50 years at the latest. In principle, the required technology is available

and for its implementation, the usual technical progress is sufficient.

Overall, these considerations show that in a future economy energy supply, material production, food generation, and agriculture will be strongly interlinked. It is obvious that on top of technological, economic, and ecological considerations, also ethical aspects are relevant. A holistic systems view needs to be taken because only then the major interrelations can be appreciated. Of course, further aspects like water use and scarcity or the effect of climate change could be included. In the current considerations these have been excluded to focus on those factors that can be quantified relatively easily and which are directly linked via balances that can be overviewed and clearly communicated. This also limits the complexity, which may lead to a more reliable overall description. Increasing complexity can result in an only seemingly better description, hiding that the uncertainty of the additional parameters to characterize the system may be increasing [49]. It is apparent that the very fundamental balances used allow gaining significant insight into the major drivers of the system [50, 51]. Since ethical aspects will be of major relevance for establishing sustainable wellbeing, a clear and easily comprehensible representation of the major interrelations is required to support the systems view and to induce behavioral changes. The comparably simple balances presented here may contribute to this goal. To guide individual behavior, these insights, including a certain understanding of the system as a whole, would need to be realized on an individual level, which in a democratic environment would then allow the corresponding societal trends to gain political impetus [52].

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References

- [1] www.unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement (Accessed on September 26, 2018)
- [2] *2017 Revision of World Population Prospects*, United Nations, DESA/Population Division, New York **2017**. population.un.org/wpp/
- [3] *Climate Change 2014: Mitigation of Climate Change. Working Group III contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)* (Eds: O. Edenhofer et al.), Cambridge University Press, Cambridge **2014**.
- [4] OECD/IEA, *World Energy Outlook 2016*. webstore.iea.org/world-energy-outlook-2016 (Accessed on September 18, 2018)
- [5] T. Searchinger, R. Waite, C. Hanson, J. Ranganathan, P. Dumas, E. Matthews, *Creating a Sustainable Food Future. A Menu of Solutions to Feed Nearly 10 Billion People by 2050*, Synthesis Report, World Resources Institute, Washington, DC **2018**. www.wri.org/publication/creating-sustainable-food-future
- [6] *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* (Eds: V. Masson-Delmotte et al.), World Meteorological Organization, Geneva **2018**. www.ipcc.ch/sr15/
- [7] J. Randers, in *The Future in Practice: The State of Sustainability Leadership*, Cambridge University, Cambridge **2012**. www.2052.info/wp-content/uploads/2014/01/p120801-2052-A-global-forecast-15p-illustrated-CPSL.pdf
- [8] A. Pfennig, *So gelingt unsere Zukunft*, Books on Demand, Norderstedt **2018**.
- [9] G. K. Heilig, *World Population Prospects: Analyzing the 1996 UN Population Projections*, IIASA Working Paper WP-96-146, International Institute for Applied Systems Analysis (IIASA), Laxenburg **1996**. pure.iiasa.ac.at/id/eprint/4882/
- [10] UN Department of Economic and Social Affairs, Population Division, *Long-range World Population Projections: Based on the 1998 Revision*, United Nations, New York **1998**. <https://web.archive.org/web/20180614172204/www.un.org/esa/population/publications/longrange/longrangeKeyFind.pdf>
- [11] UN Department of Economic and Social Affairs, Population Division, *World Population Prospects. The 2000 Revision*, Vol. III, United Nations, New York **2002**.
- [12] UN Department of Economic and Social Affairs, Population Division, *World Population Prospects. The 2002 Revision*, Vol. III, United Nations, New York **2004**.
- [13] UN Department of Economic and Social Affairs, Population Division, *World Population Prospects. The 2004 Revision, Highlights*, United Nations, New York **2005**.
- [14] UN Department of Economic and Social Affairs, Population Division, *World Population Prospects. The 2006 Revision, Highlights*, United Nations, New York **2007**.
- [15] UN Department of Economic and Social Affairs, Population Division, *World Population Prospects. The 2008 Revision, Highlights*, United Nations, New York **2009**.
- [16] UN Department of Economic and Social Affairs, Population Division, *World Population Prospects. The 2010 Revision*, Vol. I, United Nations, New York **2011**.
- [17] UN Department of Economic and Social Affairs, Population Division, *World Population Prospects. The 2012 Revision*, Vol. I, United Nations, New York **2013**. population.un.org/wpp/Publications/
- [18] UN Department of Economic and Social Affairs, Population Division, *World Population Prospects. The 2015 Revision*, Vol. I, United Nations, New York **2015**. population.un.org/wpp/Publications/
- [19] UN Department of Economic and Social Affairs, Population Division, *World Population Prospects. The 2017 Revision*, Vol. I, United Nations, New York **2017**. population.un.org/wpp/Publications/
- [20] B. Wynne, *NATO ASI Ser., Ser. I* **1992**, 2(2), 111–127. DOI: [https://doi.org/10.1016/0959-3780\(92\)90017-2](https://doi.org/10.1016/0959-3780(92)90017-2)
- [21] J. R. Ravetz, *Sci. Commun.* **1987**, 9, 87–116. DOI: <https://doi.org/10.1177/107554708700900104>
- [22] P. Gerland, *Personal communication*, 01.08.2018.
- [23] www.ipcc.ch/report/ar5/wg3/assessing-transformation-pathways/01_figure_6-1/ (Accessed on March 04, 2019)
- [24] *A Clean Planet for all. A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy*, European Commission, Brussels **2018**, COM(2018) 773 final.
- [25] N. Scovronick, M. B. Budolfson, F. Dennig, M. Fleurbaey, A. Siebert, R. H. Socolow, D. Spears, F. Wagner, *PNAS* **2017**, 114 (46), 12338–12343. DOI: <https://doi.org/10.1073/pnas.1618308114>
- [26] W. Lutz, *PNAS* **2017**, 114(46), 12103–12105. DOI: <https://doi.org/10.1073/pnas.1717178114>
- [27] D. Huppmann et al., *IAMC 1.5°C Scenario Explorer and Data hosted by IIASA*, International Institute for Applied Systems Analysis, Laxenburg **2018**. DOI: <https://doi.org/10.22022/SR15/08-2018.15429>
- [28] *BP Statistical Review of World Energy June 2018*. www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html (Accessed on September 21, 2018).
- [29] F. Joos, R. Roth, J. S. Fuglestad, G. P. Peters, I. G. Enting, W. von Bloh, V. Brovkin, E. J. Burke, M. Eby, N. R. Edwards, T. Friedrich, T. L. Frölicher, P. R. Halloran, P. B. Holden, C. Jones, T. Kleinen, F. T. Mackenzie, K. Matsumoto, M. Meinshausen, G.-K. Plattner, A. Reisinger, J. Segschneider, G. Shaffer, M. Steinacher, K. Strassmann, K. Tanaka, A. Timmermann, A. J. Weaver, *Atmos. Chem. Phys.* **2013**, 13, 2793–2825. DOI: <https://doi.org/10.5194/acp-13-2793-2013>
- [30] www.fao.org/faostat/en/#data (Accessed on October 10, 2018)
- [31] K. S. Lackner, S. Brennan, J. M. Matter, A.-H. A. Park, A. Wright, B. van der Zwaan, *PNAS* **2012**, 109 (33), 13156–13162. DOI: <https://doi.org/10.1073/pnas.1108765109>
- [32] K. S. Lackner, *Eur. Phys. J. Special Topics* **2009**, 176, 93–106. DOI: <https://doi.org/10.1140/epjst/e2009-01150-3>
- [33] T. Marzi, G. Deerberg, C. Doetsch, A. Grevé, M. Hiebel, S. Kaluza, V. Knappertsbusch, D. Maga, T. Müller, H. Pflaum, A. Pohlig, M. Renner, U. Seifert, S. Stießel, C. Unger, T. Wack, E. Weidner, *Kohlendioxid, Biomasse und*

- regenerativer Strom – Ressourcen einer neuen Kohlenstoffwirtschaft, UMSICHT-Diskurs Heft 1, Verlag Karl Maria Laufen, Oberhausen 2017.
- [34] E. S. Sanz-Pérez, C. R. Murdock, S. A. Didas, C. W. Jones, *Chem. Rev.* **2016**, *116*, 11840–11876. DOI: <https://doi.org/10.1021/acs.chemrev.6b00173>
- [35] T. Wang, K. S. Lackner, A. Wright, *Environ. Sci. Technol.* **2011**, *45*, 6670–6675. DOI: <https://doi.org/10.1021/es201180v>
- [36] J. Artz, T. E. Müller, K. Thenert, J. Kleinekorte, R. Meys, A. Sternberg, A. Bardow, W. Leitner, *Chem. Rev.* **2018**, *118*, 434–504. DOI: <https://doi.org/10.1021/acs.chemrev.7b00435>
- [37] Bayer MaterialScience CO₂-to-Plastics Pilot Plant. www.chemicals-technology.com/projects/bayer-co2-plastics/ (Accessed on September 27, 2018)
- [38] George Olah CO₂ to Renewable Methanol Plant, Reykjanes. www.chemicals-technology.com/projects/george-olah-renewable-methanol-plant-iceland/ (Accessed on September 27, 2018).
- [39] Y. Chisti, in *Microalgal Biotechnology: Potential and Production* (Eds: C. Posten, C. Walter), Walter de Gruyter, Berlin **2012**.
- [40] S. J. Gerssen-Gondelach, D. Saygin, B. Wicke, M. K. Patel, A. P. C. Faaij, *Renewable Sustainable Energy Rev.* **2014**, *40*, 964–998. DOI: <https://doi.org/10.1016/j.rser.2014.07.197>
- [41] P. Frenzel, R. Hillerbrand, A. Pfennig, *Chem. Eng. Res. Des.* **2014**, *92*, 2006–2015. DOI: <https://doi.org/10.1016/j.cherd.2013.12.024>
- [42] Maximale Anbaukonzentration von Feldfruchtarten bzw. -gruppen, nach Zielen der nachhaltigen Pflanzenproduktion in %, Landwirtschaftskammer NRW, Münster **2018**
- www.landwirtschaftskammer.de/landwirtschaft/ackerbau/fruchtfolge/tabellen-fruchtfolge-pdf.pdf
- [43] M. Kröhl, in *32. Bundestagung DLKG Mainz*, Mainz, September **2011**. www.dlkg.org/media/files/bundestagung/dlkg_bt2011_kroehl.pdf
- [44] J. Althoff, K. Biesheuvel, A. De Kok, H. Pelt, M. Ruitenbeek, G. Spork, J. Tange, R. Wevers, *ChemSusChem* **2013**, *6*, 1625–1630. DOI: <https://doi.org/10.1002/cssc.201300478>
- [45] Ethylene from Ethanol. <https://chematur.se/process-areas/bio-chemicals/bio-ethylene-ethene/> (Accessed on December 28, 2018)
- [46] N. Scarlat, F. Fahl, E. Lugato, F. Monforti-Ferrario, J. F. Dallemand, *Biomass Bioenergy* **2019**, *122*, 257–269. DOI: <https://doi.org/10.1016/j.biombioe.2019.01.021>
- [47] Directive (EU) 2015/1513 of the European Parliament and of the Council of 9 September 2015 amending Directive 98/70/EC relating to the quality of petrol and diesel fuels and amending Directive 2009/28/EC on the promotion of the use of energy from renewable sources (Text with EEA relevance), *OJ L 239*, **2015**, 1–29. <http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32015L1513>
- [48] H. Yang, Z. Xu, M. Fan, R. Gupta, R. B. Slimane, A. E. Bland, I. Wright, *J. Env. Sci.* **2008**, *20*, 14–27. DOI: [https://doi.org/10.1016/S1001-0742\(08\)60002-9](https://doi.org/10.1016/S1001-0742(08)60002-9)
- [49] H. Hasse, in *Reactive Distillation. Status and Future Directions* (Eds: K. Sundmacher, A. Kienle), Wiley-VCH, Weinheim **2003**.
- [50] A. Pfennig, *Chem. Ing. Tech.* **2007**, *79* (12), 2009–2018. DOI: <https://doi.org/10.1002/cite.200700083>
- [51] A. Pfennig, *Biotechnol J.* **2007**, *2*, 1485–1496. DOI: <https://doi.org/10.1002/biot.200700129>
- [52] www.vision3000.eu (Accessed on May 07, 2019)

