

Supporting Information

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

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In this supplementary material, more information on the scenario evaluation and additional graphs are collected. They are arranged under the same headlines as in the main publication. Numbering of figures and references within this supplementary material is preceded by an 'S', while numbers without this 'S' refer to figures and references in the main publication.

S1. Background

Balances have already been used in recent years to gain quantitative understanding on scenarios of future development. For example Marzi et al. [33] draw a picture of a future scenario mainly for Germany, linking available data and including cement as well as steel industry, relying to a large degree on carbon dioxide as key component. While accounting also for biomass as carbon source, the critical balances do not depict the competition for land area between food and other uses of biomass. Schaub and Turek [S01] on the other hand set up balances for earth as a whole and thus develop a rather detailed picture of many aspects including energy and material flows. For future development, a variety of options are discussed but not linked to yield the complete picture desired here. Such balance-based approaches led to integrated assessment models (IAM), e.g. the many for which the data and results have been collected in the IPCC reports (Intergovernmental Panel on Climate Change) [6, S02, S03], which have been continually increasing in complexity from the first start to improve the description of global processes [S04]. Unfortunately, it has to be realized that more complex models do not necessarily allow more accurate description of reality [48], but increase the demand for the accuracy of the model parameters. Thus also refining the models as in many IAM does not overcome the fundamental impossibility to predict the future.

To illustrate the urgency of action needed, Fig. S1 shows the development of atmospheric CO₂ concentration, which is plotted with logarithmic scale relative to a value of 280 ppm, which is close to the pre-industrial level. Since the recent development behaves linearly, the atmospheric CO₂ concentration relative to pre-industrial level is currently increasing exponentially. It is also shown that major steps in realizing and trying to manage anthropogenic influence on climate as indicated by the included major publications hardly influenced past development. The temperature limits shown, which are calculated from the correlation described below, stress how little time remains, if the currently accepted climate goals of 1.5°C or 2.0°C above pre-industrial level are to be reached. How urgent action is actually required becomes obvious, if it is recalled that the recent report of the IPCC on the 1.5 °C climate goal warns that even if that goal would be reached, the consequences as compared to today would be drastic [6].

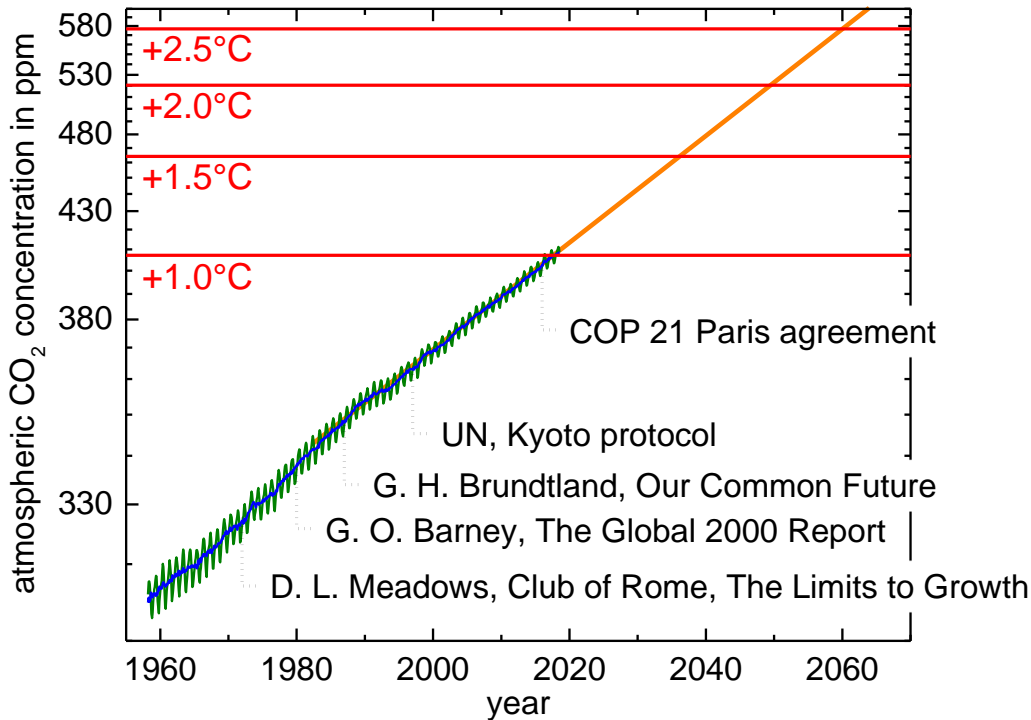


Fig. S1: Development of atmospheric CO₂ concentration [S04-S07]

S2. World Population

In the main publication, world population prospects of the UN as published during two decades with roughly bi-annual revisions have been extrapolated for 2050 [2,9-20]. This results in a projection of such a meta-analysis of 11.62 billion people in 2050. To evaluate the probability of the different scenarios of the UN world population prospects, the original data of the data base projected for 2050 have been used and fitted by a Gaussian distribution [2]. It is apparent from Fig. S2 that the high and the low variant are considered rather improbable. The value of 11.62 billion people in 2050 as obtained by a fit shown in Fig. 2 of the main publication clearly has an essentially negligible probability.

S3. Sustainable-Energy Transition

To obtain the overall primary-energy demand of humanity, the average per capita values have to be multiplied with the world population, which has been analyzed in the previous section. To characterize the situation of the current utilization of primary energy, Fig. S3 visualizes the per-capita values resolved for individual countries. The per-capita primary-energy demand is around 22 000 kWh/(cap a) on world average, in developed countries it is 48 000 kWh/(cap a).

To develop a projection into the future, the annual increase during the last decades has been linearly projected into the future including a slight leveling off towards 2100 (see Fig. S4). In 2100 a value of 28 000 kWh/(cap a) is reached, which accounts for a continued development of less developed countries, leading to a global increase in

average per-capita demand, combined with efforts to save energy in the more developed countries.

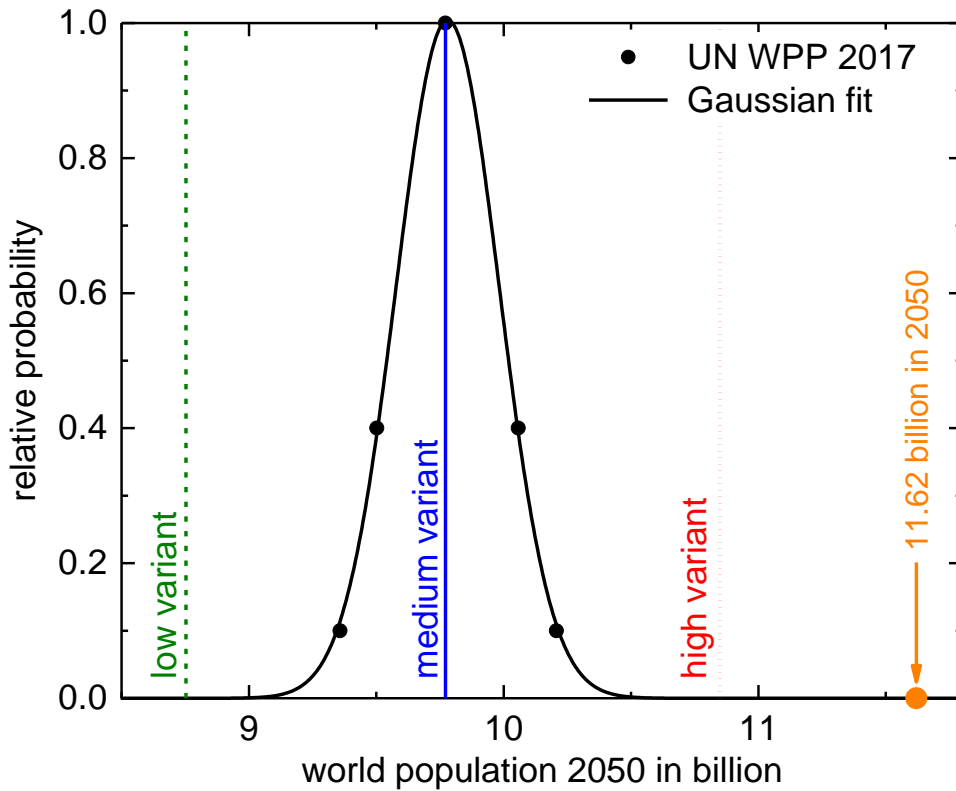


Fig. S2: Probability distribution of world population in 2050 as projected by the UN [2].

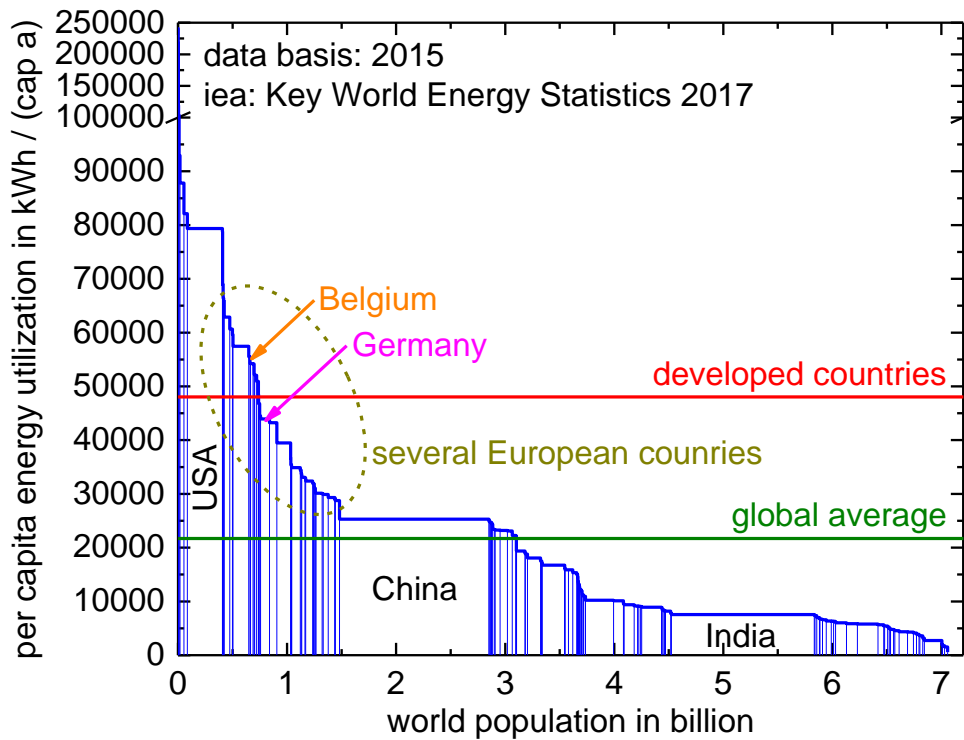


Fig. S3: Primary energy utilization per capita for all countries [2,S08].

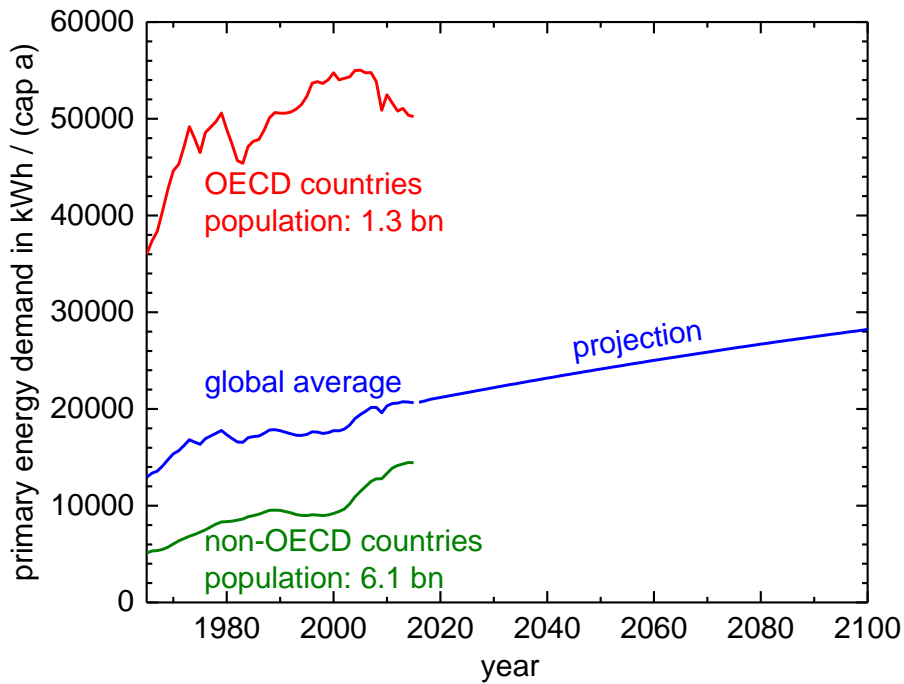


Fig. S4: Historical data of global primary energy demand per capita and projection into the future used in this study [28].

This projection has a high uncertainty, but the value reached in 2100 is close to the minimum primary energy demand in a developed country as estimated by Arto et al. [S09], who indicate that the value should be 33% above the value in 2012, which yields 27 400 kWh/(cap a). The uncertainty of this development is also rather high, because here only primary-energy demand is regarded. Actually only the final-energy demand can be characterized, where the conversion factor to primary energy depends on the energy mix and in the future on the entire energy system that will be realized, including e.g. storage losses. To account for the conversion, here for the historical data the basis of oil equivalent for all renewable energy has been assumed [28], while for the future an unchanged conversion factor is applied to keep an identical basis. That the relation between primary energy and final energy for future scenarios remains rather constant and shows different trends for different scenarios of the IPCC illustrative model pathways may be seen as an indication that this assumption induces a comparably small uncertainty [27].

If applied to characterize the sustainable-energy transition, the uncertainty is actually much less, since this projection then only describes the consumption of energy carriers still used in future years for the fossil fraction of the energy system. Uncertainties then only result from future shifts between different fossil contributions to the energy system. Since the energetic efficiencies utilizing different fossil energy carriers are relatively similar, this introduces little uncertainty. The time horizon for the major transitions that need to take place to achieve the climate goals is of the order of just some decades. This limited horizon where this projection is relevant further limits the influence of the uncertainties.

Correspondingly, it is assumed that the carbon-dioxide emissions per fossil primary energy unit are constant, which corresponds to a constant energy mix. Major shifts during the short remaining time are only to be expected in the electricity sector, while heating and transport will continue to rely on crude oil and natural gas until substituted sustainably. Even, if in the electricity sector coal-fired power plants would be substituted by gas-fired power plants, this would only introduce a comparably small shift for the total energy system. As a consequence, with the uncertainty about the contributions of different countries and their development, any more detailed assumption on future energy mix would introduce uncertainty beyond the possible inaccuracy of this assumption.

The growth rates of renewable energy sources from past data are presented in Fig. S5. Wind and solar energy are shown in combination, because this combination shows a significantly more systematic behavior than the individual values. It is apparent that up to roughly 35 %/a have already been reached, but in recent years this has dropped continually to about 20 %/a today. In the most recent years between 20 %/a and 30 %/a have been maintained for more than a decade. It is noteworthy that the 20 %/a have been reached also during the last years, when the substitution rates were maximum.

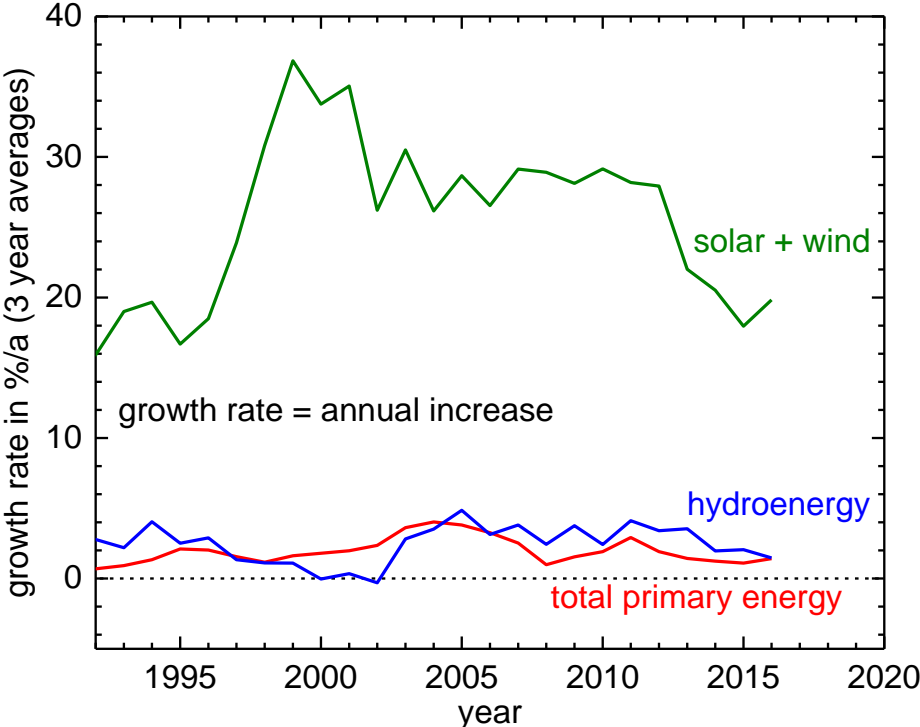


Fig. S5: Growth rates of total primary energy demand and some renewable sources [28].

In the scenarios, growth rates between 20 %/a and 30 %/a are assumed. A constant growth rate would imply exponential growth. While this has actually almost been achieved during the past decades, such exponential growth would quickly exceed

e.g. 10 %/a substitution rate in the near future. This would mean that in one year solar and wind-energy systems would need to be installed globally supplying an additional 10 % of the total primary-energy demand. Since this appears unrealistic, this growth has to be limited.

To assess feasible limits of the substitution rate, typical values of replacement rates for fossil energy technologies can be compared. This comparison assumes that fossil-based and renewable energy technologies have a similar overall cost, which according to a recent very detailed study may indeed be approximately the case [S10]. Of course the cost structure is quite different, because for fossil energy the primary energy carriers have to be continually supplied, while sunlight and wind are free of charge. If the overall cost is comparable, the investment for renewable energy technologies thus is significantly larger than that for fossil-based technologies, which corresponds to what is expected.

To estimate replacement rates, different energy sectors need to be considered. As an example, electrical power plants have an economic life time between 25 and 40 years, depending on the data source and the type of power plant regarded [S11,S12]. The economic life time can be understood as that time, after which the plant is obsolete and has to be replaced or after which by continual maintenance, repairs, and partial replacements the value of the power plant has been completely substituted. Thus for electrical power plants between 2.5 and 4 %/a of their value has to be invested for long-term continual energy supply. This replacement rate only refers to the power plants already installed. Since today electricity is responsible for only one quarter of the final-energy demand, the overall capacity to generate renewable electricity has to increase in the future to cover the remaining rest, which is not realized with e.g. bio-energy.

The major contributions to the remaining three quarters of the final-energy demand relate to transport and heating. Currently, in these areas the end user substitutes the corresponding equipment on time scales of 10 years for transport, e.g. for cars and trucks, and around 25 years e.g. for heating boilers. These energy sectors rely on energy carriers like gas, oil, gasoline, and coal, which are supplied e.g. via refineries, which contribute only a minor fraction to the cost of these energy carriers. Also these industries supplying the energy carriers to the end user need to be substituted with sustainable-energy technology.

Additionally, the growth rate of primary energy demand may be regarded, because this rate corresponds to the capacity to install new energy technology. This growth rate has an average value of 2 %/a during the last 20 years [28].

To estimate a realistic maximum value for the substitution rate from these data, it also has to be considered that for transport and heating the price for the energy carriers has to be paid, which is of comparable magnitude as the investment for the end-user equipment. Thus, overall substitution rates could be expected which are of the

order of twice the replacement rates discussed. This would lead to maximum possible substitution rates of the order of 5 %/a to 10 %/a. On the other hand this has to be related to past and current substitution rates with solar and wind energy as shown in Fig. S6. It is apparent that the values for the world as well as the EU currently lie somewhat below 1 %/a. For the EU a certain leveling off may be realized during the last years, with highest values for individual years around 1 %/a. Also the global values show a slight slowing down, both trends indicating that further increasing substitution rates implies significant effort of national economies. This levelling may currently be induced by missing energy storage capacities of significant capacity. Instead of storing excess renewable energy, today fossil power plants react to how much electricity is currently provided by sun and wind by reducing their production accordingly. This capacity to respond to current renewable electricity is thus limited and represents a natural limit to the further development of renewable energy. If the entire energy system is to become sustainable quickly enough to ensure reaching current climate goals, we must immediately start to implement large-scale energy storage. This as well as conversions within the future energy system will create extra costs, which until now have been mostly avoided. This in turn means that installing a complete energy system will be more expensive than until now, where just additional solar and wind energy is being installed without taking care of other components of the future energy system. With an annual investment as today this will lead to relatively slower substitution rate once the complete energy systems are realized. To reach the climate goals, as will be seen from the scenario evaluations, a substitution rate of 3 %/a will be required, which means an increase of a factor of around 6 for the EU and of 10 globally.

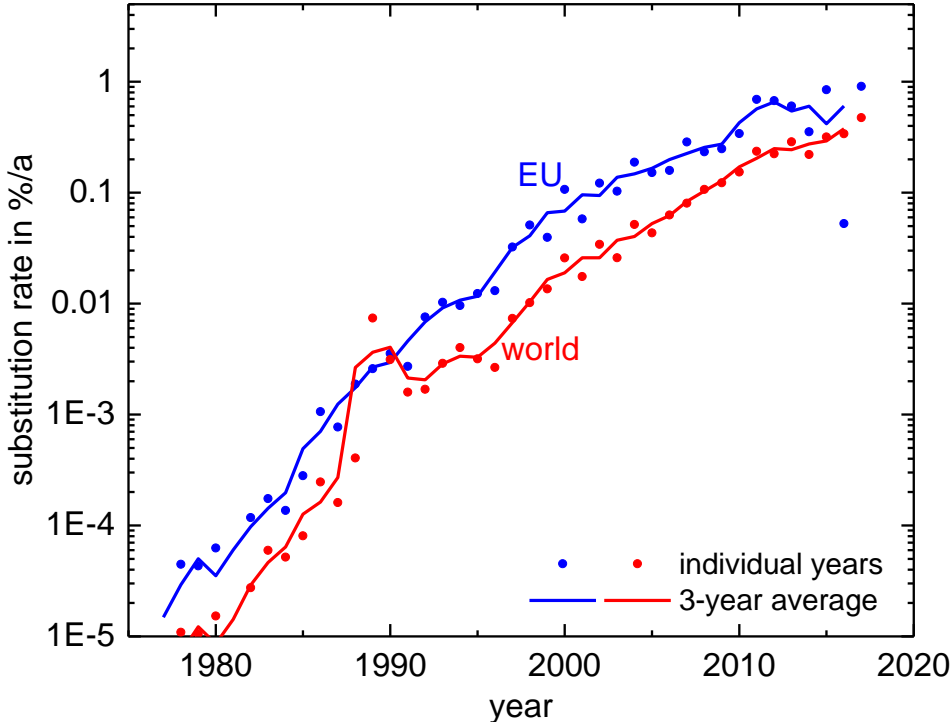


Fig. S6: Substitution rates for wind and solar energy combined [16].

Since

- the substitution rate has to apply globally, i.e. for all countries, especially also those with a lower developmental status,
- realizing that of the order of 2.5 %/a to 4 %/a in the electricity sector can be reached, if all current investment in power plants would be used to substitute fossil energy by wind and solar energy technology,
- accounting for the increased efforts, if storage and other conversions are implemented to reach a complete sustainable energy system,
- while realizing the current substitution rate and
- realizing that it may be significant effort to exceed a substitution rate of 1 %/a as indicated by recent stagnation in the EU,

a maximum of 3 %/a is assumed as being a realistic maximum that can globally be achieved. Based on these considerations, three energy scenarios are regarded with growth rates in solar and wind energy by 20 to 30 %/a until a substitution rate of 2.0 to 3.0 %/a is reached, which is then maintained for the following years until the sustainable-energy transition is completed. These intensities of sustainable-energy transition have to be realized on global average, which effectively means that more developed countries have to proceed significantly faster, because of their higher contributions of CO₂-emissions, and because in less developed countries significant investment is required to foster development, e.g. reducing population growth, which is then not available for sustainable-energy transition in the beginning.

To link the carbon-dioxide emissions to atmospheric carbon-dioxide concentration, available data have been evaluated [28,S13]. In the evaluation, a kinetic transfer between the atmosphere and the upper ocean layers has been considered. Also the capacity of the upper ocean layers for capturing carbon dioxide to equilibrium has been regarded as an adjustable parameter. From fitting the data on CO₂ emissions [S13] and the atmospheric CO₂ content [S05] with this model it was found that 46 % of carbon dioxide are transferred into the oceans within few decades while the remaining 54% stay in the atmosphere. This is very consistent with the evaluations by other studies [S14, 28]. From the IPCC reports the temperature increase per total emitted amount of carbon dioxide has been evaluated as 6.09×10^{-4} K/GtCO₂ (Fig. SPM-10 in [S14]). This climate model is simple but properly describes major aspects, one of which is that after equilibrium between atmosphere and upper layers of the ocean is reached within few decades, successive transfer steps e.g. into deep ocean layers will take many centuries [29]. The climate change is thus not like a little fever which vanishes once we managed the sustainable-energy transition but which will stay with us together with its consequences for very long time.

The results for the energy scenarios with the medium UN population variant are presented in Fig. S7. Comparing the results with those of Fig. 5 for the high variant, it is obvious that the shifts due to population variant are small but especially for the easiest energy scenario the benefit of reducing population growth is significant.

The corresponding scenarios for the medium population variant are slightly shifted to somewhat shorter time scales, which are reduced by at most a decade, and final global mean temperatures, which are 0.04 to 0.17 °C lower than with the high variant (see Fig. 5). For the challenging scenario the difference is much less than for the easiest scenario, because the energy transition for the challenging scenario will be completed much faster, so that the difference between the population scenarios during that transition period is smaller than for the easiest scenario.

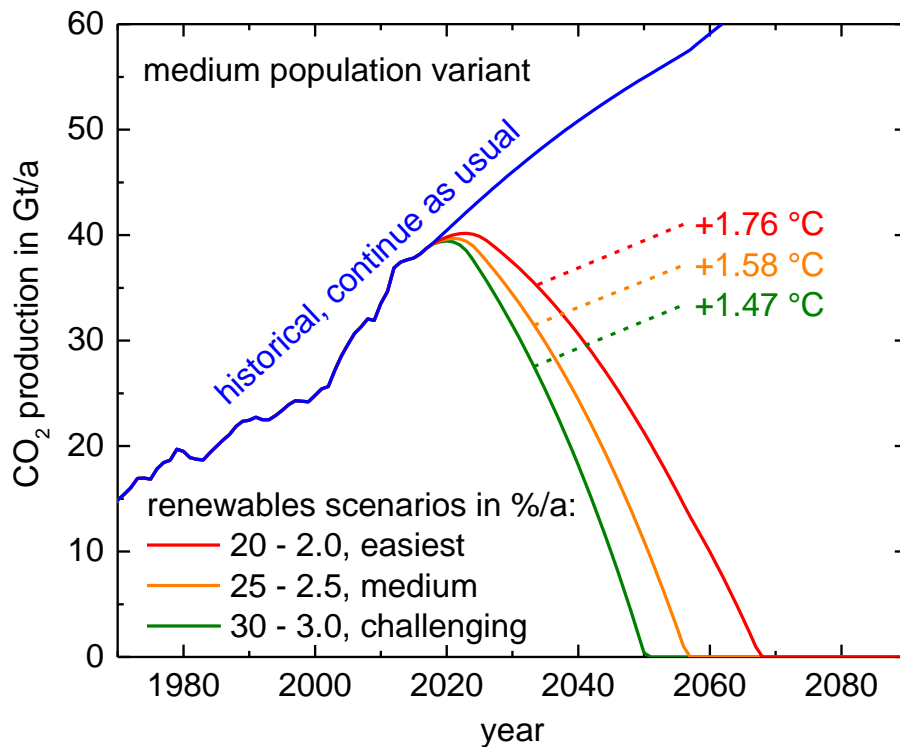


Fig. S7: Reduction of carbon-dioxide emissions according to the three investigated sustainable energy-transition scenarios for the medium UN population scenario.

If the climate goals are taken seriously, major changes in the energy system will strongly influence global economy within 3 to 20 years from now. Keeping these risks in mind and accounting for the corresponding challenges for world economy, sustainable-energy transition would need to be of highest priority, if the described growth and substitution rates for reaching the +1.5 °C goal shall be realized, which are well above current efforts even in developed countries. Especially in economically good times effort would need to be even higher to be able to compensate for the times when the sustainable-energy transition with the corresponding restructuring of major industrial sectors leads to temporarily weaker global economy. It should again be stressed that all of these scenarios refer to global scale. Thus, every single nation would have to put corresponding effort into the sustainable-energy transition.

In some of the IPCC scenarios negative-emission technologies are utilized to capture large fractions of the emitted CO₂ [3,6]. The negative-emission technologies would allow to overshoot the limit of atmospheric CO₂ concentration corresponding to some

climate goal and then later to recover the CO₂ by suitable CDR (carbon-dioxide removal) technologies. Three prominent examples of discussed technologies are BECCS (bioenergy with carbon capture and storage), DACCS (direct air carbon capture and storage), and AR (afforestation and reforestation). But even the IPCC states: “CDR deployment of several hundreds of GtCO₂ is subject to multiple feasibility and sustainability constraints (high confidence)” [6]. Also, for the two first options it has to be realized that sequestering CO₂ without chemical conversion into suitable geological formations – irrespective of a possibly limited global capacity [S15] – would impose relatively high risks, since it may not be possible to prove experimentally in the short remaining time that the storage is safe due to the long time scales of the processes involved [29,S15]. Also, it has to be clear that there is no business case behind applying these technologies, unless CO₂ trading is established on global scale. But even, if limiting and trading emission rights would be globally realized in principle, it is not foreseeable that the trading would be kept up with certainty during the possibly economically difficult times of restructuring major industries, which introduces significant economic challenges as discussed above and in the main publication. Realizing that at the end of de-carbonization large sectors of global economy will have been severely restructured and relative strengths of nations will have significantly changed, because no longer fossil resources but e.g. available agricultural land area, rainfall and sunlight will be determining factors, it is clear that an additional commitment of even only some major nations for applying negative-emission technologies cannot be assumed with any certainty. On the contrary, at times with a significant trend towards a my-nation-first movement it is to be assumed that without strong business case negative-emission technologies will not be realized on globally relevant level. AR and BECCS on the other hand would require sufficiently available agricultural land area, where it will be realized in the sections on ‘food versus fuel’ and on bio-economy that this will possibly not be available. As a consequence, negative-emission technologies have been highly debated (e.g. [31,32,S16,S17]). It has to be realized that this topic is very political, because negative-emission technologies are important ingredient in several of those transition scenarios that will allow to reach the climate goals [6]. Finally, CDR can only buy us some extra time for realizing the sustainable-energy transition, since CDR technologies do not contribute to achieving the transition itself. Thus the question has to be answered for each of these technologies, if they do not divert budget from the actual goal of establishing a sustainable economy. As a consequence of these uncertainties, negative-emission technologies have not been considered here. If they should be realized, the shown scenarios can be regarded as net-emission scenarios.

In Fig. S8 the energy scenarios of the illustrative model pathways of the IPCC special report on 1.5°C climate change are compared to the scenarios of this work presented in Fig. S7. It is apparent that the scenarios P1 to P3 would be extremely challenging, where actually P3 is termed the “middle-of-the road scenario”. Only illustrative model pathway P4 appears to be realistically manageable. Unfortunately in that scenario a

large fraction of negative-emission technologies like BECCS are assumed, which would not be realistic with the higher population growth to be expected. Thus, also P4 could not be reached, if population develops as discussed in the corresponding section.

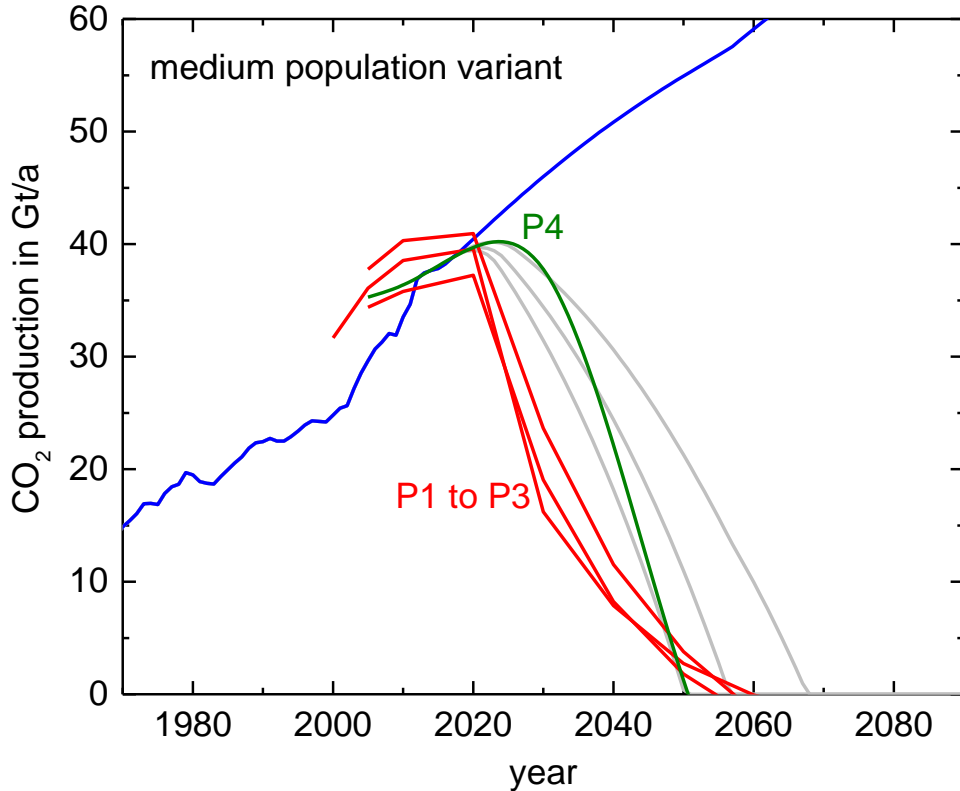


Fig. S8: Energy scenarios of the illustrative model pathways of the IPCC special report on 1.5°C climate change [6,27]

S4. Food Versus Fuel and Materials

To develop scenarios quantifying the competition for agricultural land area between food production and bio-based feedstock production for bio-materials as well as bio-fuels, past trends have been projected into the future based on the FAOSTAT database [30]. The caloric food supply is assumed to slightly increase until toward the middle of the century 3 000 kcal/(cap d) are reached as shown in Fig. S9, which is assumed to be sufficient on average to overcome undernourishment, when food distribution is optimized and the fraction of food wasted or spoiled reduced. 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 as shown in Fig. S10. Thus until the end of the century the land-area specific productivity will double from today 750 kcal/(m² a) to 1 500 kcal/(m² a) as shown for the red curve. Here, primary production refers to the directly harvested crops without losses and contribution to seeds as well as before any processing [30]. The overall productivity shows some deviation from the linear behavior during recent decades, which may be induced by relative shifts between crops as well as an increased feed production due to the increased contribution of animal-based food to overall nutrition. Fig. S10 on the other hand

shows that for the seven crops with the highest caloric contribution to primary production, the calorically averaged productivity shows surprisingly linear behavior. This linearity is seen as indication that also overall land-area specific productivity may develop not too far from linear. Of course there are principal limits in photosynthetic efficiency, implying that some limit will of course eventually be reached, i.e. productivity increase has to slow down eventually. Here it is assumed that this does not occur until 2100, i.e. agriculture is able to intensify continually at high rate. This assumption implies that productivity losses due to climate change, where increased temperatures may reduce productivity and more extreme weather events may destroy crops on the field, can be compensated on global scale by future strain development, sufficient weed and pest control, adjusted fertilization, and optimized water supply.

Also for the production of animal-based food it has been assumed that intensification continues, e.g. reducing the feed required to produce 1 kcal of animal-based food from today almost 2 kcal down to 1.5 kcal in 2100 as shown in Fig. S11. A similar trend is realized for the required pasture, where intensification to the current European average is assumed until 2100. This means that also countries with rather extensive animal production today, like Argentina and Australia, have to intensify considerably. The trend of both variables thus follows the black line shown in Fig. S11, the lower end of which is reached until 2100. The feed calories required to produce 1 kcal of animal-based food may appear rather small at first sight. This low value result from roughly half of the animal-based calories stemming from eggs and dairy products. Thus, meat production alone is significantly less efficient, as expected.

The animal-based fraction of nutrition has to be quantified for the scenario evaluation as well, which is shown in Fig. S12. Here the past trend has been continued into the future with a small quadratic term being applied leading to a levelling off towards the end of the century. The increase in the curve starting around 2000 is mainly induced by a significant increase in consumption of animal-based food in China reaching 25 % today. In India during recent decades a slight increase is observed as well, while in several developed countries like France, Germany, and USA a slight decrease is observed. It is here assumed that an overall slight increase occurs, induced by further development of less developed regions, in which people are then able to afford more animal-based nutrition.

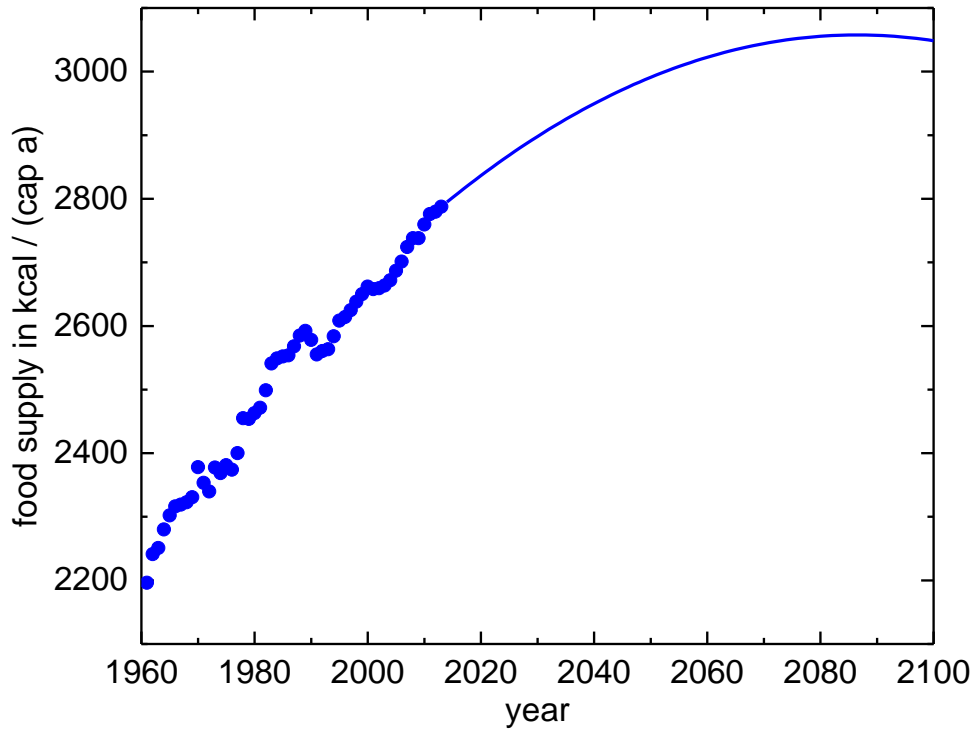


Fig. S9: Historic data on caloric food supply and projection used [30].

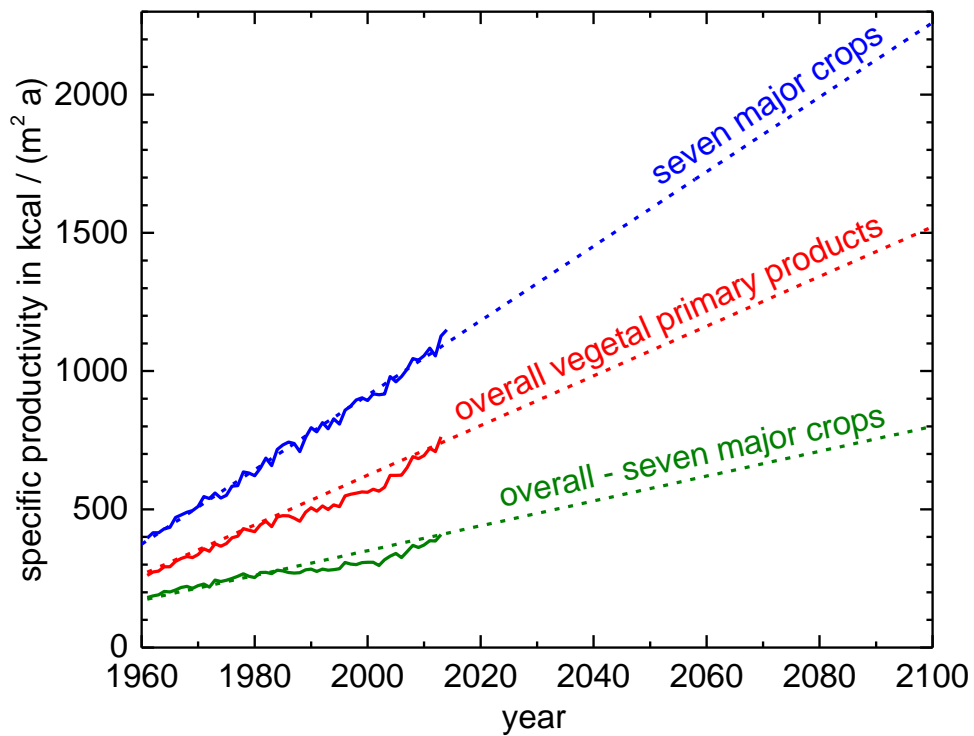


Fig. S10: Historic data on land-area specific productivity and projection used [30], where 7 major crops are barley, corn, oil palm, rice, soybeans, sugar cane, and wheat.

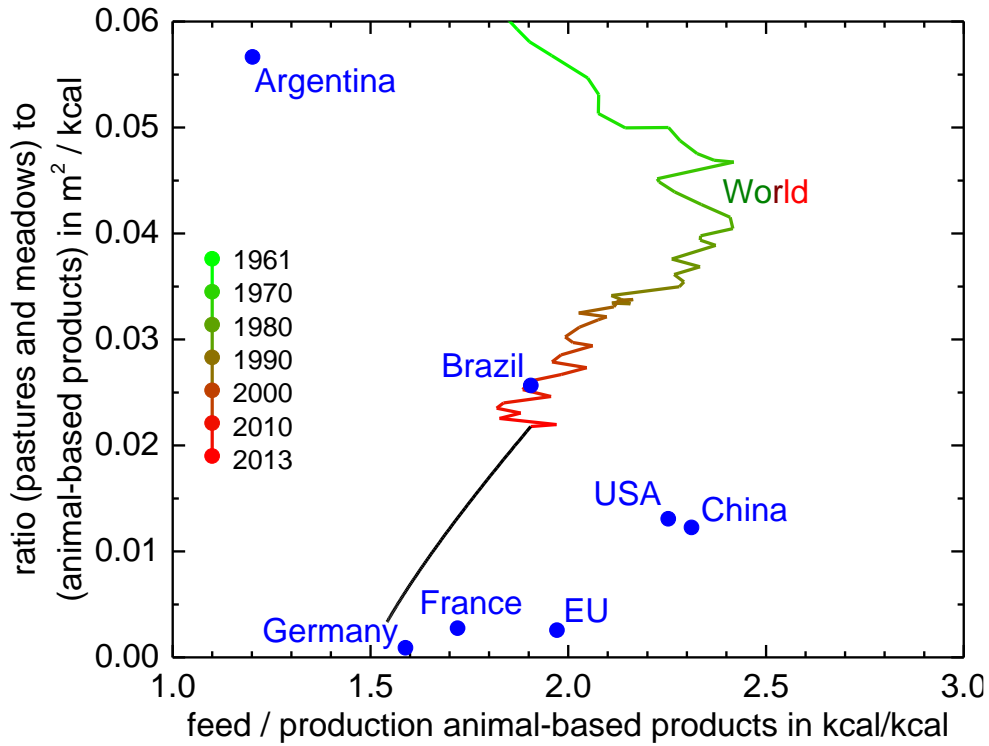


Fig. S11: Land-area demand for pasture and feed calories per caloric production of animal-based food [30].

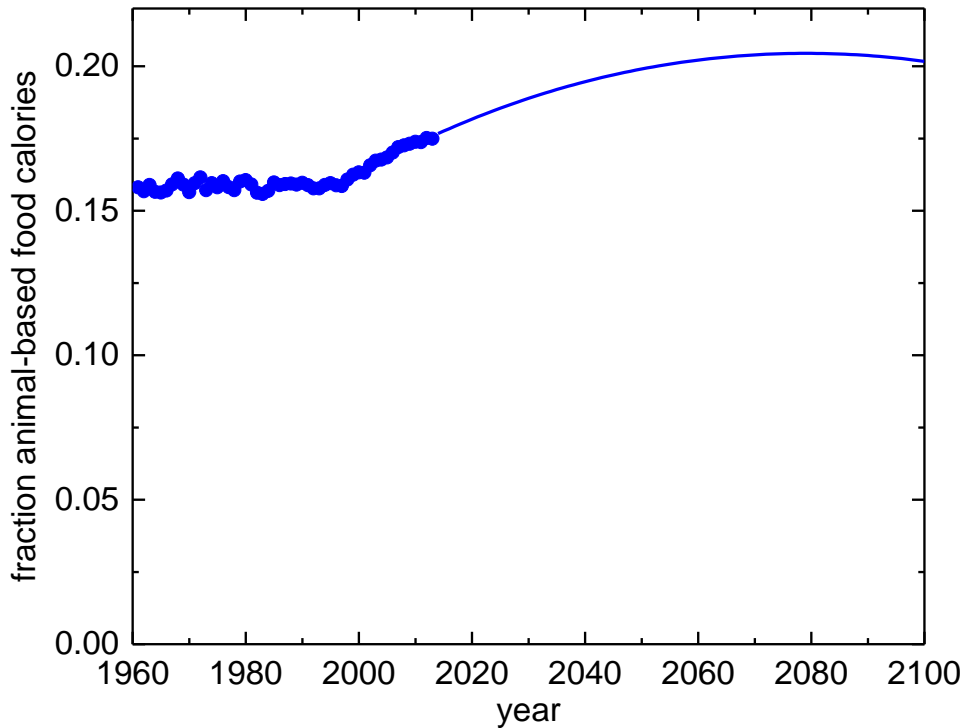


Fig. S12: Fraction of animal-based food in human nutrition [30].

Finally it is assumed that 10 % of the primary-energy demand is realized via bio-combustibles produced from dedicated biomass. The influence of the choice of this fraction can easily be deduced from the graphs shown, so that the effect of alternative choices is obvious. It has to be kept in mind that 2.5 % of the fossil energy demand

today correspond to use of jet fuel, for which until now no substitute other than liquid fuels is foreseeable. Additionally, steel as well as chemical industry require carbon input and/or a reducing atmosphere for some reactions, which up to now are realized by burning fossil carbon sources [33]. Thus, taking all these uses of bio-combustibles into account, a contribution of 10 % of the primary-energy demand is assumed here. In principle, of course also combustibles obtained from CO₂ e.g. collected from the atmosphere or available point sources can be used for these purposes. This would avoid the competition for agricultural land area as will be discussed in more detail in the corresponding sections. If CO₂-based combustibles would be used instead in the scenarios, the land area used to supply bio-based combustibles could be used otherwise.

Since the scenarios shown in Fig. 7 show significant competition between the different uses of agricultural land area, the question needs to be answered, if there are workarounds possible. One option frequently mentioned is to use genetically modified (GM) crops, which is claimed to ensure higher yields and higher stability of yields against external influences [S18,S19]. This claim can meanwhile be investigated quantitatively by comparing the land-area specific productivity of corn as grown in the USA to that in Germany. While it is until now prohibited in Germany to grow GM corn, in the USA GM corn has been used since 1996 and is grown on more than 80 % of the corn fields since more than 10 years [S20]. Fig. S13 shows that in both countries the yield developed almost identically during decades. Neither a significant increase in yield nor a significant reduction in variation between years can be observed in the USA as compared to Germany during the last decade. Thus, while GM crops possibly have advantages leading to economic benefits for the farmers as well as the seed producers, at least until today the promised significant benefits with respect to yield cannot be detected [S18,S19].

Another possible workaround is the observation that increased atmospheric CO₂ concentration increases crop yields under certain conditions [S21,S22]. Thus, it could be assumed that increasing the CO₂ concentration in the atmosphere may well lead to climate change but at the same time ensure sufficient nutrition for mankind. This promise has already been debated and shown to at least offer only limited benefit, if at all. Here another aspect shall be added to this debate. As starting point it is recalled that the fluctuations of the monthly CO₂ concentrations shown in Fig. S1 are mainly the result of the annual growth cycle of natural plant biomass in the northern hemisphere, where roughly twice the land area is located as compared to the southern hemisphere. Thus the seasons of the northern hemisphere dominate the global average carbon concentration in the atmosphere. In springtime trees and bushes are growing leaves in temperate climate zone, plants and herbs are sprouting, so that carbon from the atmosphere is converted into biomass. During fall and winter, this captured carbon is released back into the atmosphere. Thus the amplitude of the annual variation is a measure of overall plant productivity. If the peak-to-peak amplitude, which has been obtained after subtracting the sliding average, is plotted versus the

CO₂ concentration, the trend follows almost a straight line through the origin as shown in Fig. S14. This appears to imply a first-order dependency, which might not be too surprising.

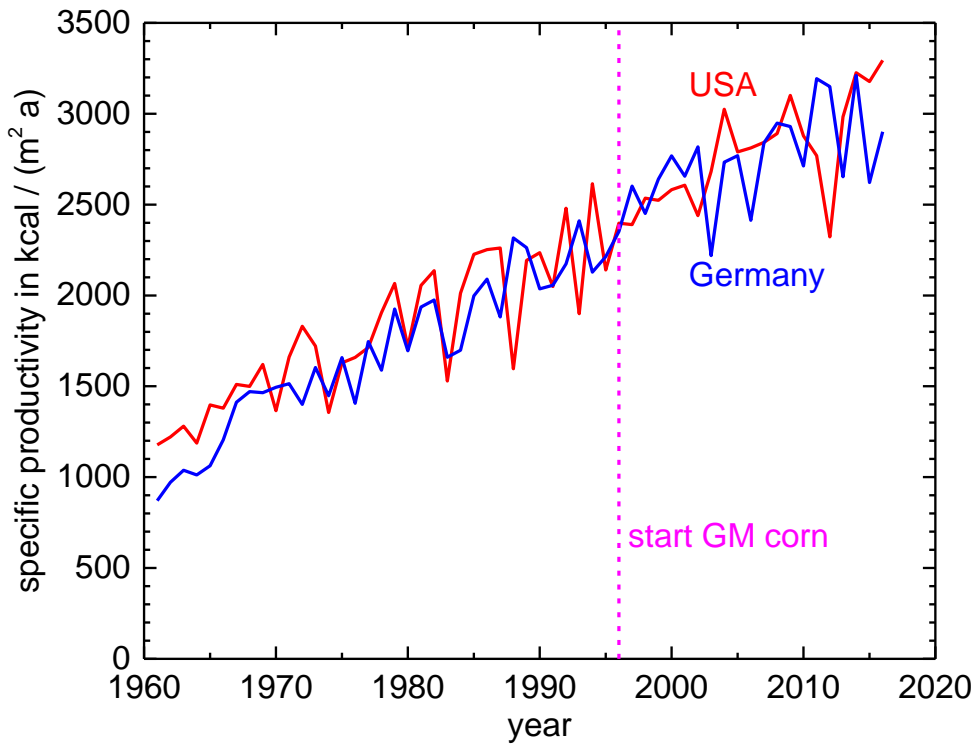


Fig. S13: Area-specific yield of corn in USA and Germany [30].

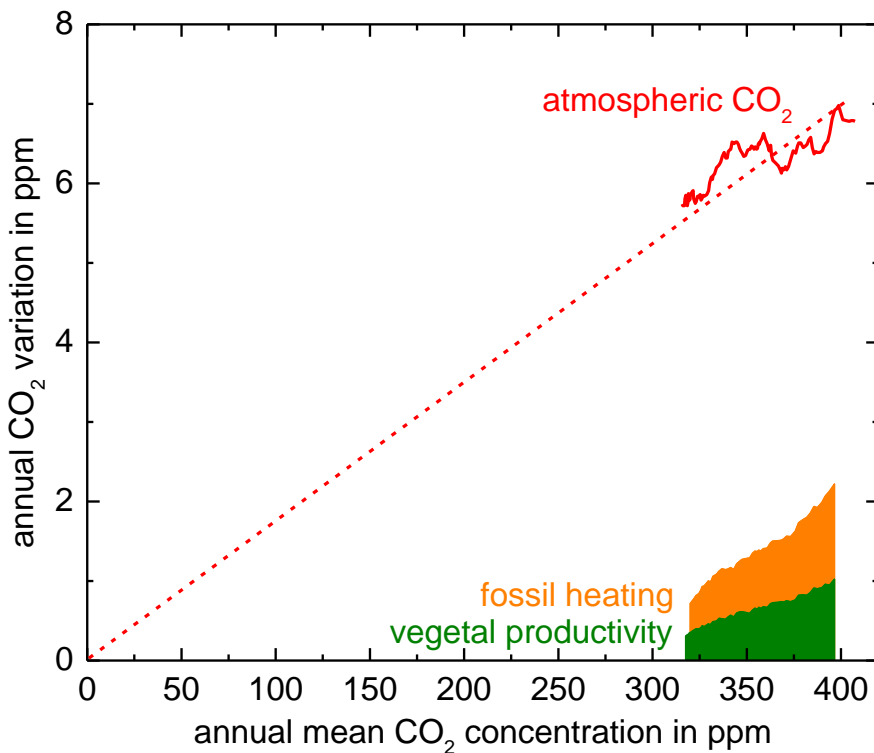


Fig. S14: Peak-to-peak amplitude of atmospheric CO₂ concentration versus CO₂ concentration [28,30,S05].

Unfortunately also increased human activity, which developed in parallel, has to be accounted for. Agricultural activity follows the same cycle as the natural flora. To account for this effect, the primary production of plant-based food has been converted into a corresponding contribution to atmospheric fluctuations of CO₂ concentrations, assuming a specific carbon content of 11 kcal/kgCO₂, which is the average between starch and plant oil, and a factor of two for the overall biomass as compared to the fraction of plant used as food component. The latter factor accounts for leafs and straw, which contribute a roughly equal amount to the plant dry mass as compared to the utilized fraction for many crops. The roots are not accounted for.

Also heating will contribute more to CO₂ emissions in winter than in summer, which induces a corresponding fluctuation. To evaluate this effect, an overall contribution of 25 % of CO₂ emissions for heating has been assumed. These contributions are shown in Fig. S14 as colored areas. It is obvious that these contributions show a similar trend as the amplitudes of the CO₂ fluctuations. Of course from this approximate evaluation no accurate agreement can be expected. Nevertheless, the comparison shows that the observed increase in fluctuation of CO₂ concentration may well be induced by increased human activity. Thus also this comparison gives no indication that overall biomass productivity is increased by higher concentrations of carbon dioxide in the atmosphere, where the corresponding influences connected to increased CO₂ concentration like climate change are implicitly included.

Also some frequent comments and questions posed during presentations on the topic should be discussed:

- **Can sufficient food supply be reached with alternatives like insects or artificial meat?** Such options to supply food, which are currently discussed in the media, also suffer from limited efficiencies. The caloric input always has to be larger than that of the product produced. Thus it is always more efficient to use the input as foodstuff directly than to waste energy in converting it to animal-based or animal-like food.
- **Can the intensification of utilizing the marine environment solve the food problem?** Since natural fish resources are already maximally exploited, increased use of the marine environment for food production would mean large-scale fish farming. Unfortunately fish farms have a significant environmental impact. Thus, fish farming increases the human influence on the global ecosystem further, where it has to be realized that taken the current effects of humanity on this ecosystem, humanity should rather try to limit this influence. Of course this is an ethical and political issue and may in the end be a question of sheer necessity, if hunger is to be eradicated globally. Also, as above the fish need to be fed, several farmed fish species even being carnivores. Thus also for fish it is more efficient to use the input as foodstuff than to convert it into fish.
- **The available land area will increase, because due to climate change land area in permafrost regions will become available for agriculture.** The land

area for arable land and permanent crops has been increasing significantly between 1960 and 1990. After that the increase was significantly slower with around 1.7 % per decade. Unfortunately the area for permanent meadows and pasture has been decreasing during the same time interval by 0.3 % and the forest area by 1.2 % per decade. As a consequence, the sum of these areas, which represents that land area, which can in principle be agriculturally utilized, is currently decreasing by 0.4 % per decade. Since this time period since 1990 also roughly covers the time during which climate change has been detectable due to increasing global mean temperature, there is no indication that climate change might lead to an increase in land area that can potentially be used agriculturally. Compared to population growth this factor is of minor importance but has been properly accounted for in the balances to derive Fig. 7.

- **Protein supply will even be supported by bio-economy.** This idea misses the point that undernourishment is evaluated based on caloric content of the food supply. Thus, while indeed a bio-economy may supply the protein content of the crops for food or feed production, it utilizes carbohydrates and plant oils, which are then no longer available as food and feed. Overall the corresponding caloric content is withdrawn from human nutrition.
- **It is more efficient to produce wheat in Germany, use the starch as feedstock for bio-economy, and to supply the protein content as food or feed than to import soybeans from Asia e.g. as feed. The area-specific protein yield of wheat in Germany is significantly higher than that of soybeans in Asia [S23].** Only India and China are exporting significant amounts of soybeans, which together trade internationally only 0.55 % of the global soybean trade volume. Their land-area efficiency with respect to protein production in soybean is indeed smaller than that of wheat. But the argument misses the point in two aspects:
 - The statement is actually not a balance. Instead it is a statement on the land-area efficiency. Thus from this statement alone, no conclusion on the overall food balance can be drawn.
 - As above it is not proteins, which are defining undernourishment. Instead it is the overall calories supply. The effect of utilizing the carbohydrates of wheat grown in Germany instead of importing soybeans from Asia may be explained with Fig. S15, in which the caloric land-area efficiency of the major components are schematically shown for wheat and soybean production versus the land area on which the crops are grown. The remaining crops are continued to the right as indicated. It should be noted that the area-specific productivity multiplied with the land area on which the crop is grown is the absolute amount of caloric content supplied by that crop on global scale. Thus, the overall calories supply from the primary crop production is the sum of all the graphical areas for all crops shown in Fig. S15. That today a large fraction of humans are undernourished means that crop production with the current nutritional habits does not allow to supply calories for sufficient nutrition of everybody. This in turn just

means that this overall graphical area for all crops is too small to supply sufficient food for everyone. To feed the world not only those crops and areas have to be utilized, which have a high area-specific productivity, but crops from all available arable land, also that with lower productivity, are required. From this graph it is then obvious that using the carbohydrates from wheat produced in Germany reduces the overall graphical area and thus effectively contributes to an increase of world hunger. This statement is independent of the productivity in Asia. While the relative amount of all crops are related to market demands as well as boundary conditions of required crop rotation to ensure sustainable soil fertility, to climatic and soil conditions, the absolute amount should of course be maximized to ensure sufficient food supply. Nevertheless, any excess produced of one crop relative to another – independent of where the crop is grown – for ethical reasons should first be used to fight undernourishment. Thus, this argument may induce some confusion, but does not disprove the argument that bio-economy and human nutrition compete for the same land area.

- **Does vegetarian nutrition instead of complete avoidance of animal-based products have already a significant impact on world hunger?** From a balance point roughly half the animal-based calories are obtained from meat while the other half stems from other animal products like eggs and milk. Thus at first sight it may seem that from the balances just avoiding the meat may be beneficial. Unfortunately a vegetarian agriculture would lead to problems. For example it has to be kept in mind that cows lactate only, after they gave birth to a calf. The milk production will be efficient for around 300 days after giving birth, thus the cow has to be inseminated again in time for the next cycle. Thus, only utilizing male and excess female calves to produce cattle for human nutrition will lead to a reasonable agricultural system. Thus vegetarian nutrition may be helpful to a certain degree but at least with amounts of milk and eggs used today can not meaningfully be realized on global scale.

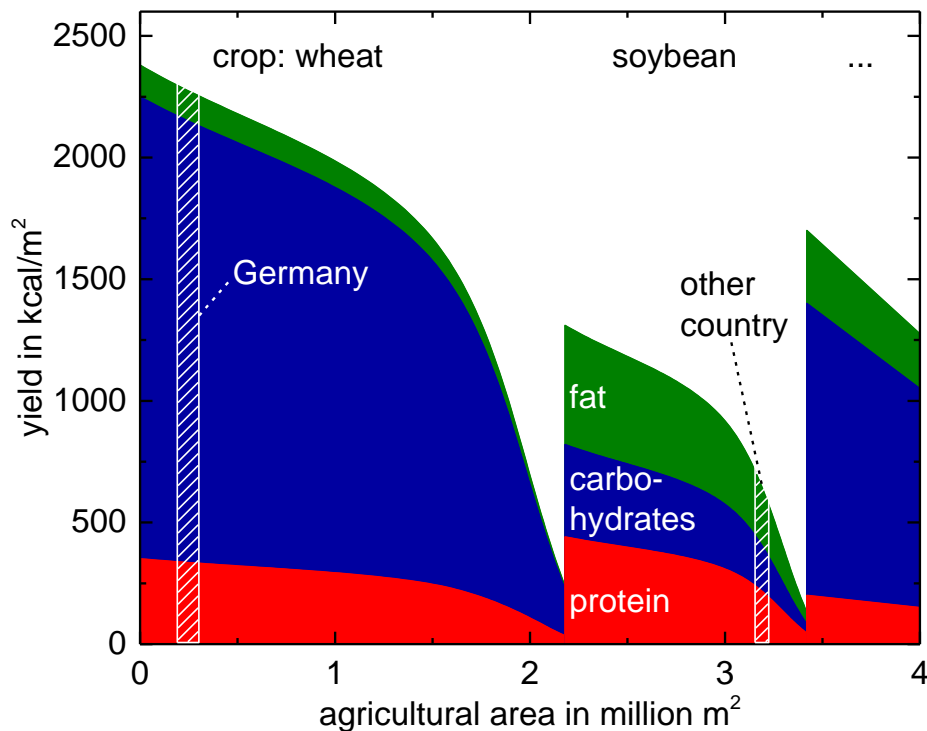


Fig. S15: Schematic caloric global yield for different drops as function of land area, on which the crops are globally grown.

As a consequence, there appears to be no obvious and immediate workaround that would allow significantly increasing land-area specific productivity for food production or allow to obtain foodstuff from other sources. Of course optimization potentials of the conventional food-supply system should be leveraged, like reduction of waste and losses, better distribution of food, and ensuring sufficiently low priced food for less developed countries. Also some farther reaching options may exist like chemical conversion of carbon dioxide into foodstuff, possibly even with artificial photosynthesis. The latter can be realized with electricity as energy supply with efficiencies significantly higher than those of plants to convert carbon dioxide into chemicals [S24]. Keeping in mind how difficult it may be to limit animal-based nutrition, it is apparent that it may be at least as difficult to introduce foodstuff stemming from 'synthetic' carbon dioxide. Also refraining from eating animal-based products is far simpler and cheaper than building up a corresponding conversion technology.

In the scenarios shown, the land areas have been used on an equivalent basis, i.e. with assumed identical productivity. Also regional distribution is not considered. Since the benefit of plant-based versus animal-based nutrition is discussed, the question needs to be addressed, if indeed the people currently undernourished could benefit from e.g. the pasture becoming available, if animal-based nutrition is reduced. Here, the concept of indirect land-use change (ILUC) has to be realized, which is e.g. applied by the EU as a basis for their bio-energy policy [47]. It is of course not to be expected that on the identical land area, where animals were grazing, the crops for the undernourished people would be grown. Instead, this land could be used for growing crops, which are now imported typically from less developed regions, from which

people in more developed countries effectively buy the corresponding land area. That land area in those countries would then be freed and induce a domino effect, which leads in the end in more available land area also in the least developed regions. While this effect may not lead to exchange of exactly compatible land area, the effect of different land-area productivities in different regions is consistently accounted for in the scenarios, since global average productivities are regarded.

Finally, it should be pointed out that changing the behavior would also directly be beneficial for the sustainable-energy transition as well. The positive influence of limiting population growth has already been pointed out above. On the other hand reducing the contribution of animal-based food would also reduce the associated significant greenhouse-gas emissions.

S5. Sustainable Chemicals and Fuels Production

As a basis for evaluating options for chemical processes and specifically to characterize the minimum energy demand for chemical reactions, exergy has successfully been applied [41,S25]. Exergy as general measure of energy is especially promising, because it generalizes different required energy inputs like heat at different temperatures and chemical energy introduced via hydrogen as reaction partner. Also, it has been shown that exergy and economy are directly related [S26]. This is of special interest, because the future energy mix is undetermined and thus actual future cost for different energy sources is unknown. Thus, exergy allows to properly attribute energy costs across different types of energy in a generalized way independent of the future energy mix.

It has been shown that the chemical exergy is the largest contribution to the total exergy of a material system, which can be used to characterize reaction pathways energetically [41,S27]. If reactions shall be efficient, the net exergy of reaction, which corresponds to the free energy of reaction at ambient conditions, should be zero or negative. If an increase of exergy would be necessary in a chemical conversion, equilibrium yield is low, requiring exponentially increasing effort for recycling the unreacted reactants [S27].

In Fig. S16 it can be seen that the conversion of crude oil via ethylene to polyethylene, one of the major pathways in chemical industry, runs almost horizontally. At the same time, it is apparent that the bio-based raw materials have exergies slightly below those of the fossil resources mostly used in chemical industry, namely natural gas and crude-oil fractions. Also, bio-based feedstock like starch, sugars or plant oil have a higher oxygen-to-carbon ratio, which is responsible for their lower molar exergy. If thus the conventional products are desired with bio-based production routes, this oxygen needs to be removed. This can be achieved e.g. via decarboxylation or hydrogenation combined with dehydration [S25]. Apparently decarboxylation removes carbon from the product, which is undesired, because the actual goal is to recover the carbon from the air via biomass. This can only be overcome, if the carbon

dioxide could be chemically used otherwise. Hydrogenation on the other hand requires additional energy for the hydrogen production, e.g. by electrolysis of water, and dehydration reduces the mass of the products obtained. Even though polymers are typically not sold by weight but by performance, it is also obvious from Fig. S16 that some of the high-performance polymers contain significant amounts of oxygen. If bio-based feedstock is used, these oxygen-containing polymers having a lower exergy per carbon are thus more efficiently obtained from bio-based feedstock than oxygen-free conventional polymers like polyethylene or polypropylene.

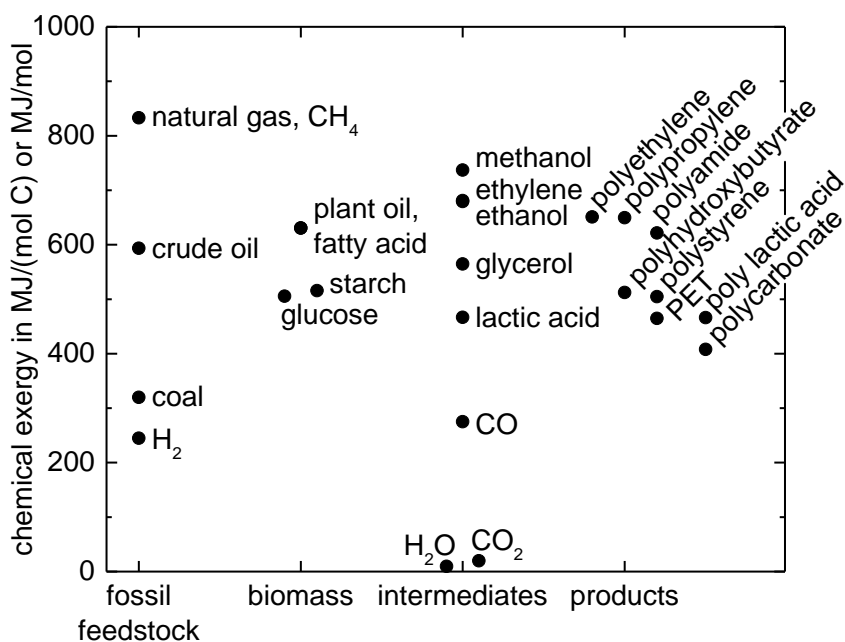


Fig. S16: Chemical exergy per mol C or per mol for C-free components.

As a consequence of these considerations, it is to be expected that a shift towards bio-based feedstock will induce a trend towards intermediates and polymers with higher oxygen content as compared to today. This requires less exergy for processing and does not reduce the mass of the product. Decarboxylation will preferably be realized only, if the carbon dioxide can be used chemically, because otherwise the land-area demand for generating the bio-based feedstock to achieve the same mass of products would increase. With these considerations, the ground is laid for a more detailed analysis of options for future bio-based routes in chemical industry, which will be based on land-area demand and the consequences of these exergetic considerations.

5.1 CO₂ in Chemical Industry

Here, in addition to the aspects discussed in the main paper, the energy efficiency of algae cultures for utilization of carbon dioxide shall be discussed. For algae cultures, a theoretical upper limit for the photon efficiency of 8.3 % has been reported [39]. Photon efficiencies that can be achieved in technical equipment will of course be significantly less due to various factors limiting the productivity. This has to be compared with photovoltaics with an efficiency around 20 % practically realized today, which

could be used to supply the energy required for the electrolysis to produce hydrogen in the alternative chemical routes. Thus, also with respect to photon efficiency and correspondingly land-area requirement, algae cultures are less efficient than photovoltaics combined with chemical routes of CO₂ conversion.

Finally a comment on CCU (carbon capture and use) shall be made. CCU is one option to minimize carbon-dioxide emissions. It has to be kept in mind that today only at most 4 % of the fossil energy carriers are used materially. Since after sustainable-energy transition the carbon-based sectors including bio-materials and unavoidable bio-combustibles will have a contribution of around 10 % as compared to fossils today, CCU may well lead to a significant contribution of an industrial carbon cycle. Nevertheless, this material cycle will only be small as compared to today's fossil raw-material stream. But in principle it can be imagined that the waste produced or at least the carbon-containing fraction is incinerated and the CO₂ obtained at that point source converted to chemical feedstock or CO₂-based fuels. In that case only the makeup streams would need to be supplied by carbon-capture techniques or via biomass.

5.2 Bio-Based Chemical Industry

As basis for evaluating the land-area required to fulfill the material demand of humanity, it has been assumed that the plastics demand is 80 kg/(cap a), which is significantly less than current values in developed countries of above 130 kg/(cap a). From this results a feedstock demand of chemical industry of 125 kg/(cap a), assuming that the production of plastics corresponds to roughly 75 % of the output of chemical industry and an overall assumed efficiency with respect to the feedstock of 85 % [41,S28]. Crops considered are containing sugar, starch, plant oil, or cellulose as major component to be used as starting point for the (bio-) chemical processes. Since global or national land-area specific productivities are not available for miscanthus or other reeds as well as for wood, after evaluating a variety of literature sources their values have been obtained from sources describing characteristic yields that can be obtained under realistic boundary conditions [S29-S32]. Nevertheless, the values for miscanthus/reeds and wood have thus a higher uncertainty than those for the other crops. Here also miscanthus and potential other reeds are combined, because depending on climate and soil different grasses like switchgrass or more generally alternative perennial plants like *Silphium perfoliatum* will locally lead to the highest yields. The content of starch, sugar, cellulose, and oil in the harvested crops have been obtained from the literature [S33-S47]. The overall processing efficiencies have been assumed to be 85% for most cases, because the efficiencies reported for pilot-plant scale of the individual process steps are well above 90%. The only exception is the conversion of cellulose, where an efficiency of 35 % for production of bio-ethanol is assumed, which results from values reported in the literature for industrially realized processes [S48,S49].

For the wood-based processes shown in Fig. 8, only the cellulose fraction is considered, which is already established on large scale. The separation of cellulose from

lignin is already realized in paper industry, cellulose and hemicellulose conversion to sugars and alcohol already realized technically as well [S48,S49]. The lignin fraction is typically used energetically. In principle, this fraction could also be used and has been proposed as sustainable feedstock for aromatic components. Nevertheless, the economic feasibility of processes like the OrganoCat process still needs to be demonstrated on technical scale [S50,S51].

The exemplary reactions considered in evaluating the options for bio-economy are shown in the exergy diagram in Fig. S17. As discussed above, the net exergy change for the reactions is close to zero resulting in sufficiently high conversion and thus in processes that are economically viable.

The choice between the different options is also influenced by the required investment and energy cost. In Fig. 8 technical processes for conversion of cellulose based on fermentation have been considered. In evaluating the options energy requirement and investment need to be considered. While chemical routes often require higher temperatures, biotechnological routes are realized in diluted aqueous solutions. To get an impression of orders of magnitude, it can be realized that a cellulose concentration of 14 % is required, if the energy content of the cellulose shall match the energy required to evaporate the water. The energy required has to be balanced with the equipment cost. While these are typically not specified in publications, their relative magnitude may be assessed from the area demand of the corresponding plants. For the different routes the following area demands can be estimated from available data on various larger plants combined with area estimated e.g. via google maps:

- biotechnological processes 1 to 3 m²/(t/a),
- direct biomass conversion (sugar from starch) 0.2 to 0.5 m²/(t/a),
- chemical process (e.g. steam cracker) 0.03 to 0.1 m²/(t/a).

Since only that area has been evaluated, in which process equipment and buildings are located, the area is a measure for the characteristic investment for a plant following the corresponding route. This indicates that the investment for biotechnological processes may be significantly higher as compared to chemical routes. At the same time this discussion clearly shows that bio-based economy is not equivalent to biotechnological processes as sometimes implied [S52-S54]. Direct chemical routes have to be considered as well and may be economically at least as efficient.

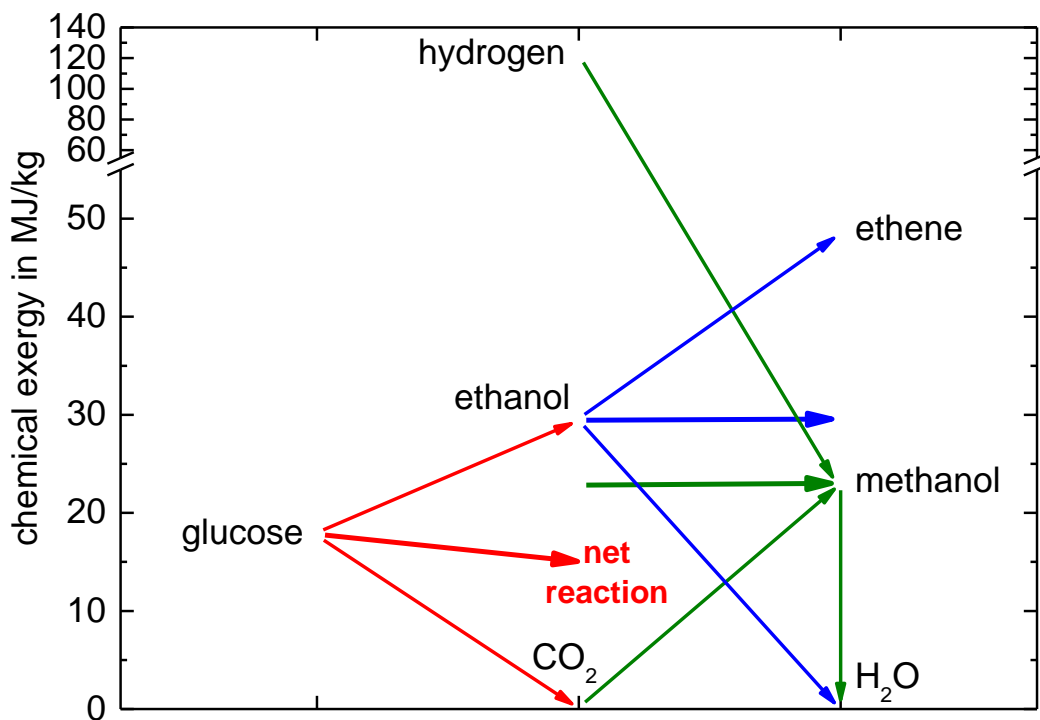


Fig. S17: Exergies of reactants and products and net exergy of reaction for the conversion routes considered.

To avoid the competition between bio-based materials and combustibles with food production, it is sometimes proposed to use crops that can be grown on marginal land. From the scenarios shown in Fig. 7 it is obvious that a relatively large fraction of agricultural land area needs to be used in the future with highest available productivity. Thus – while marginal land should of course be utilized wherever possible – it is to be expected that such option may not contribute major fractions of the biomass supply. In the scenario analysis of Fig. 7 on the other hand this has effectively already been implied to a certain degree, because it has been assumed that arable land, pastures, meadows, and forest land can be used interchangeably.

The challenges for such a transition of feedstock are manifold. Optimal processes would need to be further developed, e.g. for producing a variety of polymers from sugars directly. Also it should be mentioned that in many of the basic processes considered a large side-stream is produced, e.g. vinasse in fermentation of cellulose [S48,S49]. These large streams, which are of comparable magnitude as the major product stream, contain nutrients and thus need to be returned to the fields either directly or after dedicated treatment.

A variety of chances exist on the other hand. From biomass essentially pure components of larger molecular size can be obtained like glucose, fructose, or xylose as major building blocks. Thus it can be avoided that the molecules are first cracked to ease separation into individual components to later rebuild larger molecules from these building blocks, as is the case starting out e.g. from fossil naphta. Direct utilization of larger molecules is exergetically to be preferred. The second big chance, which should be mentioned, is that as a side stream from several of the bio-based

routes to materials and combustibles also food components like proteins can be obtained. Until now these side products are used as feed in several cases, but there is no principal reason why these components could not be upgraded to contribute to sufficient food supply. This aspect also means that the utilization of biomass for bio-materials and food may be synergistically interlinked at least to certain degree and not as strictly competing as usually discussed. Finally bio-economy opens the big chance to establish a true circular economy based on bio-based feedstock.

S6. Conclusions

From the discussions it becomes clear that in evaluating sustainability, e.g. via life-cycle assessment (LCA), accounting mostly for greenhouse gases like carbon dioxide may be relevant for today. For the future, when the sustainable-energy transition has been achieved, carbon dioxide will be of much less importance. Instead, factors like land-area used and the efficiency and sustainability of that use may become significantly more important, because these aspects relate to world hunger and sustainability of agriculture.

An argument for the requirement to change human behavior may be added here, namely a reference to 'Collapse: How Societies Choose to Fail or Succeed' by Jared Diamond [S55]. By regarding successes and especially failures to react to changes of social or natural environment, Diamond arrives at five key-factors determining the fate of a society: "Four of those sets of factors – environmental damage, climate change, hostile neighbors, and friendly trade partners – may or may not prove significant for a particular society. The fifth set of factors – the society's responses to its environmental problems – always proves significant." For the last factor, especially the mismatch between traditions and the changes in behavior that would actually be required to survive turns out to be important. Thus, if we would like to avoid major detrimental effects, we would need to question existing traditions, including those on our freedom of choice for nutritional habits and the number of children. Another key factor being "a conflict between the short-term interests of those in power, and the long-term interests of the society as a whole." This aspect is already discussed at the end of the conclusions in the main paper, where it becomes obvious that it is indeed only the individual, who with his or her behavior is in the driver seat to reach sustainability.

The entire system may be described as an interaction between the system of all humanity and that of our earthly ecosystem. Humanity continually increases the pressure on the ecosystem, which will react. Thus, either the system of humanity will change its behavior to reduce this pressure or the ecosystem will alter its response. It has to be clear that while we have the freedom of choice, which determines how we behave, the reaction of the ecosystem will invariably happen. Thus, simply because we have the freedom of choice, it is us who are responsible to arrange our life within the planetary boundaries. We should thus better change our behavior, because otherwise the ecosystem will inevitably change its response unfortunately in a direction, which is less friendly to us humans.

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