# Supplementary Material

## Region Mapping and regional GHG prices

| REMIND region | ISO code of countries belonging to this region |
|---|---|
| LAM | ABW, AIA, ARG, ATA, ATG, BES, BHS, BLM, BLZ, BMU, BOL, BRA, BRB, BVT, CHL, COL, CRI, CUB, CUW, CYM, DMA, DOM, ECU, FLK, GLP, GRD, GTM, GUF, GUY, HND, HTI, JAM, KNA, LCA, MAF, MEX, MSR, MTQ, NIC, PAN, PER, PRI, PRY, SGS, SLV, SUR, SXM, TCA, TTO, URY, VCT, VEN, VGB, and VIR |
| OAS | AFG, ASM, ATF, BGD, BRN, BTN, CCK, COK, CXR, FJI, FSM, GUM, IDN, IOT, KHM, KIR, KOR, LAO, LKA, MDV, MHL, MMR, MNG, MNP, MYS, NCL, NFK, NIU, NPL, NRU, PAK, PCN, PHL, PLW, PNG, PRK, PYF, SGP, SLB, THA, TKL, TLS, TON, TUV, UMI, VNM, VUT, WLF, and WSM |
| SSA | AGO, BDI, BEN, BFA, BWA, CAF, CIV, CMR, COD, COG, COM, CPV, DJI, ERI, ETH, GAB, GHA, GIN, GMB, GNB, GNQ, KEN, LBR, LSO, MDG, MLI, MOZ, MRT, MUS, MWI, MYT, NAM, NER, NGA, REU, RWA, SEN, SHN, SLE, SOM, SSD, STP, SWZ, SYC, TCD, TGO, TZA, UGA, ZAF, ZMB, and ZWE |
| EUR | ALA, AUT, BEL, BGR, CYP, CZE, DEU, DNK, ESP, EST, FIN, FRA, FRO, GBR, GGY, GIB, GRC, HRV, HUN, IMN, IRL, ITA, JEY, LTU, LUX, LVA, MLT, NLD, POL, PRT, ROU, SVK, SVN, and SWE |
| NEU | ALB, AND, BIH, CHE, GRL, ISL, LIE, MCO, MKD, MNE, NOR, SJM, SMR, SRB, TUR, and VAT |
| MEA | ARE, BHR, DZA, EGY, ESH, IRN, IRQ, ISR, JOR, KWT, LBN, LBY, MAR, OMN, PSE, QAT, SAU, SDN, SYR, TUN, and YEM |
| REF | ARM, AZE, BLR, GEO, KAZ, KGZ, MDA, RUS, TJK, TKM, UKR, and UZB |
| CAZ | AUS, CAN, HMD, NZL, and SPM |
| CHA | CHN, HKG, MAC, and TWN |
| IND | IND |
| JPN | JPN |
| USA | USA |

***Table S1|*** *Mapping between REMIND-MAgPIE macro regions and ISO country codes.*

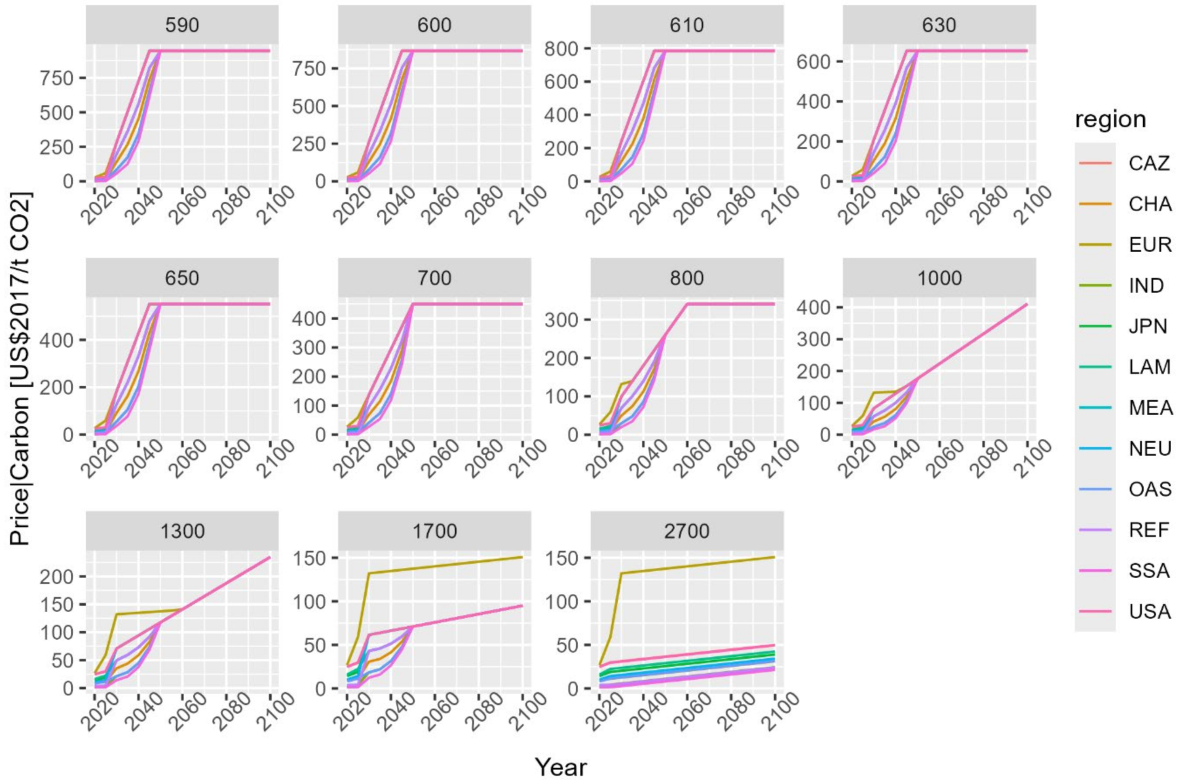


***Figure S1|*** *The elven different GHG price trajectories for the 12 different REMIND-MAgPIE macro regions. The facet titles indicate the peak carbon budget in Gt $CO_2$ from 2020 that was reached in the REMIND-standalone runs (see methods section "Scenario Framework", "Deriving GHG prices trajectories").*

## Biomass production and crop area

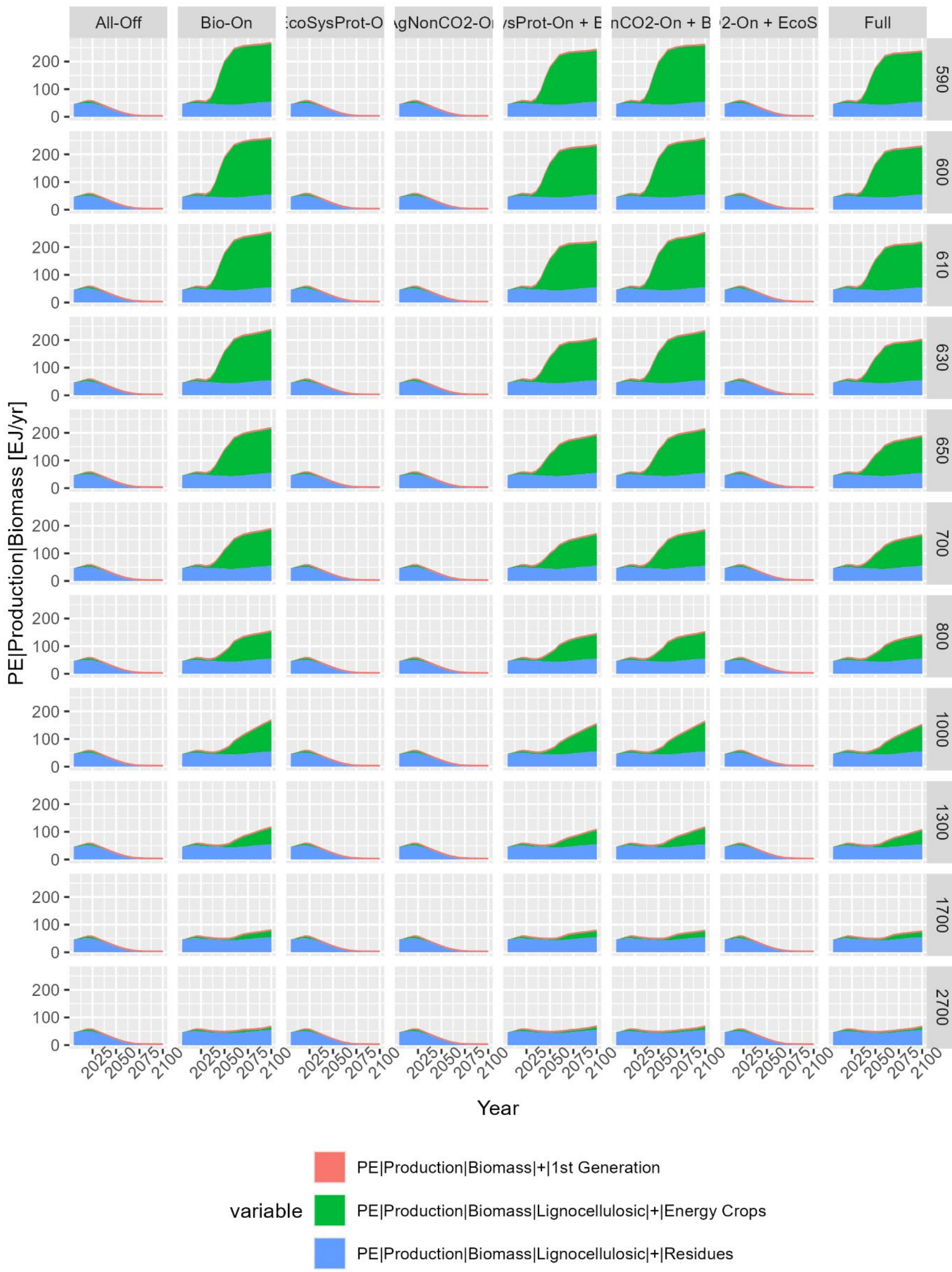


***Figure S2|*** *Bioenergy feedstock allocation over time. Please note that as of today Residues are mostly used traditionally, e.g. in conventional cookstoves. In scenarios without bioenergy, we assume that this feedstock will not become available for modern applications, so the residues production values are phased, when developing regions move away from traditional biomass use.*

*The right-hand-side facet titles indicate the peak carbon budget in Gt $CO_2$ from 2020 that was reached in the REMIND-standalone runs (see methods section "Scenario Framework", "Deriving GHG prices trajectories").*

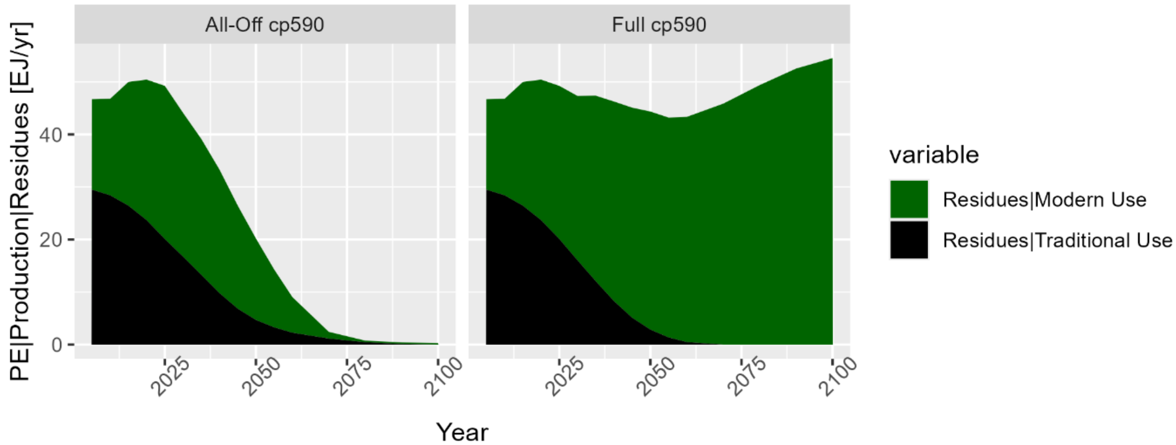


***Figure S3|*** *Allocation of residues over time for a scenario without and a scenario with bioenergy availability. As of today, a large fraction of lignocellulosic biomass residues is used traditionally, e.g. in conventional cookstoves. In scenarios without bioenergy, we assume that this feedstock will not become available for modern applications, so the residues production values are phased out, when developing regions move away from traditional biomass use. We also assume that fuelwood used in higher income regions is phased out over time.*

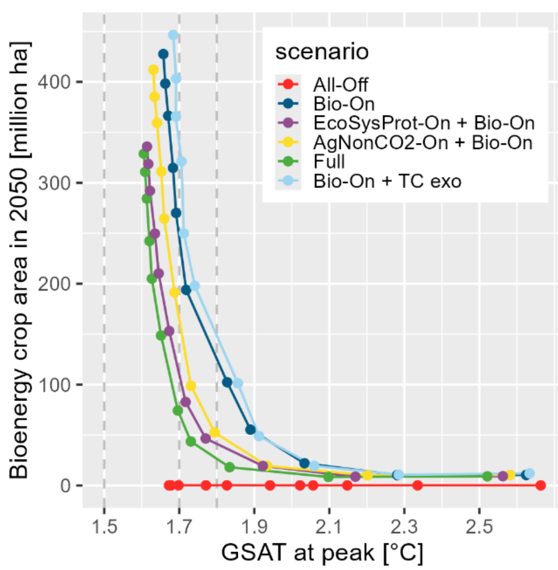


***Figure S4|*** *Achievability frontier of bioenergy crop area in 2050 for selected scenarios. Please refer to the "Sensitivities" section "Pessimistic yield assumptions" below for more details on the "Bio-On + TC exo" scenario.*

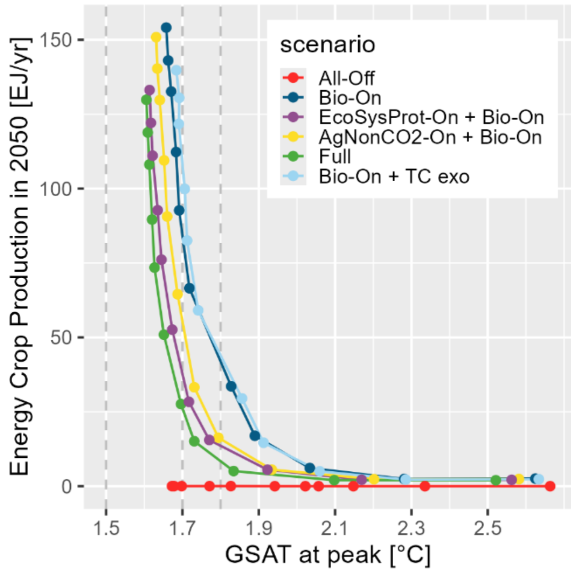


***Figure S5|*** *Achievability frontier of lignocellulosic bioenergy crop production in 2050 for selected scenarios. Please refer to the "Sensitivities" section "Pessimistic yield assumptions" below for more details on the "Bio-On + TC exo" scenario.*

## Drivers of electrification

All types of FE carriers decrease in 2030 as a consequence of climate change mitigation, also electricity consumption. However, electricity consumption decreases only by less than 3% for the scenarios with higher $CO_2$ prices (see Figure S6), while consumption of other energy carriers decreases stronger (see, e.g., final energy liquids in Figure S7). Thus, the increases in near term electricity share is rather driven by a stronger decline in other energy carriers then by increasing the total use of electricity in end-use sectors.

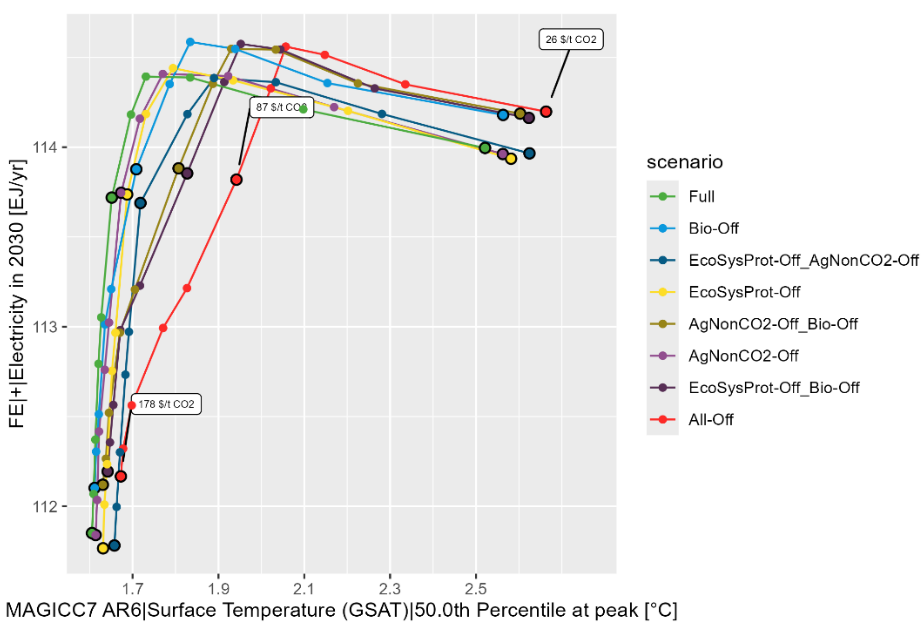


***Figure S6|*** *Achievability frontier of electricity consumption on the final energy level for all scenarios.*

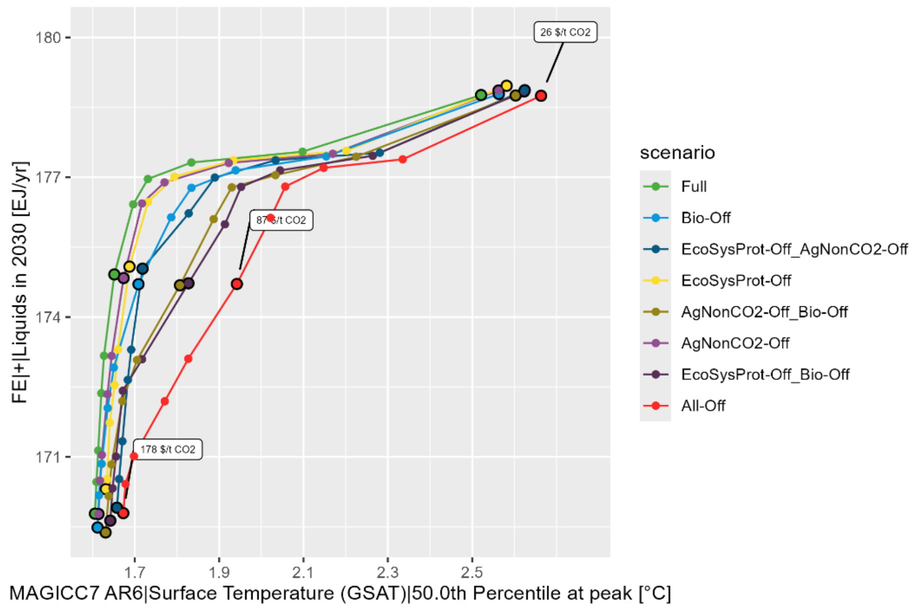


***Figure S7|*** *Achievability frontier of liquid fuel consumption on the final energy level for all scenarios.*

Despite this short-term reduction of electricity consumption, wind (Figure S8) and solar (Figure S9) capacities need to be ramped up substantially to reach ambitious climate targets, while electricity production from fossil sources is phased-out and increasingly so without AFOLU mitigation.

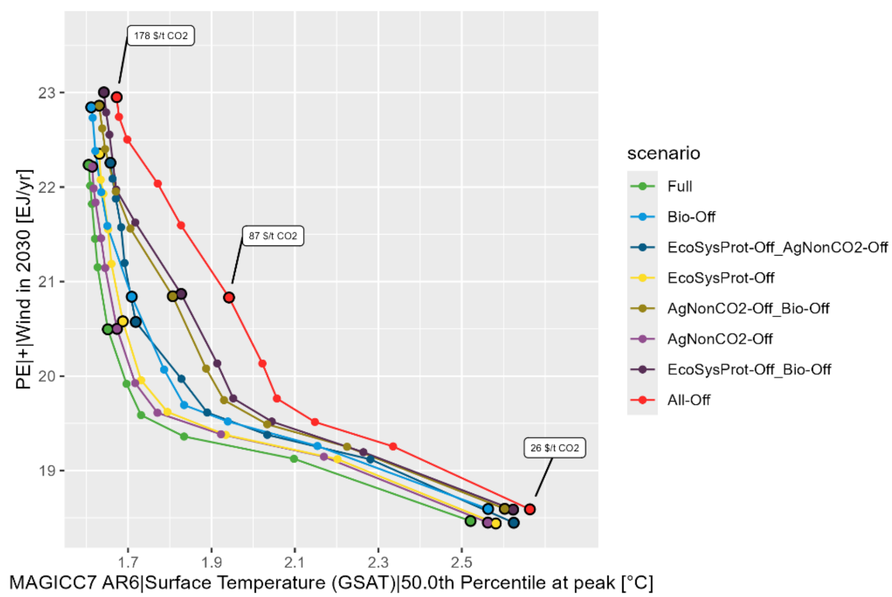


***Figure S8|*** *Achievability frontier of electricity production from wind turbines for all scenarios.*

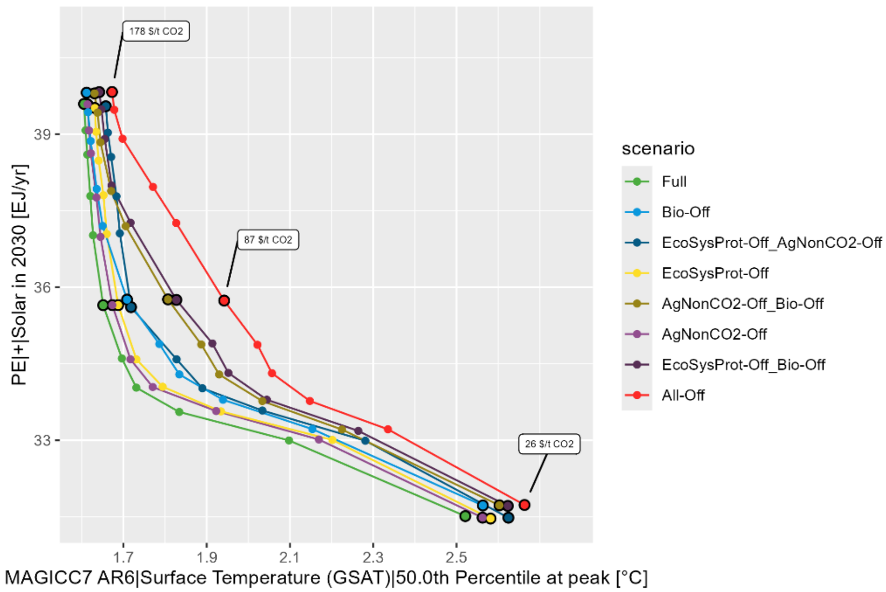


*__Figure S9|__ Achievability frontier of electricity production from solar PV for all scenarios.*

## Temperature over time

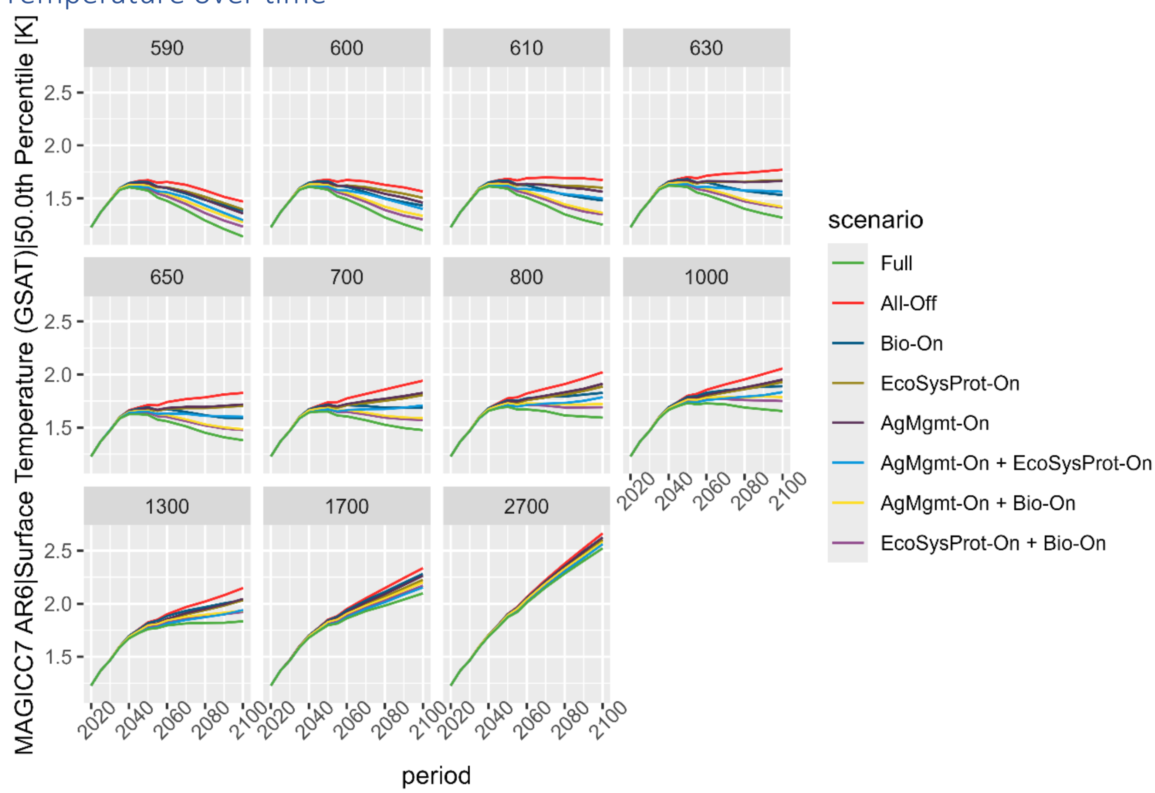


*__Figure S10|__ GSAT over time for all scenarios. The facet titles indicate the peak carbon budget in Gt $CO_2$ from 2020 that was reached in the REMIND-standalone runs (see methods section "Scenario Framework", "Deriving GHG prices trajectories").*

## Emissions over time

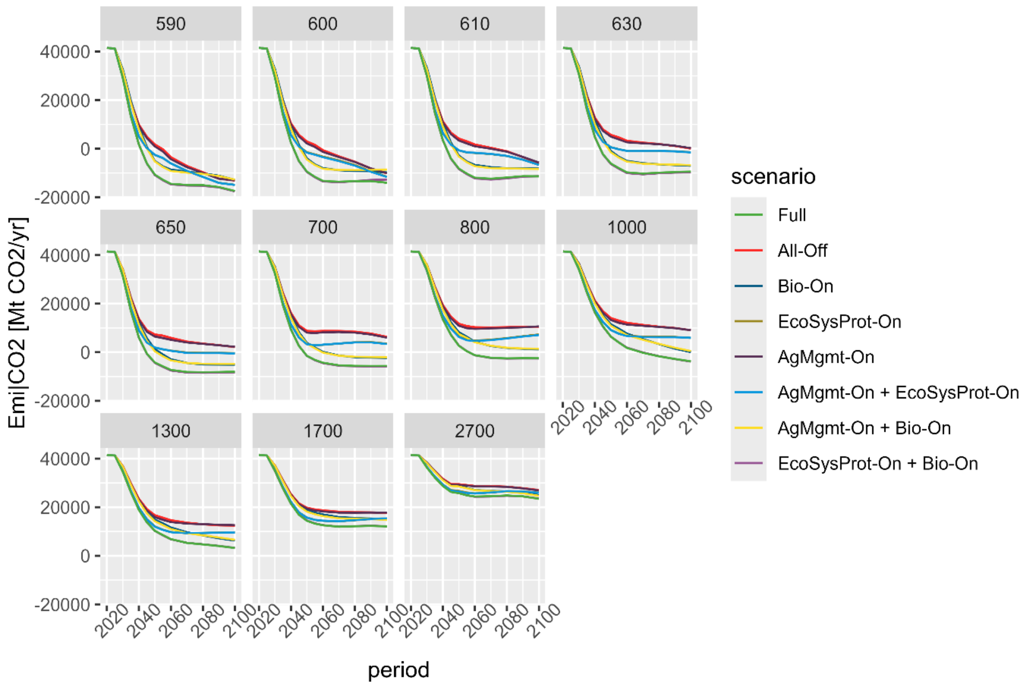


***Figure S11|*** *$CO_2$ emissions over time for all scenarios. The facet titles indicate the peak carbon budget in Gt $CO_2$ from 2020 that was reached in the REMIND-standalone runs (see methods section "Scenario Framework", "Deriving GHG prices trajectories").*

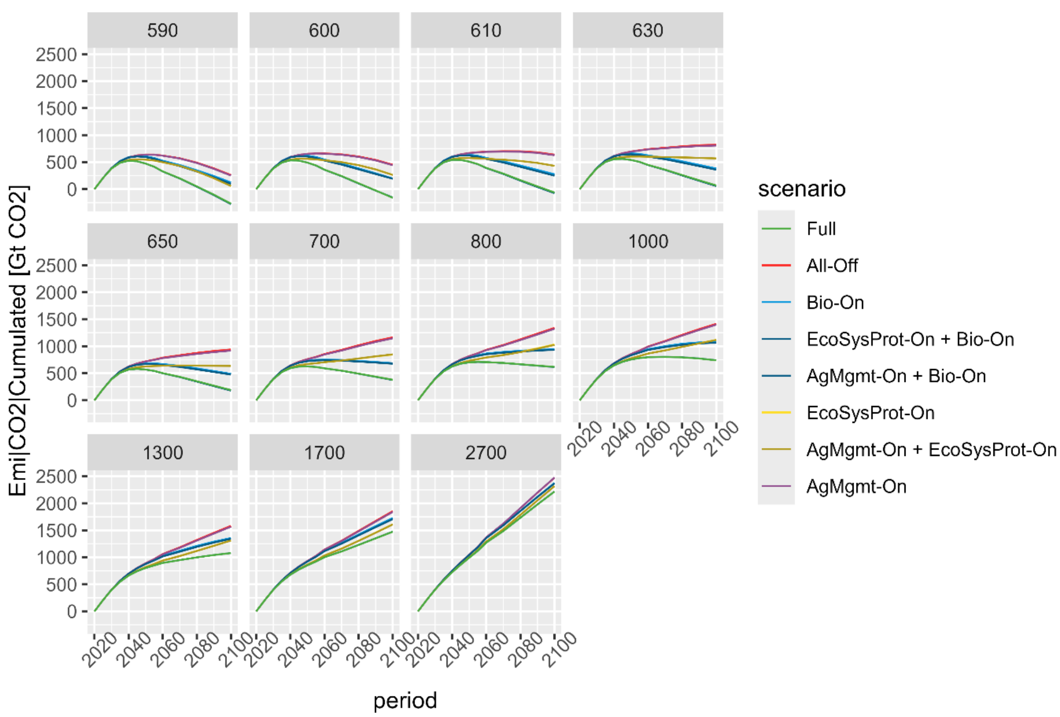


***Figure S12|*** *Cumulative $CO_2$ emissions over time for all scenarios. The facet titles indicate the peak carbon budget in Gt $CO_2$ from 2020 that was reached in the REMIND-standalone runs (see methods section "Scenario Framework", "Deriving GHG prices trajectories").*

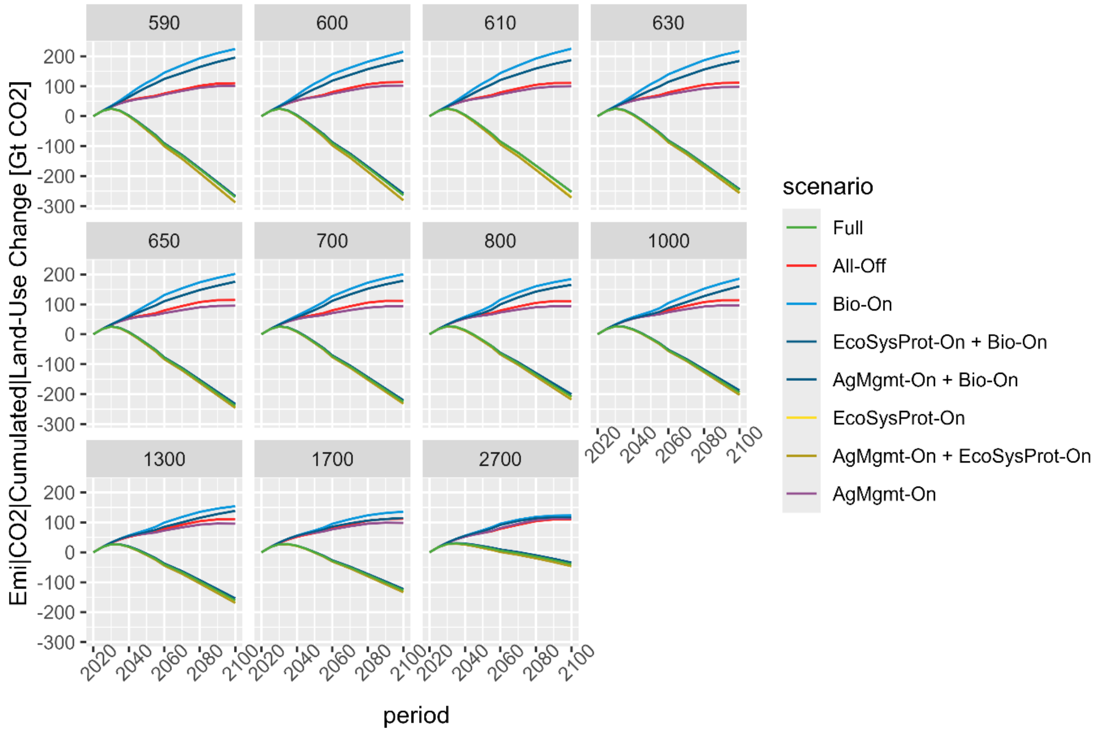


***Figure S13|*** *Cumulative LUC $CO_2$ emissions over time for all scenarios. The facet titles indicate the peak carbon budget in Gt $CO_2$ from 2020 that was reached in the REMIND-standalone runs (see methods section "Scenario Framework", "Deriving GHG prices trajectories").*

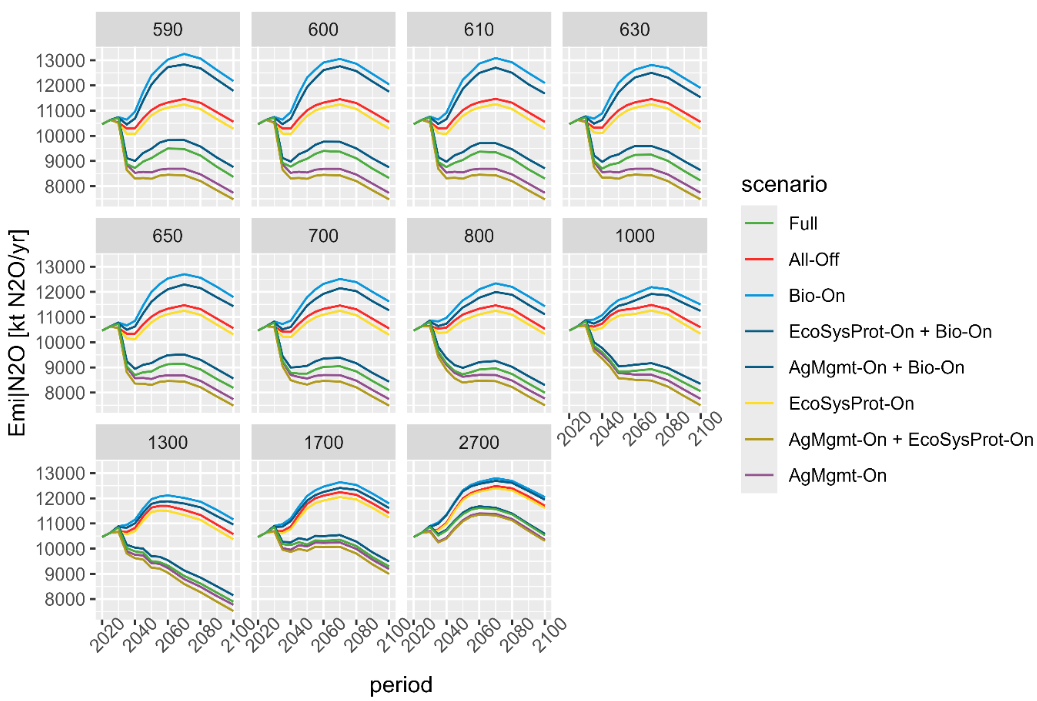


***Figure S14|*** *$N_2O$ emissions over time for all scenarios. The facet titles indicate the peak carbon budget in Gt $CO_2$ from 2020 that was reached in the REMIND-standalone runs (see methods section "Scenario Framework", "Deriving GHG prices trajectories").*

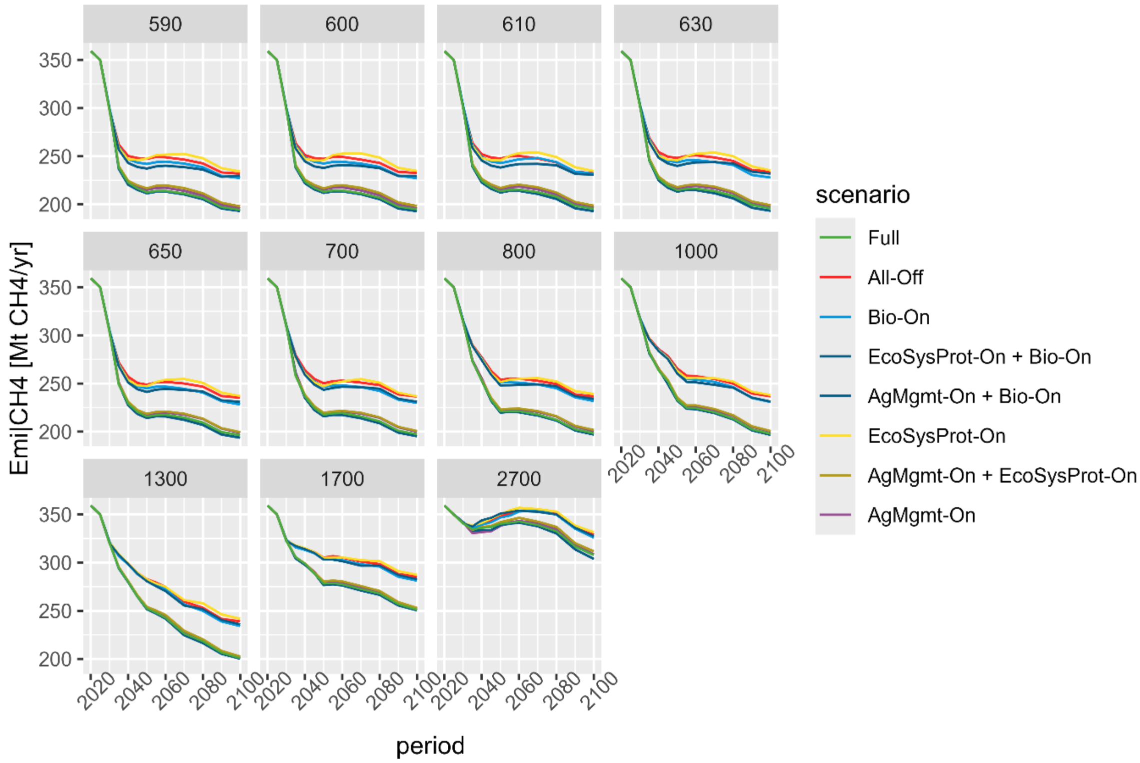


*__Figure S15|__ $CH_4$ emissions over time for all scenarios. The facet titles indicate the peak carbon budget in Gt $CO_2$ from 2020 that was reached in the REMIND-standalone runs (see methods section "Scenario Framework", "Deriving GHG prices trajectories").*

## Crop yields and land-use intensity over time

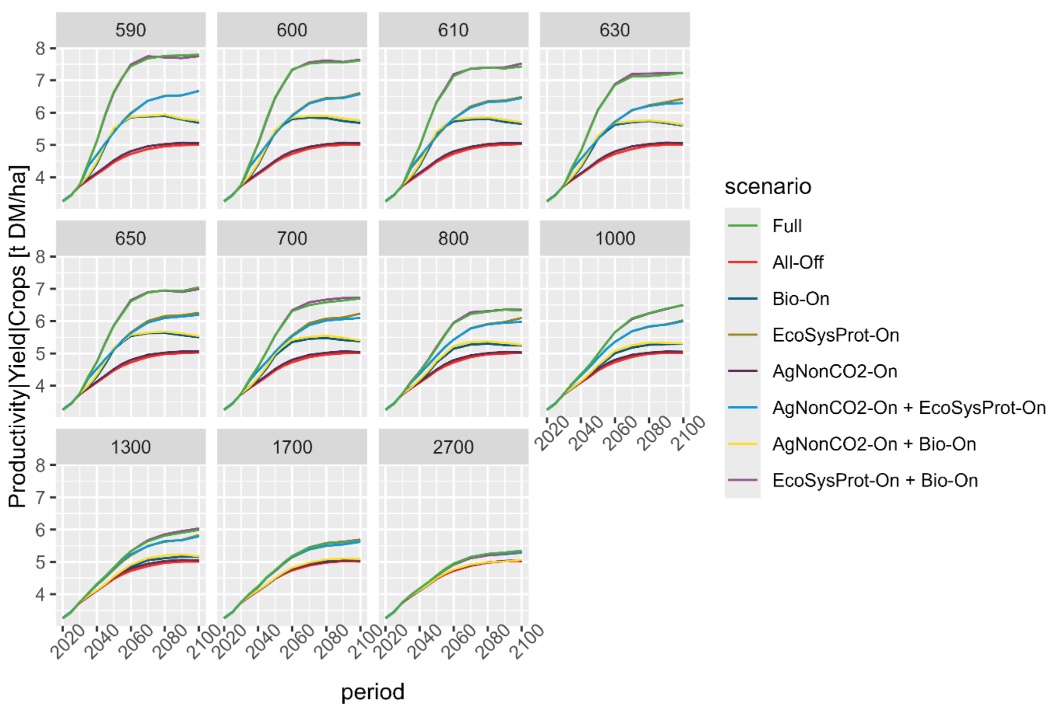


*__Figure S16|__ Non-energy crop yields over time for all scenarios. The facet titles indicate the peak carbon budget in Gt $CO_2$ from 2020 that was reached in the REMIND-standalone runs (see methods section "Scenario Framework", "Deriving GHG prices trajectories").*

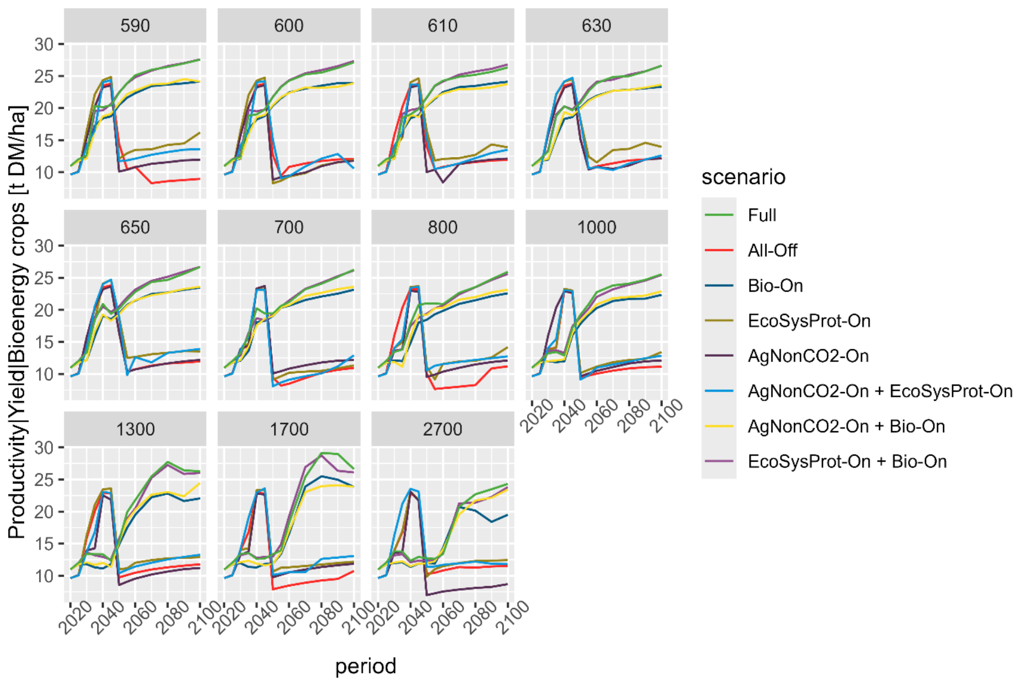


***Figure S17|*** *Energy crop yields over time for all scenarios. The facet titles indicate the peak carbon budget in Gt $CO_2$ from 2020 that was reached in the REMIND-standalone runs (see methods section "Scenario Framework", "Deriving GHG prices trajectories").*

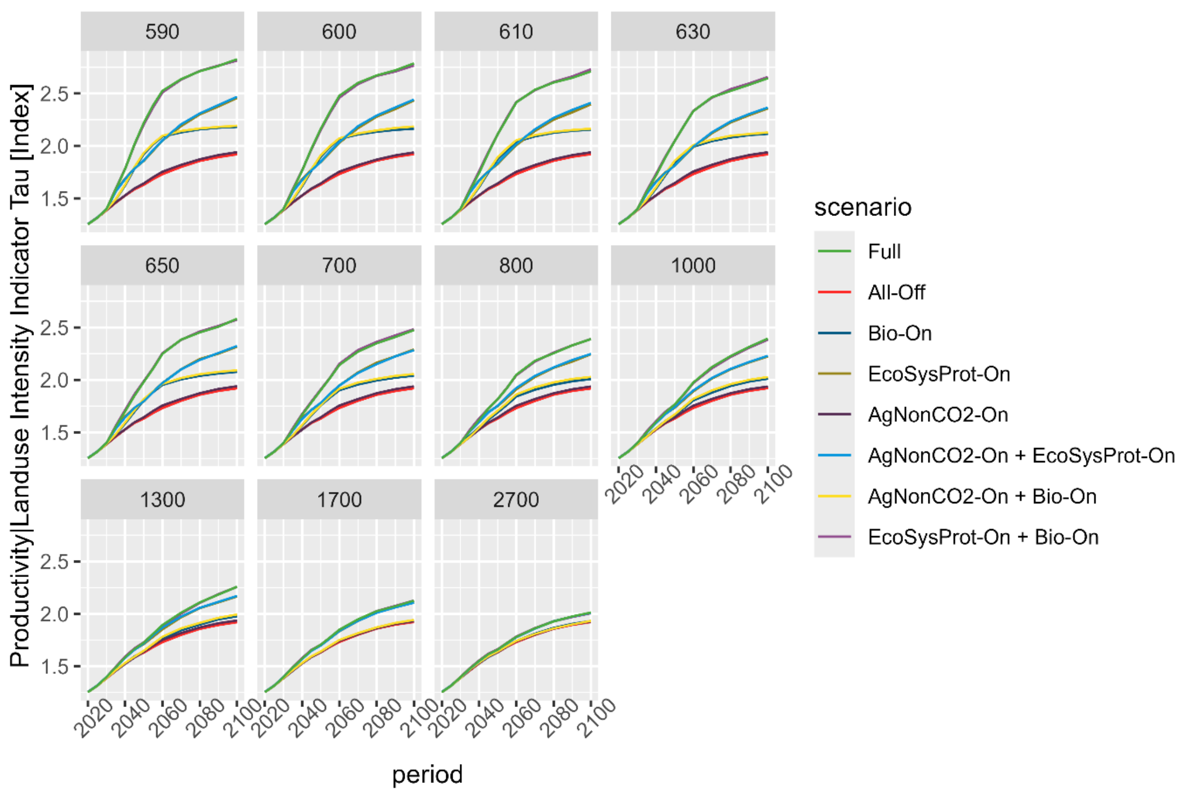


***Figure S18|*** *Land-use intensity indicator over time for all scenarios. The facet titles indicate the peak carbon budget in Gt $CO_2$ from 2020 that was reached in the REMIND-standalone runs (see methods section "Scenario Framework", "Deriving GHG prices trajectories").*

## Agricultural prices over time

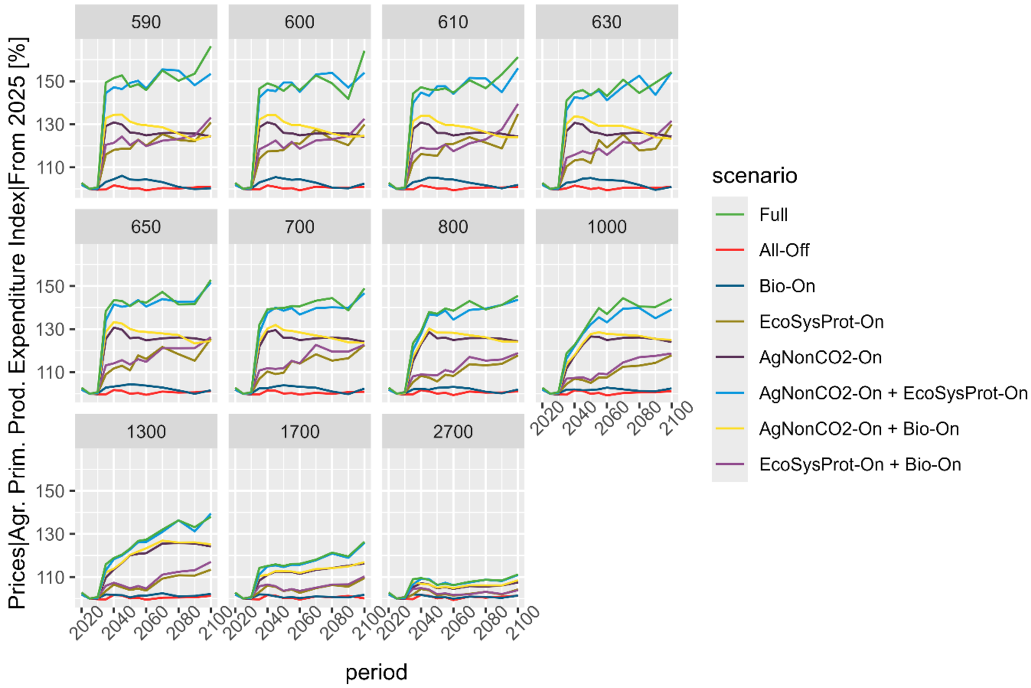


***Figure S19|*** *Agricultural Primary Production Expenditure Index over time for all scenarios. The facet titles indicate the peak carbon budget in Gt $CO_2$ from 2020 that was reached in the REMIND-standalone runs (see methods section "Scenario Framework", "Deriving GHG prices trajectories").*

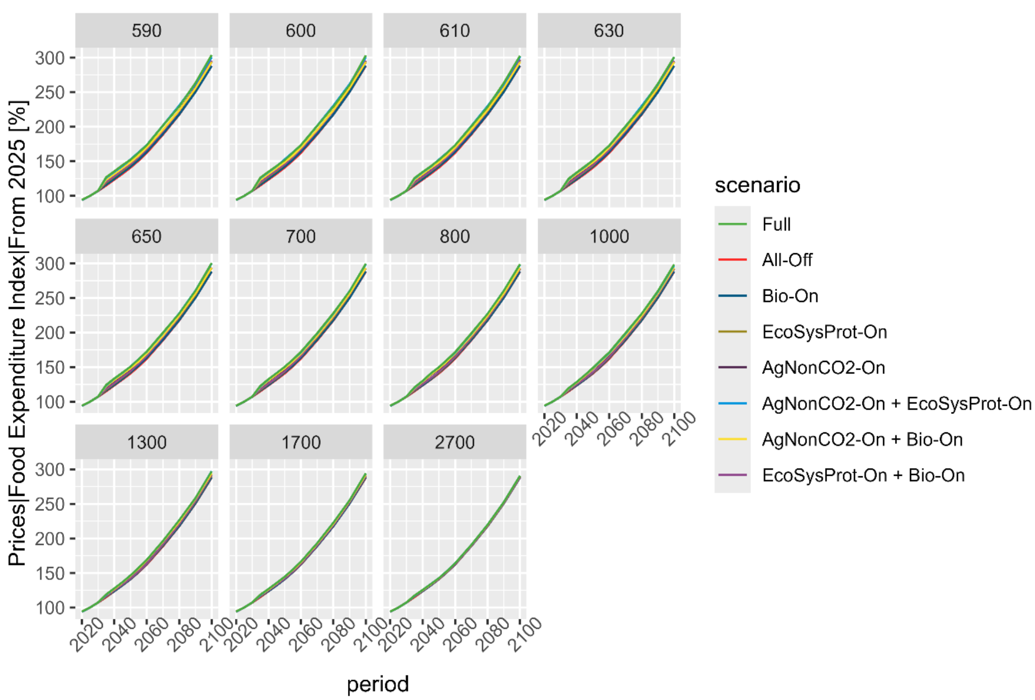


***Figure S20|*** *Food Expenditure Index over time for all scenarios. The facet titles indicate the peak carbon budget in Gt $CO_2$ from 2020 that was reached in the REMIND-standalone runs (see methods section "Scenario Framework", "Deriving GHG prices trajectories").*

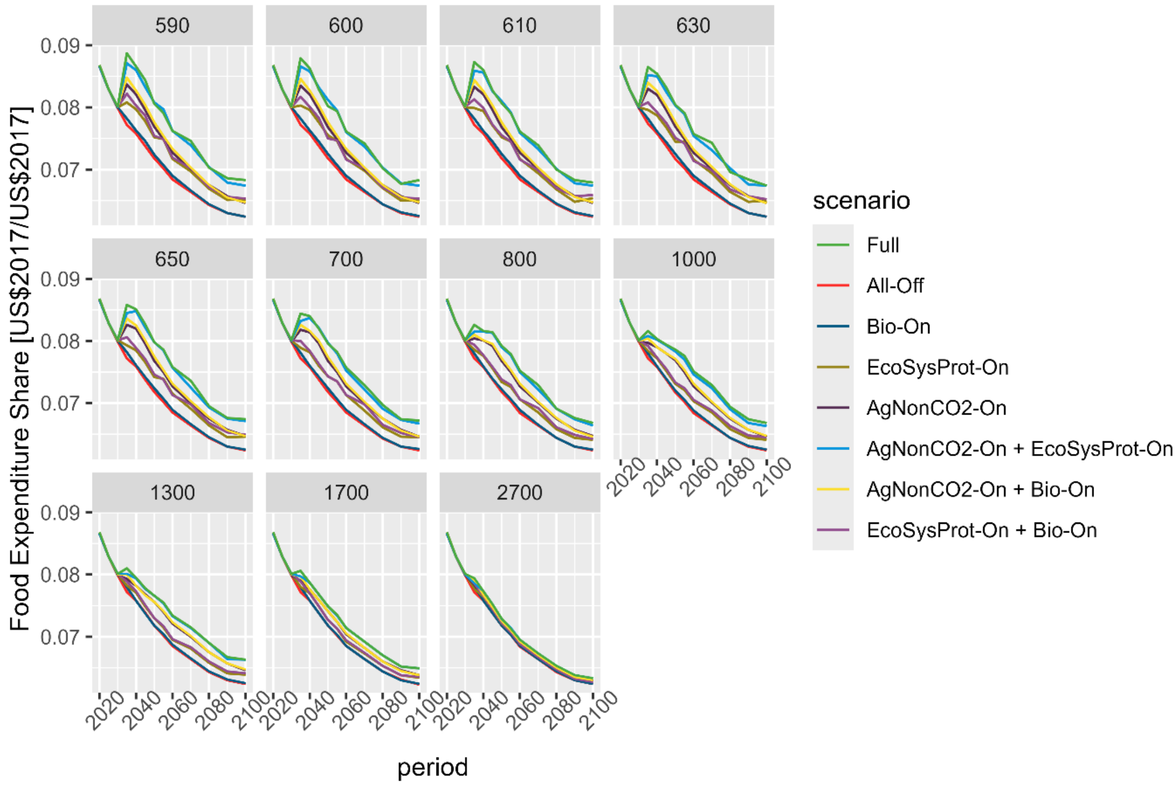


***Figure S21|*** *Food Expenditure Share over time for all scenarios. The facet titles indicate the peak carbon budget in Gt $CO_2$ from 2020 that was reached in the REMIND-standalone runs (see methods section "Scenario Framework", "Deriving GHG prices trajectories").*

## Sensitivities

### Residues on

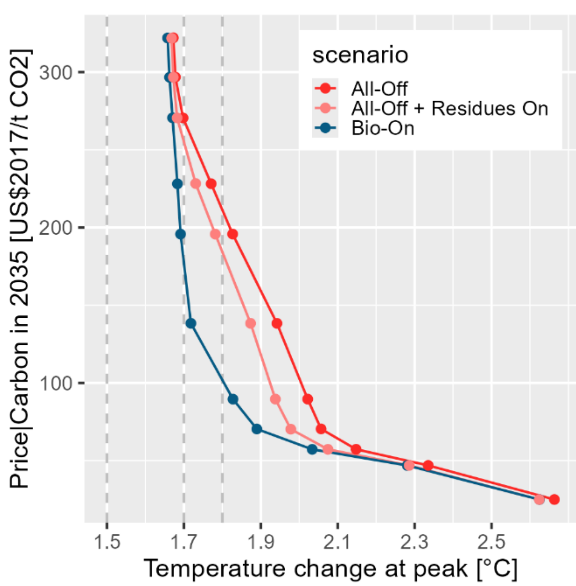


***Figure S22|*** *Achievability frontier of GHG prices in 2030 for selected scenarios including the sensitivity scenarios with residues being available.*

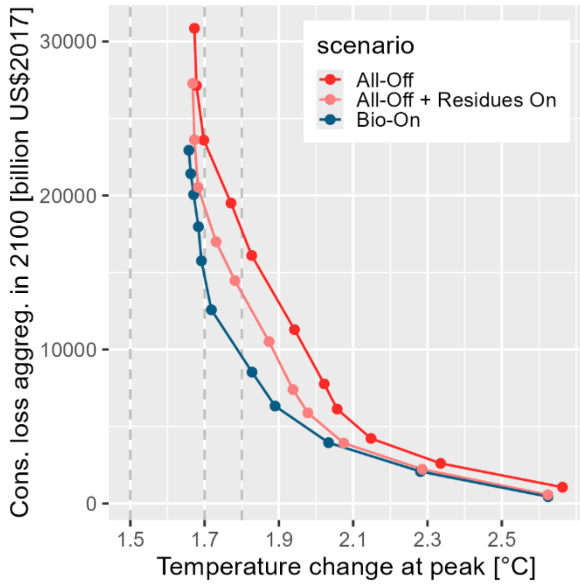


***Figure S23|*** *Achievability frontier of cumulative consumption losses in 2100 for selected scenarios including the sensitivity scenarios with residues being available.*

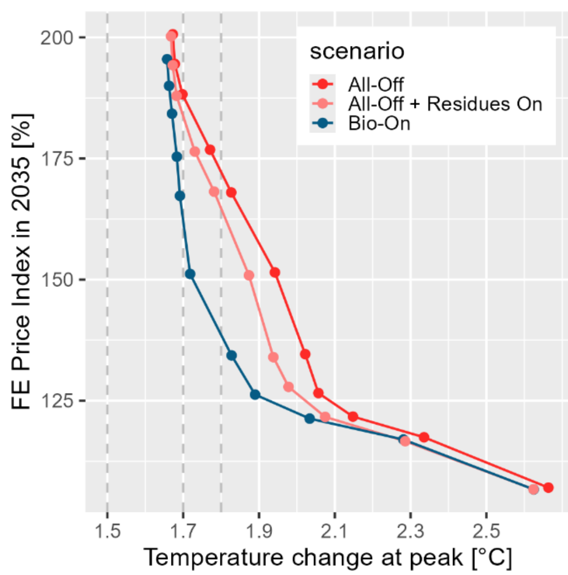


***Figure S24|*** *Achievability frontier of the final energy price index in 2035 for selected scenarios including the sensitivity scenarios with residues being available.*

## DACCS off

Without DACCS available in the All-Off scenario, the peak temperatures that are still feasible, even at very high carbon prices, are substantially higher. Please note that for the Full scenario DACCS does not play a role for the peak temperature, since even under the highest GHG price scenario, it is only deployed towards the end of the century and removals are small (50 Gt $CO_2$ cumulative removals until 2100). Thus, peak temperature achievability frontier of a Full + DAC off scenario would be identical to the one in the default Full scenario, and the end-of-century achievability frontier would differ only marginally.

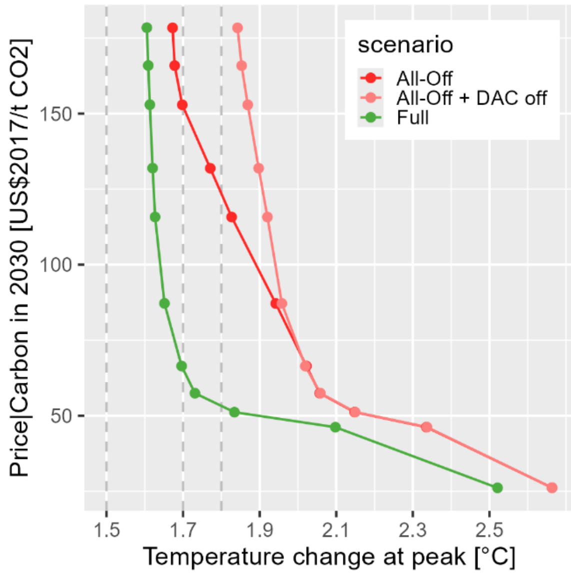


*Figure S25|* *GHG price for sensitivity scenarios without DACCS*

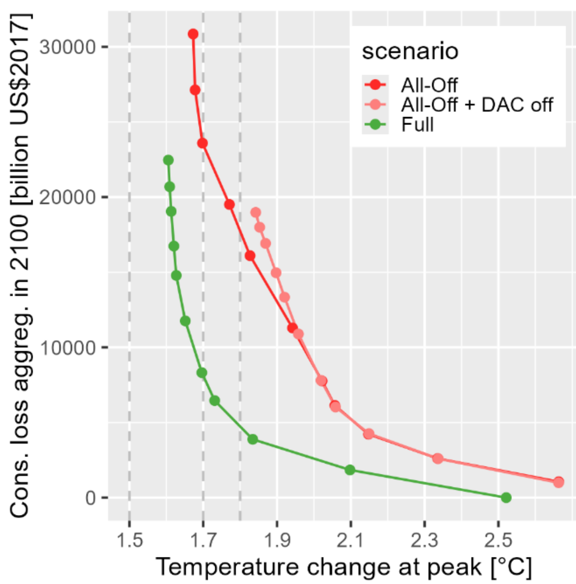


*Figure S26|* *Policy costs for sensitivity scenarios without DACCS*

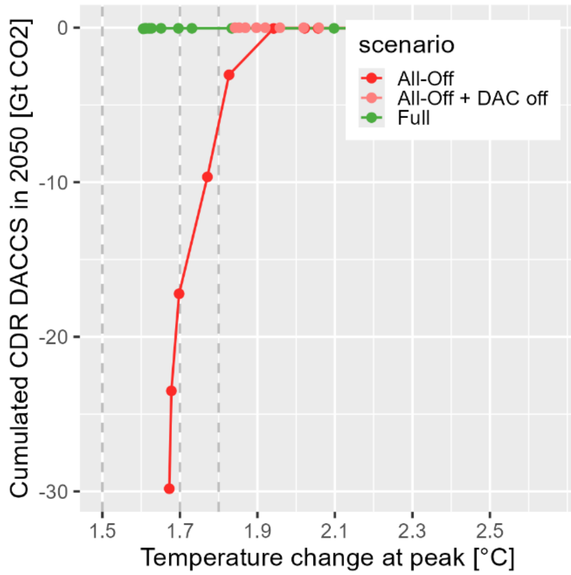


***Figure S27|*** *Cumulated CDR from DACCS in until 2050 for sensitivity scenarios without DACCS*

## Pessimistic yield projections

To test the sensitivity of yield improvements on the results from bioenergy, we computed an additional scenario, in which the agricultural intensity that leads to crop yield improvements does not respond dynamically to the pressure on land. To that end we took the trajectory of the agricultural intensity of the “All-Off” scenario with lowest carbon prices (in which thus neither ecosystem protection and restoration nor bioenergy production drives up yield rates) and applied it exogenously to the “Bio-On” scenario (see Figure S28), thereby creating the “Bio-On + TC exo” scenario with exogenous Technological change (TC). Yields do still increase over time in that scenario, but they cannot respond to higher bioenergy demand when GHG prices rise. As a consequence, we observe substantially higher levels of extensification and LUC emissions increase strongly (see Figure S29 and Figure S30) despite similar levels of bioenergy production (Figure S31). Also, food expenditures increase more strongly (see Figure S32 and Figure S33). The lack of land-use intensification furthermore increases carbon prices (Figure S34) and policy costs (Figure S35).

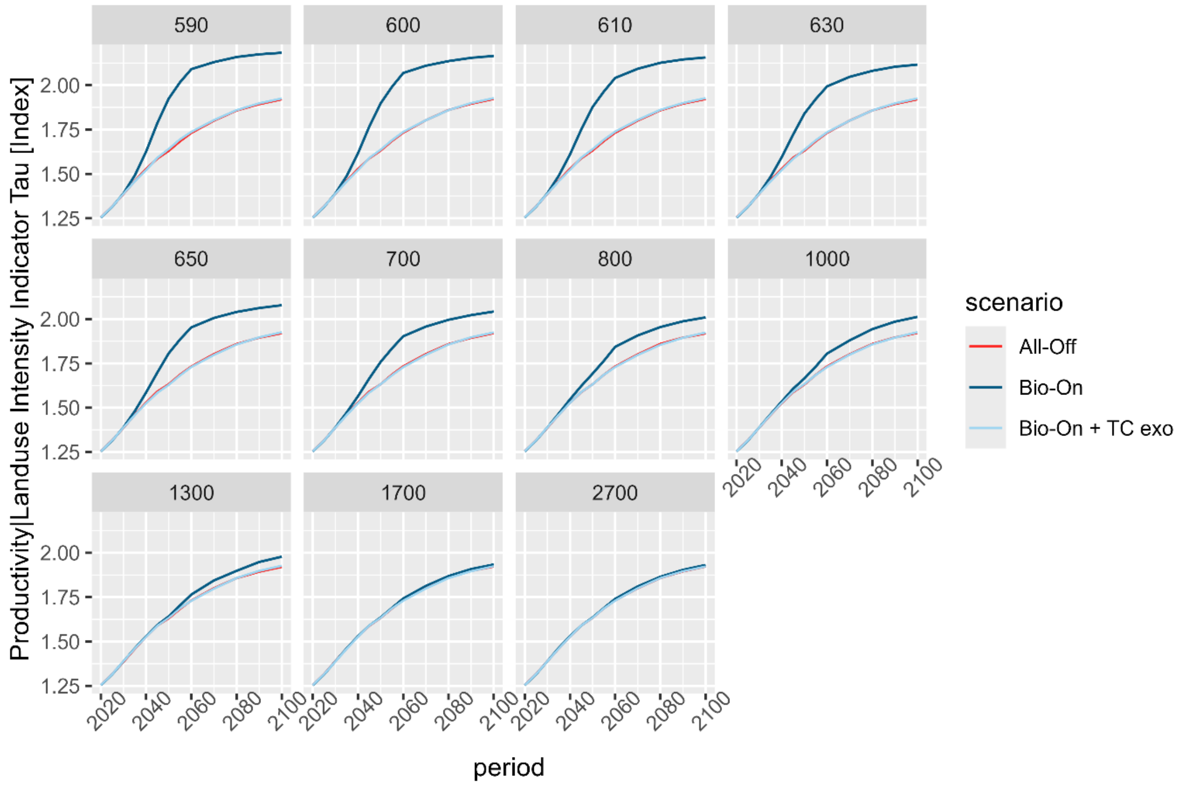


***Figure S28|*** *Land-use intensity indicator over time for selected scenarios including the sensitivity scenarios with an exogenous Technological Change (TC). Note, the trajectories for the "All-Off" and the "Bio-On + TC exo" scenarios are identical. The facet titles indicate the peak carbon budget in Gt $CO_2$ from 2020 that was reached in the REMIND-standalone runs (see methods section "Scenario Framework", "Deriving GHG prices trajectories").*

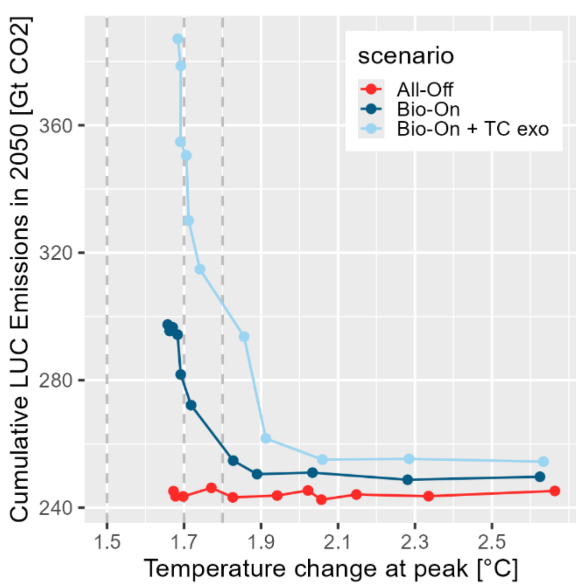


***Figure S29|*** *Achievability frontier of cumulative LUC emissions in 2050 for selected scenarios including the sensitivity scenarios with an exogenous Technological Change (TC).*

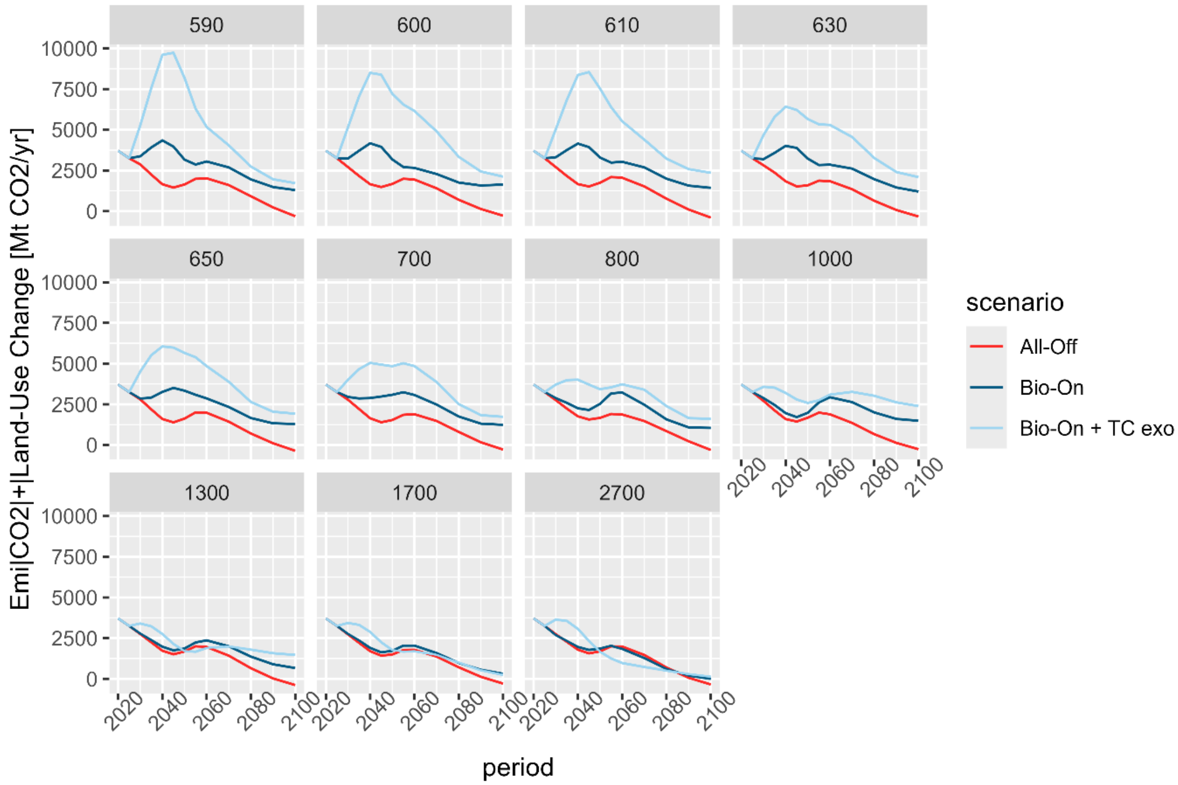


***Figure S30|*** *LUC emissions over time for selected scenarios including the sensitivity scenarios with an exogenous Technological Change (TC). The facet titles indicate the peak carbon budget in Gt $CO_2$ from 2020 that was reached in the REMIND-standalone runs (see methods section "Scenario Framework", "Deriving GHG prices trajectories").*

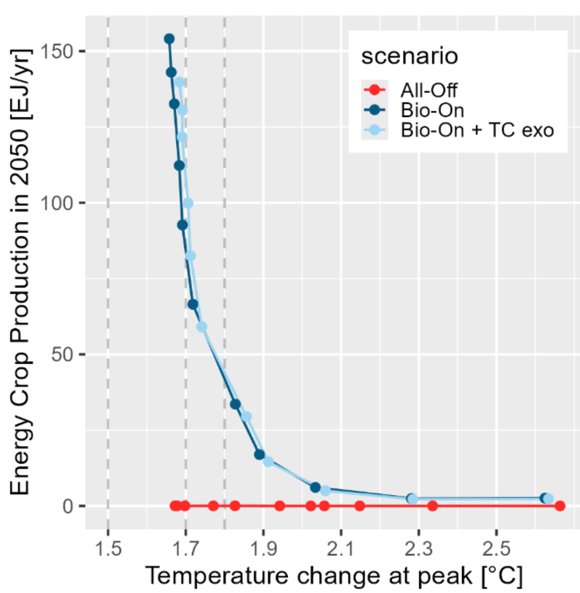


***Figure S31|*** *Achievability frontier of lignocellulosic bioenergy crop production in 2050 for selected scenarios including the sensitivity scenarios with an exogenous Technological Change (TC).*

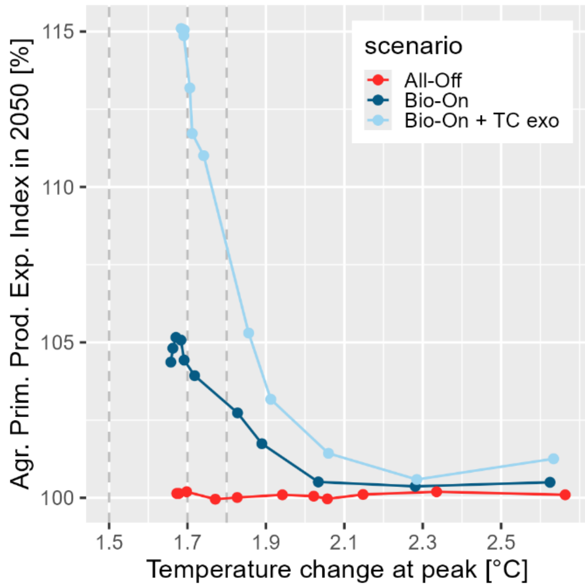


***Figure S32|*** *Achievability frontier of the Agricultural Primary Production Expenditure Index in 2050 for selected scenarios including the sensitivity scenarios with an exogenous Technological Change (TC).*

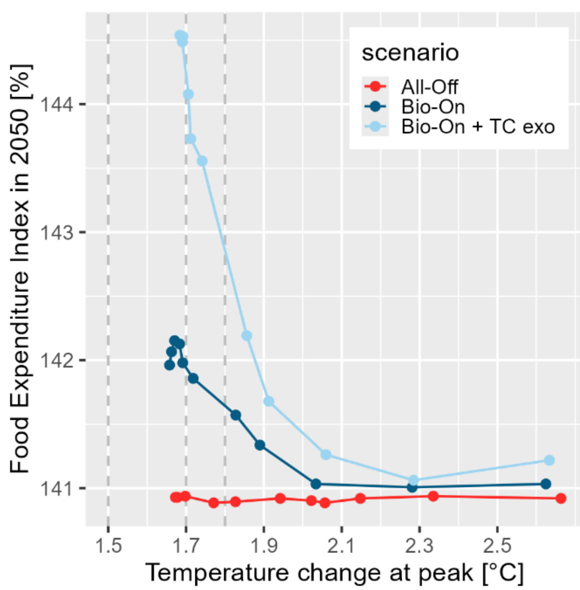


***Figure S33|*** *Achievability frontier of the Food Expenditure Index in 2050 for selected scenarios including the sensitivity scenarios with an exogenous Technological Change (TC).*

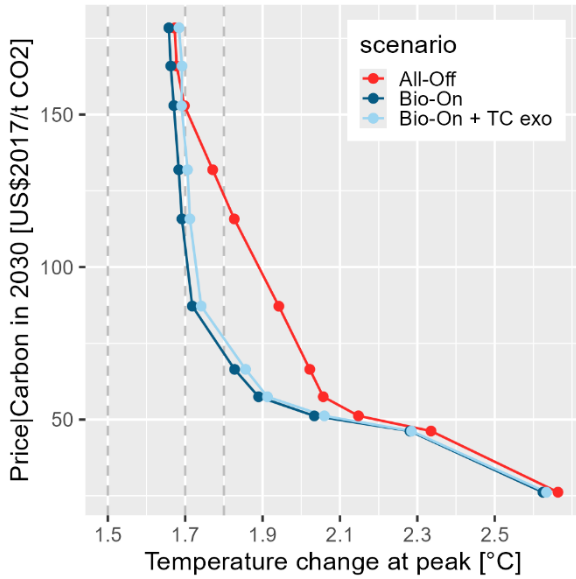


***Figure S34|*** *Achievability frontier of GHG prices in 2050 for selected scenarios including the sensitivity scenarios with an exogenous Technological Change (TC).*

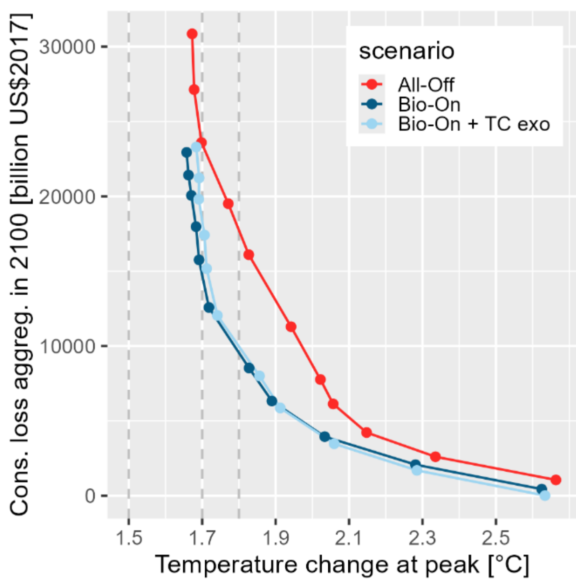


***Figure S35|*** *Achievability frontier of cumulative consumption losses in 2100 for selected scenarios including the sensitivity scenarios with an exogenous Technological Change (TC).*

## No non-$CO_2$ price cap

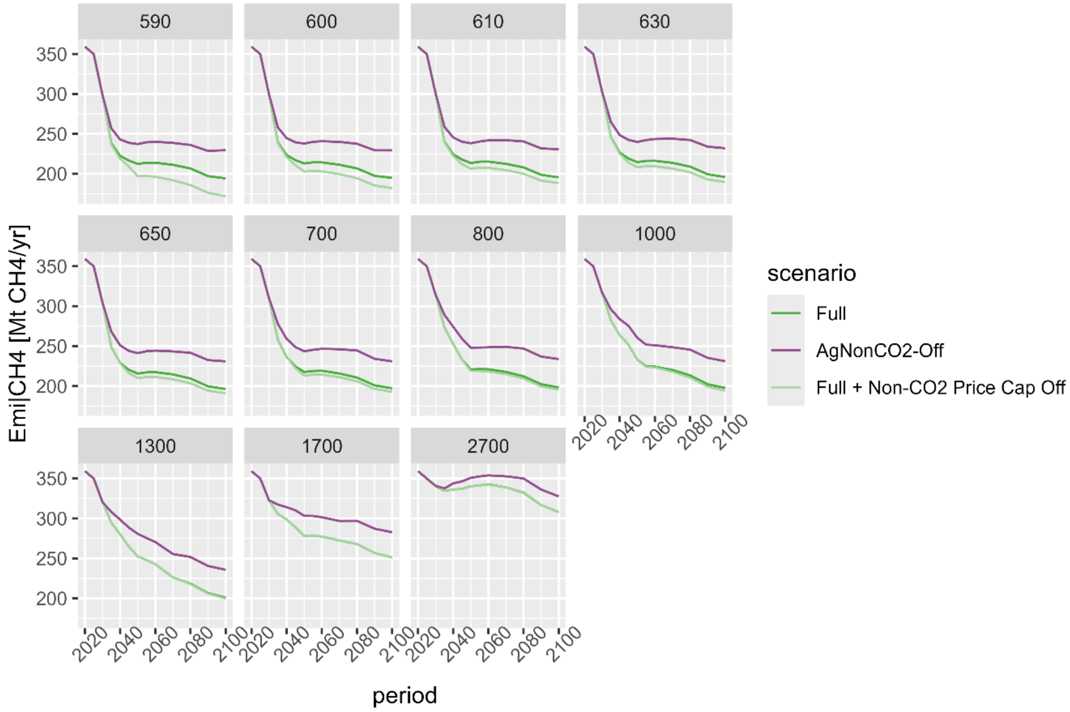


*__Figure S36|__ $CH_4$ emissions over time for selected scenarios including the sensitivity scenarios without a price cap on non-$CO_2$ GHG prices. The facet titles indicate the peak carbon budget in Gt $CO_2$ from 2020 that was reached in the REMIND-standalone runs (see methods section "Scenario Framework", "Deriving GHG prices trajectories").*

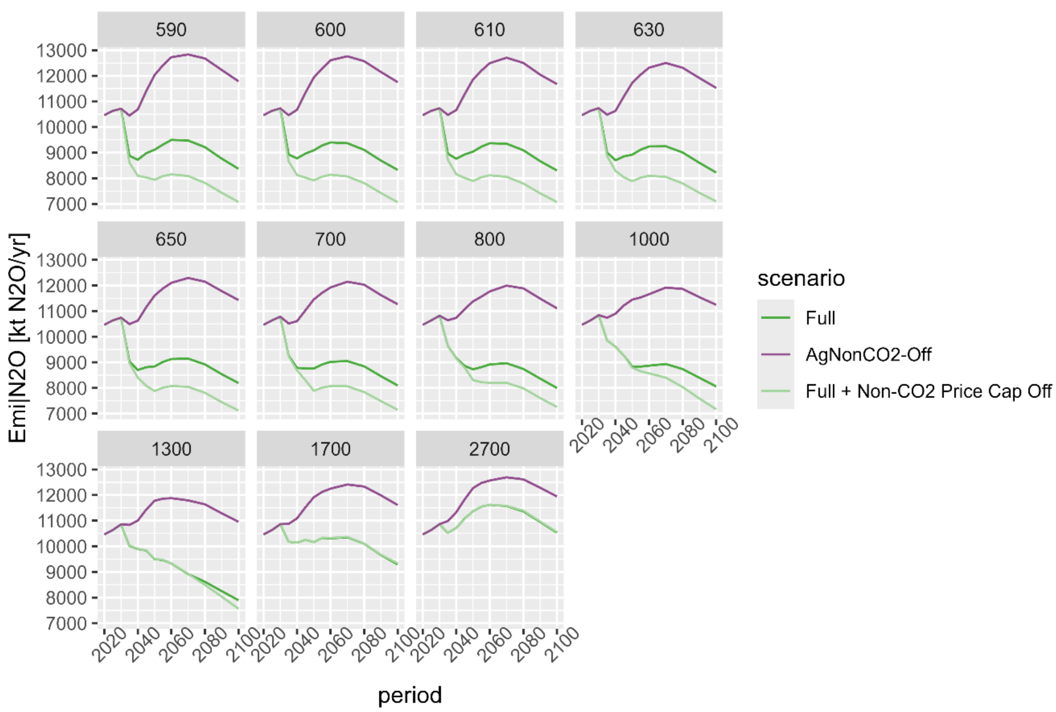


*__Figure S37|__ $N_2O$ emissions over time for selected scenarios including the sensitivity scenarios without a price cap on non-$CO_2$ GHG prices. The facet titles indicate the peak carbon budget in Gt $CO_2$ from 2020 that was reached in the REMIND-standalone runs (see methods section "Scenario Framework", "Deriving GHG prices trajectories").*

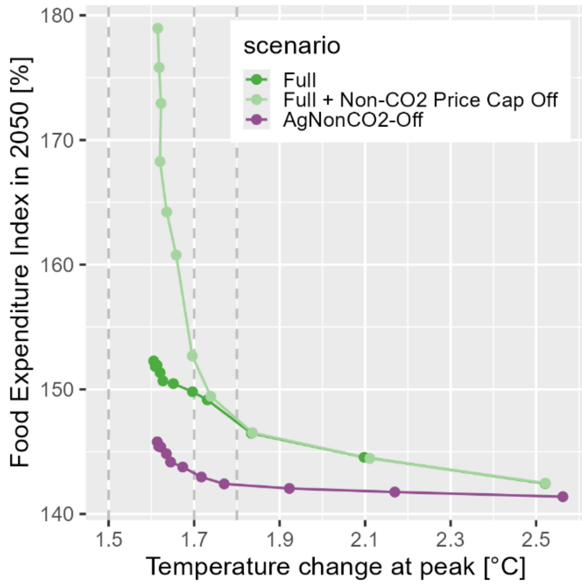


***Figure S38|** Achievability frontier of the food expenditure index (reference year 2025) in 2050 for selected scenarios including the sensitivity scenarios without a price cap on non-$CO_2$ GHG prices.*

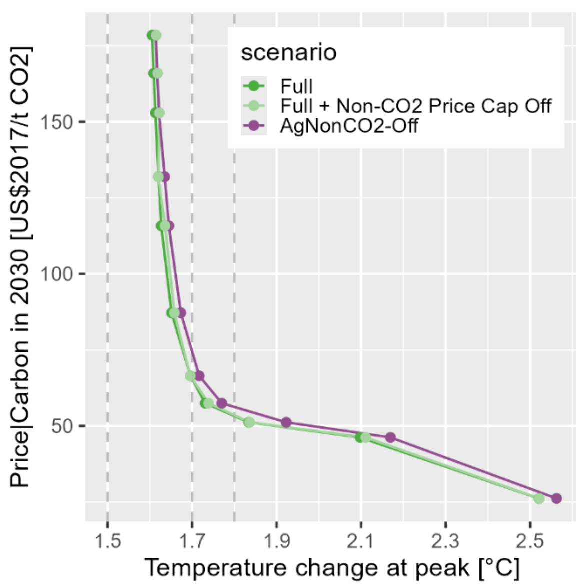


***Figure S39|** Achievability frontier of the GHG prices in 2030 for selected scenarios including the sensitivity scenarios without a price cap on non-$CO_2$ GHG prices.*

## Climate sensitivity

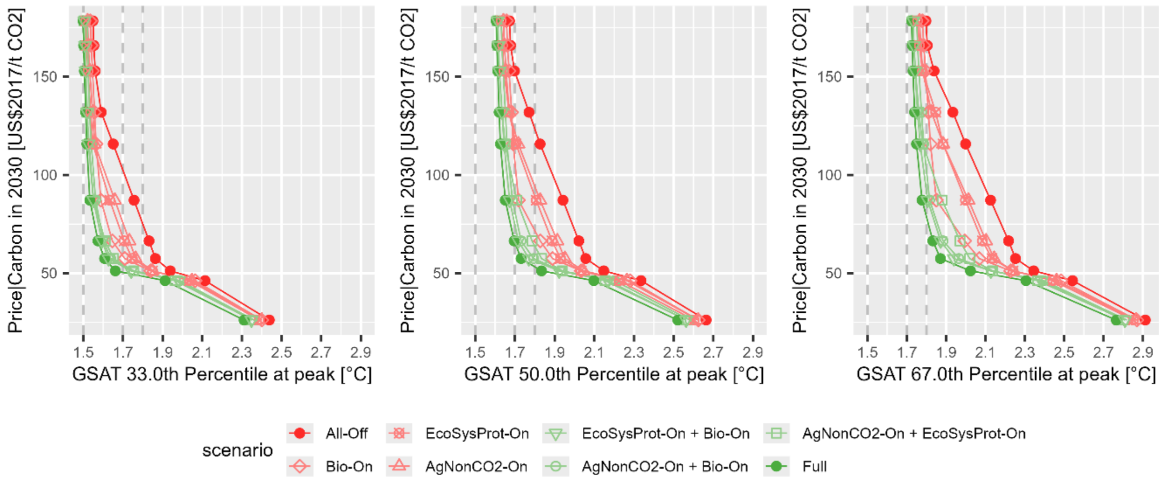


*Figure S40| Achievability frontiers of the GHG price in 2030 for different assumptions on climate sensitivity. In contrast to the other achievability frontiers shown in this study, we here show different values on the x-axis, varying the confidence level of keeping warming below a certain value between 33%, 50% and 67%. Temperature values are derived with MAGICC.*

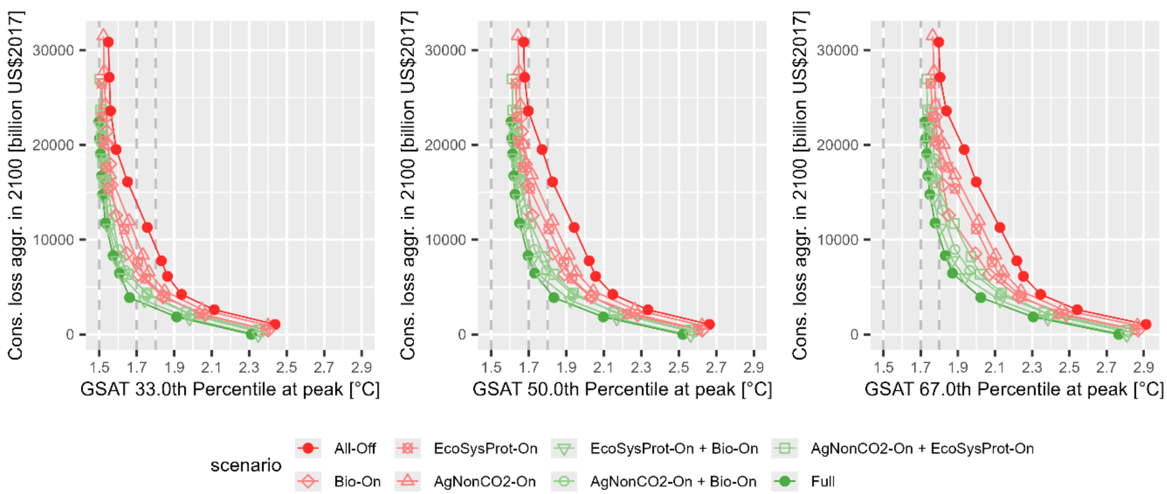


*Figure S41| Achievability frontiers of cumulative consumption losses in 2100 for different assumptions on climate sensitivity. In contrast to the other achievability frontiers shown in this study, we here show different values on the x-axis, varying the confidence level of keeping warming below a certain value between 33%, 50% and 67%. Temperature values are derived with MAGICC.*