Supplementary information

Tab. S1: Sector *Other GHG (fugitive) emissions* not allocated to industry, transportation, buildings, or agriculture [2].

Sector	Gt CO_{2eq}
Fugitive emissions related to fossil fuels	
N_2O from burning of fossil fuels[1]	0.50
CH_4 from burning of fossil fuels (mobil & stationary sources)	0.24
CH_4 from fugitive emissions related to natural gas[2]	0.85
CH_4 from fugitive emissions related to crude oil[2]	0.85
CH_4 from fugitive emissions related to coal mining[2]	0.94
CO_2 from fugitive emissions (gas flaring related to oil production and refining)[3]	0.25
Total	**3.63[4]**

[1] Burning of fossil fuels leads to N_2O; the number 0.5 Gt CO_{2eq} from [6] represents the average annual emission in the period 2007 to 2016.

[2] Fugitive emissions of CH_4 are accidental leakages during oil and gas extraction and transportation, from damaged or poorly maintained pipes. Oil wells can also release gases, including methane, during extraction - producers often don't have an existing network of pipelines to transport it. Here a share of 50% for oil and gas is assumed. Fugitive emissions are also accidental leakage of methane during coal mining.

[3] Fugitive emissions also includes flaring (intentional burning of gas at oil facilities, 150 billion m^3 gas in 2016 (www.statista.com), equivalent to 0.25 Gt CO_2.

[4] Number depends on the consumption of fossil fuels, which is considered in the model.

Tab. S2: *Global iron & steel*[1] 2016 (data from [2]).

Fuel/Energy	Gtoe	t CO_2/toe	Gt CO_2
Base case (2016)			
Electricity (and heat)	0.34	5.14	1.75
Fuel (coal/coke)	0.62 coal/coke	3.96	2.46
		Total	**4.20**
Best case (measure 1 to 5, i.e. 100% renewable electricity and steel based on H_2)			
Electricity (and heat)	0.88	0	0

[1] 1.36 Gt of iron were mined in 2016 [12]. Coke consumption was 0.648 Gt (0.45 Gtoe) [13]. Hence, 0.48 t of coke are needed per ton Fe. 1.43 t of coal are needed per t of coke, and thus the coal consumption of the iron & steel industry is 0.93 Gt (0.64 Gtoe). The value of [14] is 0.59 Gtoe coal. Here we use 0.62 Gtoe as average. According to WRI, 1.74 Gt of CO_2 are related to electricity and heat of the iron and steel industry, which is equivalent to 0.34 Gtoe (global average of 5.14 t CO_2/$toe_{elect/heat}$). 0.84 Gtoe of coal are used by the industry, mainly for the iron & steel industry and for cement production (IEA). Coal as fuel for cement production alone is responsible for about 1.6 Gt of CO_2 [12], which corresponds to 0.38 Gtoe of coal for cement. So iron/steel and cement consume 0.84 Gtoe of coal/coke, which is in excellent agreement with the number from IEA.

Tab. S3: *Global cement* 2016 (data from [2]).

Fuel/Energy	Gtoe	t CO_2/toe	Gt CO_2
Base case (2016)			
By-product (conversion of $CaCO_3$)	-	-	1.50
Coal (fuel)	0.34	3.96	1.35
Petroleum coke (fuel)	0.04	3.07	0.12
Electricity	0.031[1]	5.14	0.16
		Total	**3.13**
Best case (measures 1 to 5, i.e. 100% renewable electricity)			
By-product (conversion of $CaCO_3$)	-	-	1.50
Electricity	0.411	0	0
		Total	**1.50**

[1] 0.0073 toe electricity are needed per t cement [15]. For a global cement production of 4.2 Gt, this leads to 0.031 Gtoe electrical energy.

Tab. S4: *Global chemical and petrochemical Industry* 2016 (electricity, fuels and by-products); for feedstocks see Tab. S13.

Standard model (electricity & heat in 2016)			
Fuel/electricity/by-product	**Gtoe**	**t CO_2/toe**	**Gt CO_2**
Electricity and heat[1]	0.17	5.14	0.87
CO_2 related to fuel consumption (11% ammonia, olefins 71%, rest other)[2]			0.56
CO_2 as by-product (ammonia)[2]			0.33
Production of F-gases (incl. 0.1 Gt CO_2 electronics/other industry)[3]			**1.04**
		Total CO_2	**2.8**

Best case (measures 1 to 5)		
Subsector within petrochemisty/chemistry	**Gt CO_2 as by-product**	**Gtoe electricity**
NH_3 based on natural gas	0.23[2]	0.03[4]
Naphtha from crude oil[5]	-	0.15
Heavy oil for 0.15 Gt lubricants/bitumen	-	0.02
Other chemicals	-	0.04[2]
	Total CO_2	**0.24**
N_2O (both in base and best case; mainly HNO_3 production)		**0.20**

1 Estimated based on electricity related CO_2 emissions given by WRI [2].

2 The fuel and feed related CO_2 emissions of 0.89 Gt CO_2 are given by WRI [2]. The majority is related to production of olefins, aromatics etc. by steam crackers: NH_3 production is based on natural gas (72%), coal (22%), and oil (6%) [16]. The CO_2 emissions per t NH_3 for coal are 1.6 t CO_2 as fuel plus 3.6 t CO_2 as feed; for oil we have 1.2 t CO_2 as fuel plus 2.4 t CO_2 as feed, and for natural gas: 0.6 t CO_2 as fuel plus 1.3 t CO_2 as feed [12]. This leads to emissions of NH_3 production (without electricity) of 0.32 Gt CO_2 related to fuel consumption and 0.06 Gt CO_2 as by-product (feed). According to IEA, a naphtha steam cracker consumes 0.35 toe as fuel and 0.02 toe electricity per ton high value chemicals (olefins, aromatics) [17]. Hence, the fuel related CO_2 emissions are 1 t/t product, which leads to 0.4 Gt CO_2 (for 0.4 Gt steam cracker products in 2016). In total, we have 0.79 Gt CO_2 related to these two processes. The difference to the number of WRI [2] of 0.1 Gt CO_2 is regarded as fuel (0.04 Gtoe) for other processes such as methanol production.

3 Fluorinated gases (mainly 1,1,1-trifluoroethane) are mostly (80%) used for refrigeration and air conditioning, as blowing agents in insulating foam or as components in fire-extinguishers.

4 Ammonia synthesis based on natural gas with substitution of fuel demand by electricity needs about 0.17 toe electricity per t NH_3 [12]; in total we get 0.03 Gtoe (0.175 Gt NH_3 in 2016).

5 An electrical steam cracker needs 0.37 toe electrical energy per ton of product (see footnote 2). For 0.4 Gt products (2016) we get 0.15 Gtoe electrical energy.

Tab. S5: Industrial subsector *Non-ferrous metals*

Fuel/Energy	Gtoe	t CO_2/toe	Gt CO_2[1]
Electricity/heat	0.082 electricity	5.14	0.42
Fuel	0.041 coal 0.008 gas 0.002 oil	3.96 2.35 3.07	0.19

[1] The emissions of 0.35 million t CO_2 given by the WRI [2] for non-ferrous metals are a bit too low: Global (primary) Al production is 60 million t/a; typical emissions are 10 t CO_2/t Al, which leads to 0.6 Gt CO_2. 15 MWh electrical energy and 0.4 tonnes of carbon (electrode from petroleum coke) are needed per t Al by smelting/reduction of alumina (fused salt electrolysis). Hence 900 million MWh electrical energy (0.07 Gtoe) and 0.024 Gt carbon (petrocoke) are needed. According to [5], Alumina production accounts for 0.016 Gtoe coal, 0.008 Gtoe gas, 0.002 oil, and 0.002 Gtoe electricity. In total we have 0.072 Gtoe electricity, 0.04 coke/coal, 0.008 Gtoe gas, and 0.002 Gtoe oil. Other non-metals play a minor role, e.g. for Cu (19 million t in 2016) 0.01 Gt CO_2 (0.0003 Gtoe) related to fuels and 0.02 Gt CO_2 to electricity (0.004 Gtoe). For simplification, it is assumed that for Cu and all other non-Fe metals, we have additional 0.001 Gtoe fuels (coal) and 0.01 Gtoe electricity.

Tab. S6: Industrial subsector *Machinery, Food and Tobacco, Paper, pulp and printing* (data from [2]).

Fuel/Energy	Gtoe	t CO_2/toe	Gt CO_2
Electricity/heat	0.094	5.14	0.48
Oil products	0.07	3.07	0.54[1]
Natural gas	0.14	2.35	

[1] allocated to gas and oil (Gtoe) assuming a ratio of 2 to 1.

Tab. S7: Industrial subsector *other industrial processes*[1] (data of [2]).

Fuel/Energy	Gtoe	t CO_{2}/toe	Gt CO_{2eq}
Oil	0.18	3.07	0.55
Natural gas	0.16	2.35	0.38
Electricity/heat	0.22	5.14	1.13
N_2O			**0.05**

[1] According to WRI [2], the emissions of the "other industry sector" (incl. refineries own use and fuel for cement) are 5.3 Gt CO_2, 2.6 Gt CO_2 related to electricity/heat and 2.7 Gt CO_2 to fuels. 1.5 Gt CO_2 are related to fuel (coal) consumption of cement production (Tab. S3) and 0.78 Gt CO_2 to own use of refineries (oil, see Tab. S8). Electricity for own use of power and heat plants and transportation losses are 2 Gt CO_2. Hence, the remaining amounts are 0.42 Gt CO_2 related to fuels (assumed as 0.06 Gtoe oil and 0.11 Gtoe gas) and 0.6 Gt CO_2 related to electr./heat (0.12 Gtoe). According to IEA, 0.1 Gtoe electricity and 0.02 Gtoe oil are used for non-specified users, and 0.1 Gtoe oil and 0.03 Gtoe gas are used for other transformations and losses (0.02 Gtoe gas).

Tab. S8: Energy industry own use (allocated to end user industry [8]).

Energy industry own use of fuels	Gtoe	t CO_2/toe	Gt CO_2
Coal (considered as own use of power plants)	0.080	3.96	0.32
Oil (products) considered as own use of refineries	0.254	3.07	0.78
Natural gas (considered as own use of power plants)	0.278	2.35	0.65

Tab. S9:*Global residential and commercial buildings* 2016 (data from [2]; shares of fuels from [8]).

Fuels	Gtoe	t CO_{2eq}/toe	Gt CO_{2eq}
Standard model (2016)			
Coal	0.11	3.96	0.44
Crude oil products	0.29	3.07	0.89
Natural gas	0.62	2.35	1.46
Biomass/solar	0.13	0	0
Traditional biomass	0.62	0.44	0.27[1]
Electricity and heat	1.13	5.14	5.81
Total	2.9[2]	**-**	**8.87**[2]
Best case (measures 1 to 4)			
Biomass/solar	0.13	-	-
Traditional biomass	0.31[3]	0.44	0.14
Electricity and heat	1.57[4]	-	-
Total	1.91		**0.14**

[1] CO_2 from combustion of traditional biomass (unsustainable share) is included in deforestation, see Tab. S10). Here only CH_4 and N_2O from biomass burning are considered. A typical emission factor of biomass combustion (fuel) is 13 kg CH_4/toe (0.39 t CO_{2eq} /toe). For N_2O, we have 0.17 kg N_2O/toe (0.05 t CO_{2eq}/toe). In total, we get 0.27 Gt CO_{2eq} for CH_4 and N_2O.

[2] 74% of energy consumption and 62% of GHG emissions are related to residential buildings.

[3] Assumption of 50% reduction of the use of traditional biomass

[4] Assumption that (electrical) heat pumps are used instead of natural gas and heating oil. The substitution factor is 0.33 toe electrical energy per toe oil or gas.

Tab. S10: *Global agriculture* 2016 (data from [2] and [8]).

Emissions not related to (fossil) fuels			**Gt $CO_{2,e}$** (share)
CO_2 from burning of agricultural residues			0.89
CH_4 from burning of agricultural residues			0.59
CH_4 from livestock and manure			2.72
CH_4 from rice cultivation			0.64
N_2O from burning of agricultural residues			0.25
N_2O from livestock and manure			0.15
N_2O from agricultural soils			2.03
		Subtotal	7.27 (64.7%)
Emissions related to fuels for agriculture, forestry and fishing			
Fuels	**Gtoe**	**t CO_2/toe**	**Gt CO_2**
Electricity/heat	0.05	5.14	0.31
Coal	0.02	3.96	0.08
Crude oil products	0.11	3.07	0.34
Natural gas	0.01	2.35	0.02
Biomass/biofuels	0.02	0	0
		Subtotal	0.75 (6.7%)
Emissions related to land-use change and waste			**Gt CO_{2eq}**
CO_2 from forest land (deforestation)[1]			1.09
CO_2 from cropland[2]			0.69
CH_4 from landfills			0.94
CH_4 from wastewater			0.49
		Subtotal	3.21 (28.6%)
		Total	**11.23 (100%)**
50% less meat + 50% less food waste (details in Tab. S7)			**8.2**

[1] This is the value according to *WRI*. Deforestation leads to net CO_2 emissions from changes in forestry cover. According to Tab. S9, 0.62 Gtoe of trad. biomass (2.85 Gt CO_2) is used in households in developing countries. Hence, the unsustainable share is 38% (1.09/2.85), in agreement with data from Bailis et al., who estimated that 27 to 34% are unsustainable [18].

[2] CO_2 is emitted when croplands are degraded, which is actually the case on global average.

Tab. S11: Assumptions for change of fuel in (road) transportation (estimation for gasoline and diesel oil and battery electrical or fuel cell car based on [9])

Fuel/engine	Tank-to-wheel efficiency[1] rel. to ICE	Remark
ICE vehicle (ICEV with oil)	1	*Efficiency of oil refinery is 93%*
Battery electric vehicle (BEV)2	4	CO2 emissions depend on electr. mix
H_2-fuel cell vehicle (HFCV)[2]	2	*H_2 from electrolysis with 70% efficiency*

[1] Tank-to-wheel efficiency considered as independent of today´s fuels for road transportation (gasoline, diesel, CH_4, biofuel). Examples: Change of ICEVs consuming 1 Gtoe to HFCV: 0.5 Gtoe H_2 = 0.71 $Gtoe_{elect}$ and for BEV 0.25 $Gtoe_{elect}$. Changes in losses/own use of power plants and of own use of refineries are already considered by the model in sector electricity and industry (own) use.

[2] In the model (measure 2), cars and busses are BEVs and trucks HFCVs.

Tab. S12: Change of food related GHGE for reduction of waste/losses and/or of meat consumption (estimated by data from [8, 10, 25].

Base case 2016	
Food supply chain	**Gt CO_{2eq}**
Transport of food for base case (2016)	0.8 (CO_2)
Food industry (incl. retail & packaging) (base case, 2016)	1.6 (CO_2)
Subtotal	2.4
Agriculture	11.2
Total food	**13.6**
Case of reduced waste and/or reduced meat	
Transport of food for 50% less waste[1]	0.7 (CO_2)
Food industry (incl. retail & packaging) for 50% less waste[1]	1.4 (CO_2)
Subtotal	2.1
Agriculture for less food waste and/or less meat	
Agriculture for 50% less waste	9.8
Agriculture for 50% less meat[2]	9.3
Agriculture for 50% less waste and 50% less meat[2]	8.2
Subtotal	8.2 - 9.8[3]
Total food	**10.3 - 11.9[3]**

[1] Within the food supply chain, 24% of the food (related to kcal) is lost or wasted, 7% agricultural losses, 5% postharvesting losses, 1% processing losses, 3% distribution waste, and 8% consumption waste [24].

[2] for details see also section 4.

[3] These values are only valid for today´s mix of electricity and transportation. For 100% renewable electricity and transportation by battery electric vehicles the absolute numbers and the reduction compared to waste and meat of today is lower (about 20% less reduction of GHG emissions). This effect is considered by the model.

Tab. S13: *Non-energetic use of fossil fuels* 2016 (see also Tab. S4); numbers are used to calculate fuel consumption (data from [8, 11]).

Non-energetic use (base case 2016)	**Gtoe**
Natural gas (feedstock for ammonia and methanol synthesis)	0.17[1,2]
Crude oil (20% for bitumen/lubricants, 80% for olefins and aromatics)	0.62[1]
Coal (feed for ammonia/methanol; not counting blast furnace coke)	0.06[1]

[1] Consumption depends on the structure of the petrochemical and chemical industry (see Tab. S4), which is considered in the model (measure 5).

[2] Number of IEA (0.17 Gtoe gas) most probably includes natural gas also as fuel (for ammonia); 0.12 Gtoe is feed and 0.05 Gtoe is fuel.

Tab. S14: Results of the model for different consecutive measures (part 1). Note that both the global population and the average prosperity (heat demand, use of different modes of transportation, industrial production of materials and goods etc.) are here (simplifying) considered as constant.

n	**Measure M_n**	**$\Delta E_{renew}/\Delta CO_{2eq}$** in toe/t CO_2		**ΔCO_{2eq}** in Gt
		M_0 to M_n	M_{n-1} to M_n	
0	Base case (World 2016)	-	-	0
1	Replacement of coal for electricity by wind/solar	0.09	0.09	10.8
2	M_1 + transport by BEV (cars) and HFCV (trucks)[1]; additional electricity by wind/solar	0.12	0.15	18.1
3	M_2 + sector building 100% based on renewables[2]; additional electr. by wind/solar; 50% less trad. biomass	0.12	0.13	22.0
4	M_3 + electricity (almost) completely from renewables[2]	0.13	0.15	27.4
5	M_4 + industry electrified (steel based on H_2, no F-gases); replacement of fossil fuels for agriculture by renewables	0.16	0.26	35.9
6	M_5 + 50% less meat + 50% less food waste	0.16	0	38.7[3]

[1] Shipping and aviation still based on fuel oil and jet-fuel, respectively. Rail completely electrified.

[2] Modell assumes that nuclear power is still produced as in 2016.

[3] Value for reduction of waste only is 37.1 and value for reduction of meat only is 37.6.

Tab. S15: Results of the model for different consecutive measures (part 2; global population and average prosperity considered as constant).

n	Measure M_n	**Electricity** in Gtoe/a		CO_{2eq} in Gt/a
		total	renewable	
0	Base case (World 2016)	2.66	0.57 (21%)	50.5
1	Replacement of coal for electricity by wind/solar	2.66[1]	1.61 (60%)	39.8
2	M_1 + transport by BEV (cars) and by HFCV (trucks)[2]	3.72	2.67 (72%)	32.5
3	M_2 + buildings based on renewables, -50% trad. biomass	4.24	3.19 (86%)	28.5
4	M_3 + electricity 100% based on renewables	4.24[3]	4.01 (95%)	23.1
5	M_4 + industry electrified, steel based on H_2, no F-gases, replacement of fossil fuels for agriculture by renewables	6.37[3]	6.15 (97%)	14.5
6	M_5 + 50% less meat + 50% less food waste	6.37[3]	6.15 (97%)	11.8

[1] 0.729 Gtoe (27.4% of total) electricity still based on natural gas; the respective numbers for nuclear and oil are 0.227 Gtoe (8.5%) and 0.097 Gtoe (3.6%).

[2] The additional electricity need is again covered by wind and solar electricity, but the same result is reached for other renewables such as hydro, solar thermal, geothermal, and modern biomass. Shipping and aviation still based on fuel oil and jet-fuel, respectively. Rail completely electrified.

[3] 0.227 Gtoe electricity is still based on nuclear energy.

Tab. S16: Regional distribution of capacity of coal power plants 2009 and 2019 [22], share of global capacity, and share of coal in primary energy (PE) supply in 2018 [8].

Country/region	**Capacity in GW** (share)		**Average change of capacity/a** (period 2019 - 2019)	**Share of coal in PE supply**
	2009	2019		
China	581	1005 (49%)	+6%	62%
USA	335	246 (12%)	-3%	14%
India	89	229 (11%)	+10%	45%
Asia other	124	202 (10%)	+5%	22%
EU28	189	143 (7%)	-3%	14%
Former USSR	85	87 (4%)	0%	16%[1]
Africa & Middle East	45	53 (3%)	+2%	7%
Non-EU-Europe	19	28 (1%)	+4%	24%
Latin America	10	18 (1%)	+6%	5%
Other	48	33 (2%)	-4%	-
Total	**1525**	**2044**	**+3%**	**27%**

[1] only Russian Federation

Tab. S17: Data of sector *Total industry including other subsectors such as industry not related to steel, cement & chemistry* (data from [2]).

Standard model 2016		
Subsector	**Gt CO_{2eq}**	**Share**
Iron & steel (see Tab. S2)	4.20	29%
Cement (see Tab. S3)	3.13	22%
Chemical and Petrochemical Industry (see Tab. S4)	3.00	21%
Non-ferrous metals (see Tab. S5)	0.68	5%
Machinery, Food and Tobacco, paper, pulp and printing (see Tab. S6)	1.04	7%
Other industrial processes (excluding refineries; see Tab. S7)	2.45	17%
Subtotal	*14.5*	*100%*
Own use electricity of power & heat plants and losses of electr. transport[1]	2.12	-
Own use of fuels of power plants and refineries[1]	1.75	
Total	**18.4**	

[1] In the model, these two subsectors were simplifying allocated to sector industry, although electricity and fuels are also used in other sectors such as transportation and buildings.

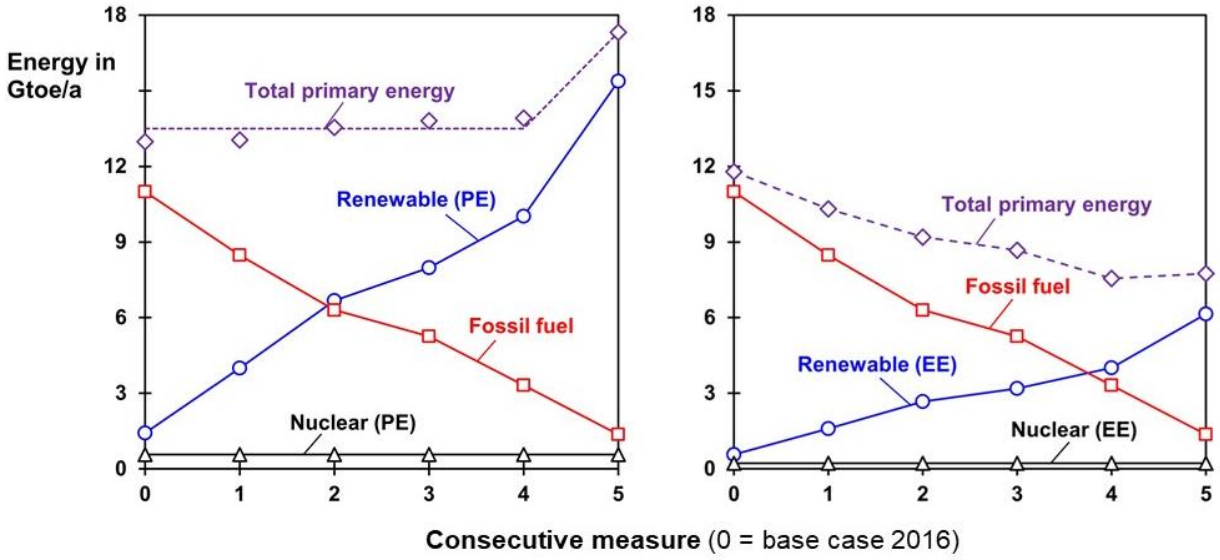

Fig. S1: Global annual energy demand in 2016 and if consecutive measures 1 to 5 are taken (constant population and prosperity). Left: Electricity produced by renewables and nuclear power converted in primary energy (PE) by assuming an efficiency of 40%, i.e. 1 Gtoe electrical energy (EE) equals 2.5 Gtoe PE; right: without EE-to-PE conversion. Fossil fuels counted according to lower heating value.

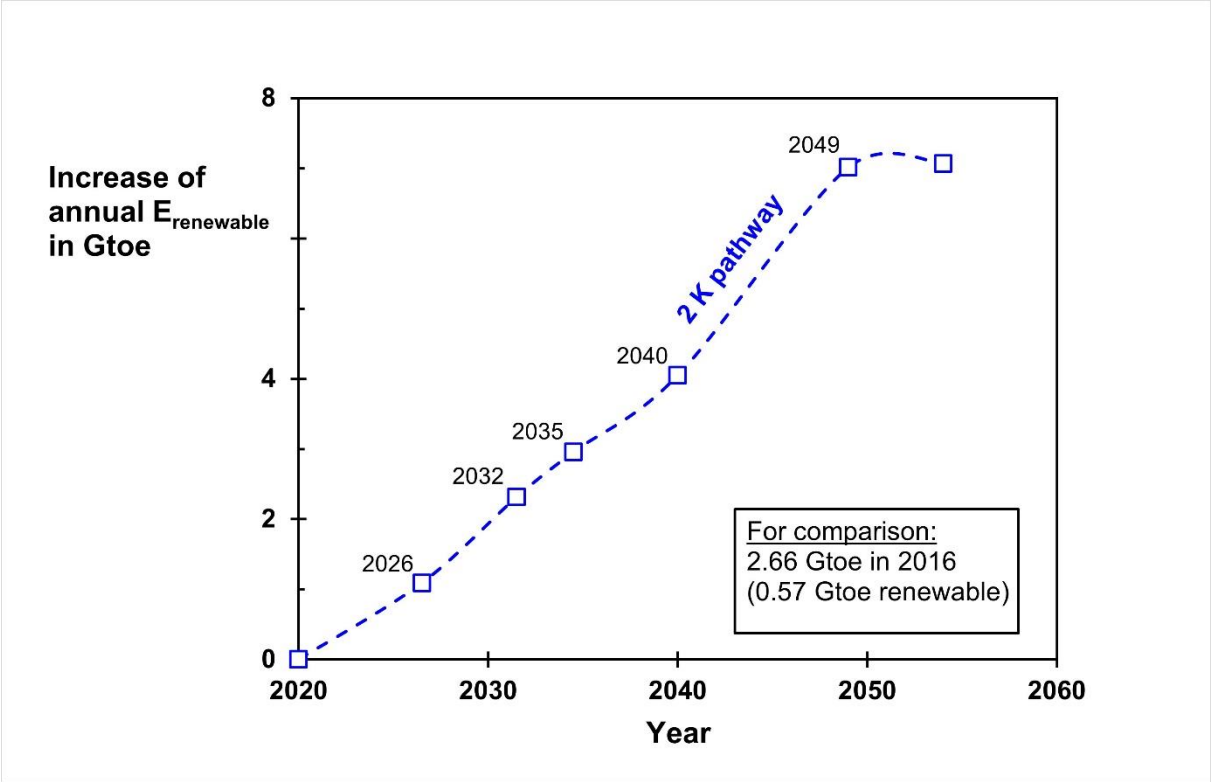

Fig. S2: Increase of global annual renewable electricity production, if the 2 K pathway (see Fig. 9) of stepwise reduction of global GHG emissions is taken.

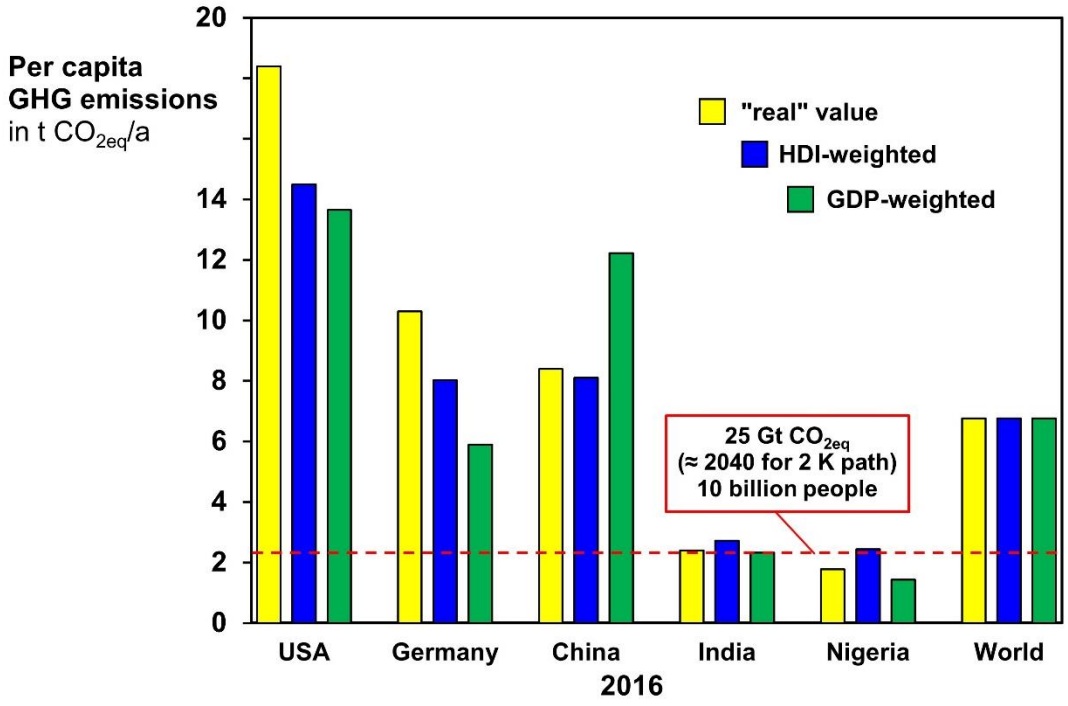

Fig. S3: Annual per capita GHG emissions (incl. LUC) in selected countries and in the world 2016. Not only the "real" values - see Fig. 10 - are shown, but for comparison also HDI-weighted values (real value x $HDI_{global\ average}/HDI_{country}$) and GDP-weighted values (real value x CO_{2eq} per 1000 $ average/CO_{2eq} per 1000 $ of country) are shown; for HDI and GDP values (global and for countries) see Tab. 1.