Supplementary Information for

Growing Metaverse Sector Can Reduce Greenhouse Gas Emissions by 10 Gt CO2e in the United States by 2050

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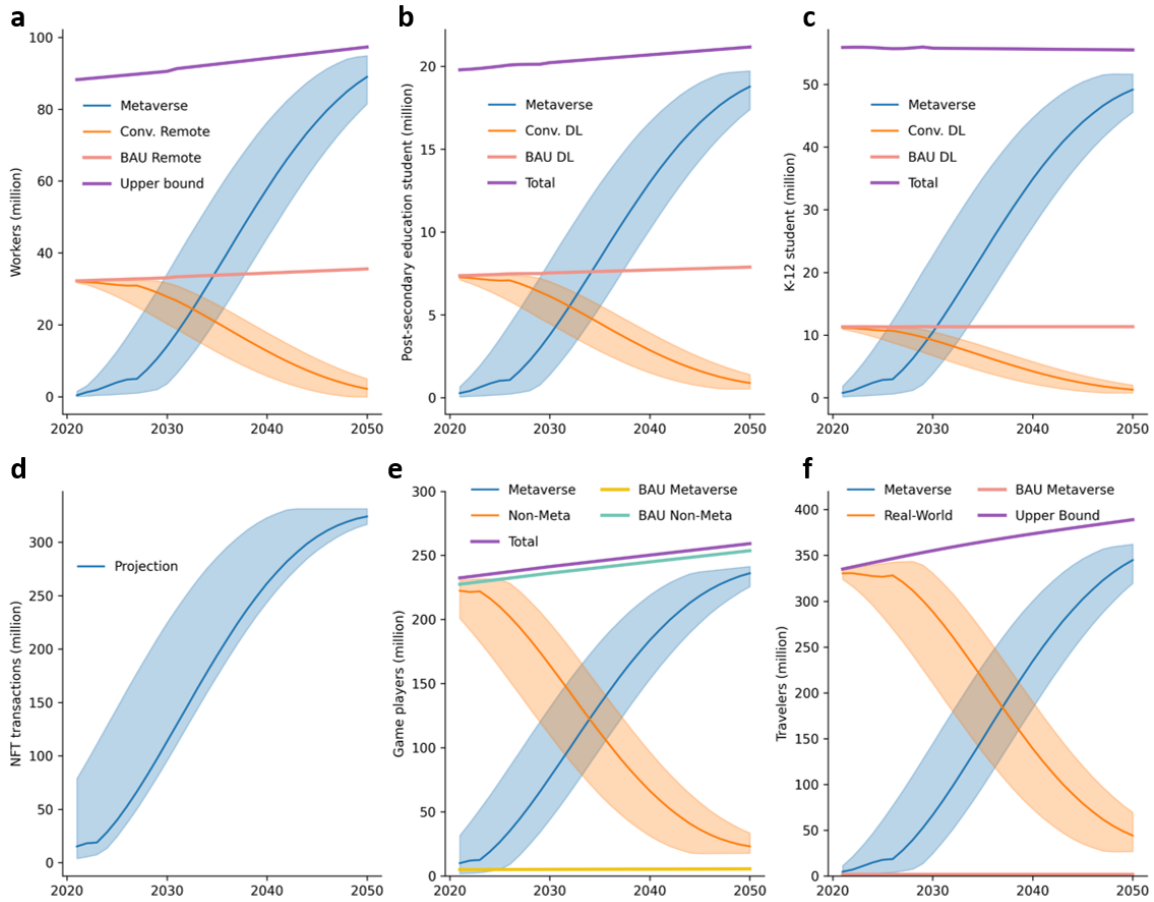
Supplementary Note 1: Adoption curves for the metaverse growth

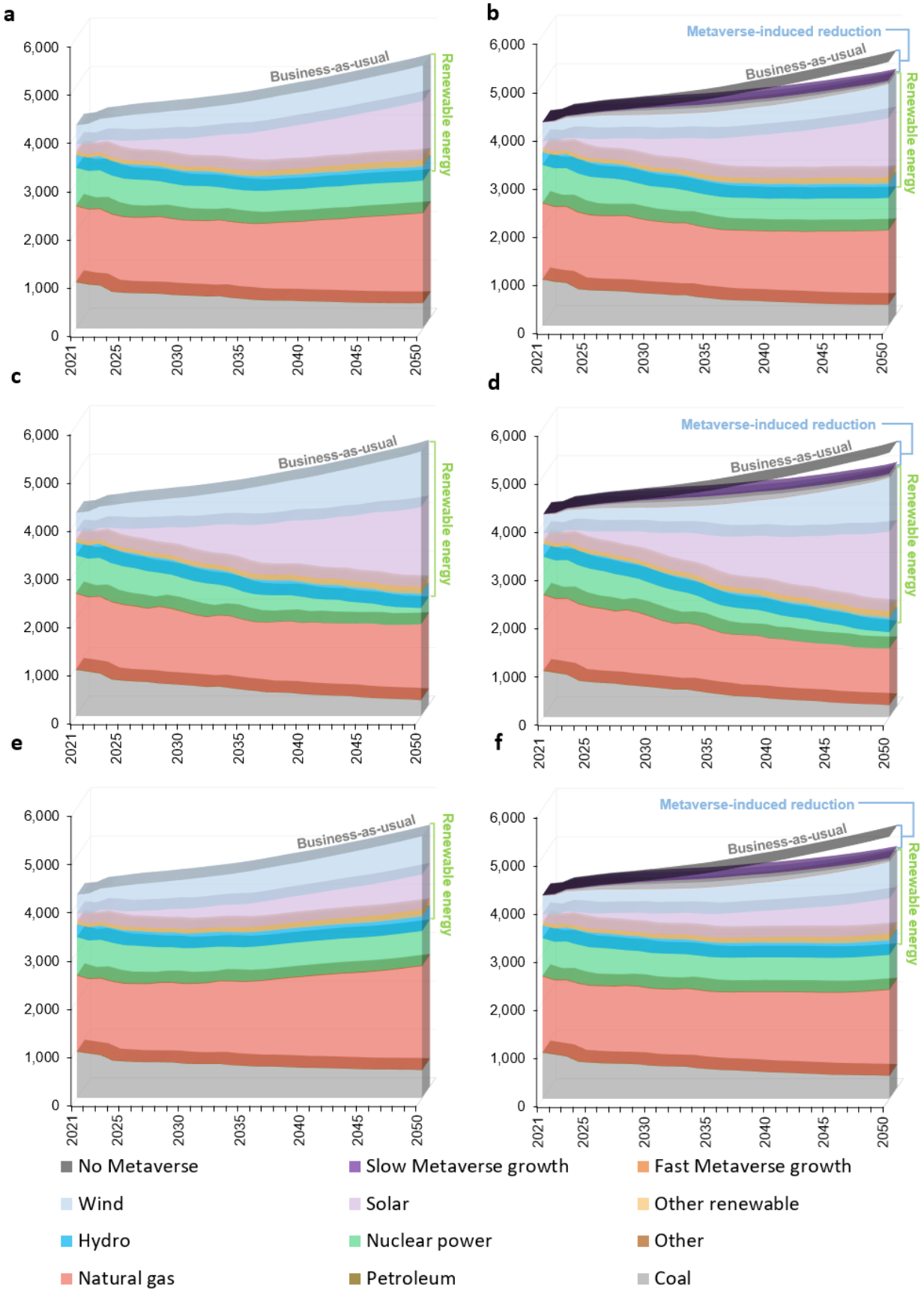
Supplementary Fig. 1 projects the adoption growth trajectories for each of the applications in the metaverse sector, including metaverse-based remote work, virtual traveling, distance learning, gaming, and non-fungible token (NFT). The consequent reduction of the non-virtual counterpart of the metaverse-based applications is also visualized in orange. Distance education in the metaverse is categorized into K-12 and post-secondary. The blue curves and blue areas indicate the nominal expansion trajectory and growth deviations of the metaverse, respectively. The orange curves and orange areas represent the physical-world counterparts for the projected nominal metaverse growth trend and adoption deviations, respectively.



Supplementary Fig. 1 Projected expansion trajectories for metaverse applications and non-virtual counterparts. a, Metaverse-based remote working. **b**, Metaverse-based distance learning for post-secondary education. **c**, Metaverse-based distance learning for K-12 education. **d**, Non-fungible token. **e**, Gaming in the metaverse. **f**, Metaverse-based virtual traveling.

Supplementary Note 2: Electricity consumption for all metaverse growing scenarios

Supplementary Fig. 2 presents the impacts of the metaverse sector growth on the electric power sector by source throughout the coming decades. The stacked areas in each subgraph depict the scenario with the nominal projected metaverse growth trajectory, while the deviations from the slower and faster metaverse adoption deviations are plotted in purple and orange curves. The total annual electricity consumption in the business-as-usual scenario without metaverse industry expansion is presented on the top of each subgraph in grey. Three energy systems projections, namely the reference projection, the projection with low renewable energy cost, and the projection with high renewable energy cost, are obtained from the Energy Information Administration (EIA)[1].


a
b
c
d
e
f
Business-as-usual
Metaverse-induced reduction
Renewable energy
6,000
5,000
4,000
3,000
2,000
1,000
0
2021
2025
2030
2035
2040
2045
2050
No Metaverse
Slow Metaverse growth
Fast Metaverse growth
Wind
Solar
Other renewable
Hydro
Nuclear power
Other
Natural gas
Petroleum
Coal

Supplementary Fig. 2 Impacts of the metaverse sector growth on the electric power systems in TWh by year and energy source. a, Reference scenario without rapid growth of the metaverse. **b**, Reference scenario with the rapid growth of the metaverse. **c**, Scenario with low renewable energy cost and without rapid metaverse growth. **d**, Scenario with low renewable energy cost and the rapid metaverse growth. **e**, Scenario with high renewable energy cost and without rapid metaverse growth. **f**, Scenario with high renewable energy cost and the rapid metaverse growth. Grey surfaces in scenarios with metaverse growth (**b**, **d,** and **f**) indicate the overall electricity consumption in the corresponding business-as-usual scenarios (**a**, **c,** and **e**), while the purple and orange curves depict the deviations owing to the slower or faster metaverse growth compared to the projected nominal growth rate.

Supplementary Note 3: Energy efficiency projections

Supplementary Table 1 lists the projected power efficiency improvements for electricity-consuming activities throughout the metaverse expansion period of three decades. Supplementary Table 2 presents the energy efficiency improvements for natural gas and petroleum, and the fuel efficiency of petroleum is measured by miles per gallon (MPG). The market share and power efficiency information of gaming platforms are listed in Supplementary Table 3.

Supplementary Table 1 Electricity efficiency projections by activity throughout the metaverse industry expansion period[1-4].

Year	Space Heating	Space Cooling	Water Heating	Refrigeration	Cooking	Freezer	Light	Dishwasher	Computer
2021	100%	100%	100%	100%	100%	100%	100%	100%	100%
2022	101%	101%	101%	102%	100%	102%	104%	101%	105%
2023	102%	103%	101%	103%	100%	103%	108%	102%	111%
2024	103%	104%	102%	105%	100%	105%	112%	103%	117%
2025	104%	106%	102%	107%	100%	107%	115%	104%	123%
2026	105%	107%	103%	108%	100%	108%	118%	105%	129%
2027	105%	108%	104%	110%	101%	110%	121%	106%	136%
2028	106%	110%	104%	111%	101%	111%	125%	106%	143%
2029	107%	111%	105%	112%	101%	112%	129%	107%	151%
2030	108%	112%	105%	114%	101%	114%	135%	108%	159%
2031	108%	113%	105%	115%	101%	115%	142%	108%	167%
2032	109%	114%	106%	116%	101%	116%	148%	109%	176%
2033	110%	114%	106%	117%	101%	117%	154%	110%	185%
2034	110%	115%	106%	118%	101%	118%	159%	110%	195%
2035	111%	115%	106%	119%	101%	119%	165%	110%	205%
2036	111%	116%	106%	119%	101%	119%	170%	111%	216%
2037	111%	116%	106%	120%	101%	120%	175%	111%	227%
2038	111%	116%	106%	120%	101%	120%	179%	111%	239%
2039	111%	117%	106%	121%	101%	121%	183%	112%	252%
2040	112%	117%	106%	121%	101%	121%	188%	112%	265%
2041	112%	117%	106%	121%	101%	121%	193%	112%	279%
2042	112%	117%	106%	121%	101%	121%	198%	113%	293%
2043	112%	117%	106%	121%	101%	121%	202%	113%	309%
2044	112%	117%	106%	121%	101%	121%	205%	113%	326%
2045	112%	117%	106%	121%	101%	121%	208%	113%	342%
2046	112%	117%	106%	121%	101%	121%	211%	113%	361%
2047	112%	117%	106%	121%	101%	121%	214%	113%	379%
2048	112%	117%	106%	121%	101%	121%	216%	114%	400%
2049	112%	117%	106%	121%	101%	121%	219%	114%	420%
2050	112%	117%	106%	121%	101%	121%	221%	114%	442%

Supplementary Table 2 Fossil fuel efficiency projections by activity for natural gas (NG) and for transportation petroleum (MPG stands for miles per gallon) [1,3-5].

Year	Gasoline MPG	Diesel MPG	NG for Space Heating	NG for space Cooling	NG for Water Heating	NG for Cooking	NG for Clothes Dryers
2021	24.5	10.7	100%	100%	100%	100%	100%
2022	25	10.9	101%	100%	101%	100%	100%
2023	25.5	11.1	101%	100%	101%	100%	100%
2024	26	11.4	102%	100%	101%	100%	100%
2025	26.5	11.6	102%	100%	102%	100%	100%
2026	27	11.8	102%	100%	102%	100%	100%
2027	27.4	12	103%	100%	102%	100%	100%
2028	27.8	12.1	103%	100%	102%	100%	100%
2029	28.2	12.3	104%	100%	102%	100%	100%
2030	28.6	12.5	104%	100%	102%	100%	100%
2031	28.9	12.6	104%	100%	102%	100%	100%
2032	29.2	12.8	105%	100%	101%	100%	100%
2033	29.5	12.9	105%	100%	101%	100%	100%
2034	29.8	13	105%	100%	101%	100%	100%
2035	30.1	13.1	105%	100%	101%	100%	100%
2036	30.3	13.2	105%	100%	101%	100%	100%
2037	30.5	13.3	105%	100%	101%	100%	100%
2038	30.7	13.4	105%	100%	101%	100%	100%
2039	30.9	13.5	105%	100%	101%	100%	100%
2040	31.1	13.6	105%	100%	101%	100%	100%
2041	31.3	13.7	105%	100%	101%	100%	100%
2042	31.4	13.7	105%	100%	101%	100%	100%
2043	31.6	13.8	105%	100%	101%	100%	100%
2044	31.7	13.8	105%	100%	101%	100%	100%
2045	31.8	13.9	105%	100%	101%	100%	100%
2046	31.9	13.9	105%	100%	101%	100%	100%
2047	32.1	14	105%	100%	101%	100%	100%
2048	32.2	14	105%	100%	101%	100%	100%
2049	32.2	14.1	105%	100%	101%	100%	100%
2050	32.3	14.1	105%	100%	101%	100%	100%

Supplementary Table 3 Market shares and power efficiency of gaming platforms in 2021[6-8].

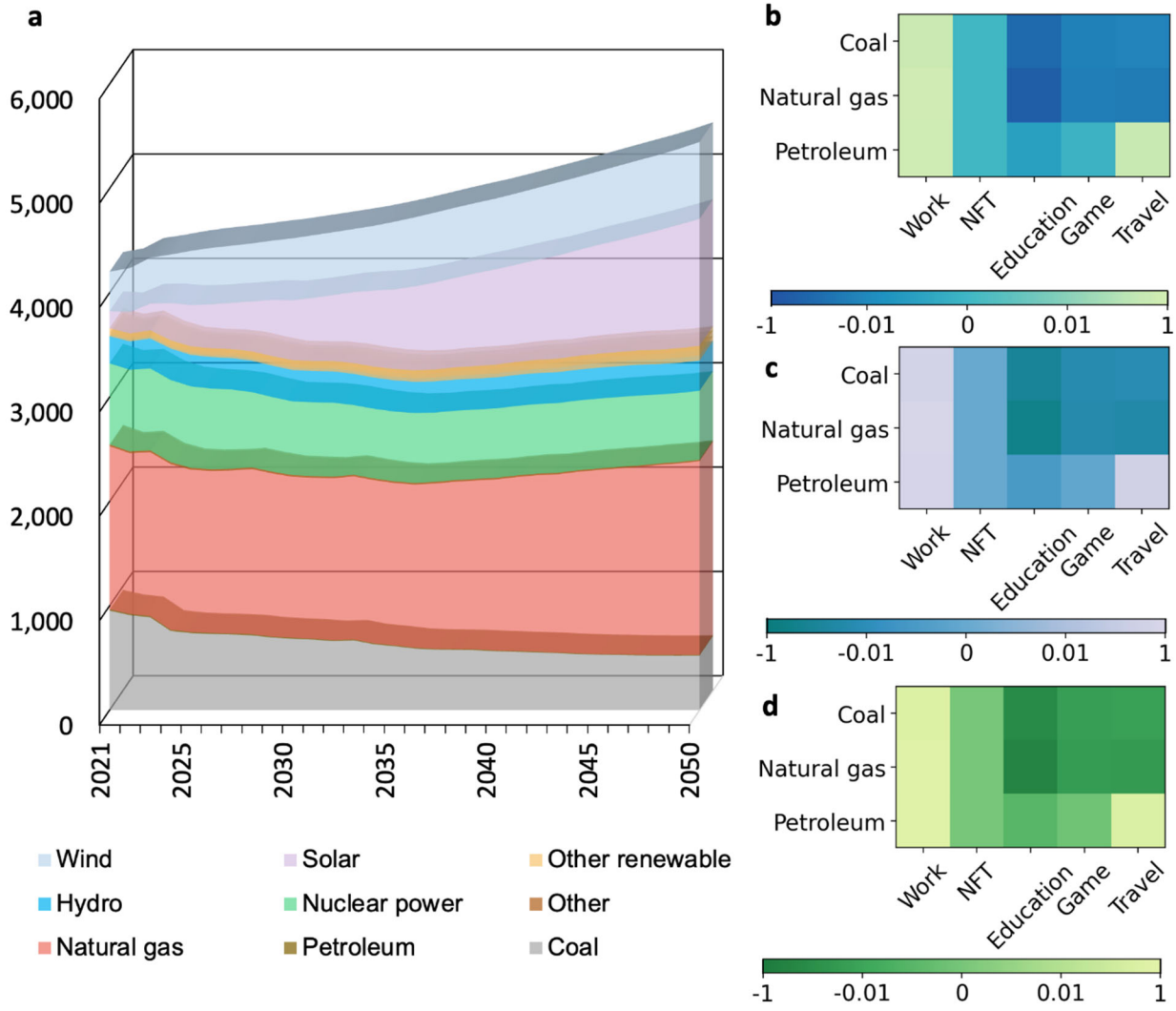
Gaming platform	Market share	Power efficiency (W)
Windows based desktop/laptop	15.6%	400
Sony PlayStation 4	13.1%	120
Apple based mobile device (iPod/iPad/iPhone)	10.1%	5.4
Microsoft Xbox 360	9.9%	160
Microsoft Xbox One	9.7%	105
Sony PlayStation 3	7.3%	170
Apple based desktop/laptop	6.9%	40

Nintendo Wii U	6.0%	34
Nintendo 3DS/2DS	4.9%	4.1
Nintendo New 3DS/3DS XL	3.4%	5.8
Sony PlayStation Vita	3.4%	7.5
Nintendo Wii	3.3%	40
Nintendo Switch	2.9%	16
Sony PlayStation 2	0.7%	50
Nintendo DS/Lite	0.7%	2.3
Sony PSP	0.5%	3.5
Nintendo DSI/DSI XL	0.4%	3.1
Microsoft Xbox	0.2%	74
Nintendo 64	0.2%	19
Sony PSP Go	0.2%	3.5
Nintendo Game Boy Advance/SP	0.2%	1.8
Nintendo GameCube	0.2%	23
Sony PlayStation	0.2%	10
Nintendo Game Boy/Color	0.1%	0.7

Supplementary Note 4: Deviations in the scenario without metaverse

Supplementary Fig. 3 lists the breakdowns for annual electricity consumption by source in the scenario without metaverse, as well as the emissions breakdowns by metaverse-based application and by energy source. Emissions breakdowns in **b-d** are presented by greenhouse gas (GHG), NO_x, and SO_x.

Supplementary Table 4 lists the prospective analysis results for the scenario without the metaverse industry. Namely, there exists no metaverse-based application in this scenario. The impacts are represented by deviations compared to the business-as-usual scenario with the reference energy system projection. The energy analysis results include deviations in domestic total energy consumption and nationwide electricity usage. The emissions are quantified by greenhouse gas, NO_x, and SO_x.



Supplementary Fig. 3 Electricity consumption breakdowns, greenhouse gas (GHG), NO_x, and SO_x breakdowns for the scenario without metaverse. a, annual electricity consumption breakdowns by source and by year for the scenario with no metaverse. **b-d**, Emissions increases and reductions by metaverse application and by energy source in 2050 for GHG, NO_x, and SO_x. The values are measured by TWh in **a**. The units for **b**, **c**, and **d** are Mt CO_2e, kt NO_x, and kt SO_x, respectively.

Supplementary Table 4 Energy consumption, greenhouse gas emissions, and gaseous air pollution deviations throughout the analysis period of three decades in the scenario without metaverse.

Deviations in the scenario without metaverse	Amount
Domestic total energy consumption increase (PJ)	764.7
Domestic electricity consumption increase (TWh)	49.2
Total greenhouse gas emissions increase (Mt CO2e)	63.8
Total NO_x emissions increase (kt)	56.9
Total SO_x emissions increase (kt)	14.6

References

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