Energy &
Environmental
Science

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

Journal:	*Energy & Environmental Science*
Manuscript ID	EE-ANA-01-2023-000081.R1
Article Type:	Analysis
Date Submitted by the Author:	22-Mar-2023
Complete List of Authors:	Zhao, Ning; Cornell University You, Fengqi; Cornell University,

Broader Context

The metaverse is a seamless convergence of physical and digital worlds that marks the next stage of human-machine interface in a 3D virtual world, and the booming metaverse sector is expected to reach billions of users and trillion-dollar global annual revenue in the coming decades. Adopting the metaverse can significantly reform physical-world activities in a digital manner, such as conveniently relocating working, learning, and traveling to interconnected virtual worlds, which will lead to consequent impacts on the energy sector, the environment, and climate change mitigation. Here, we perform prospective analyses on the metaverse-induced climate impact, environmental sustainability, and energy consumption deviations in the United States through 2050, by incorporating multiple adoption trajectories for the slow, nominal, and fast expansion of the metaverse industry. This work establishes the methodology to study both the impacts from the expansion of metaverse applications and the displacement impacts of the metaverse growth for the avoided energy and emissions associated with reduced real-world activities. It is projected that deeply integrating metaverse with various everyday social, business, and personal activities leads to combined positive effects on climate change mitigation, GHG emission reduction, air quality improvement, and energy supply alleviation, contributing to the decarbonization and climate goals.

ARTICLE

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

Received 00th January 20xx,
Accepted 00th January 20xx

DOI: 10.1039/x0xx00000x

Ning Zhao[a] and Fengqi You*[abc]

The metaverse, an immersive combination of the physical and digital world, is becoming a booming industry with the potential to reach billions of users before 2030, but the climate impacts due to its rapid expansion have not been quantitatively understood. Here we show that the growing metaverse sector will facilitate climate change mitigation, through prospective analyses that systematically investigate five prominent metaverse-based applications for working, traveling, education, non-fungible token, and gaming. We find that the increasing metaverse adoption can reduce the global surface temperature by up to 0.02 °C before the end of this century and lower the greenhouse gas emissions by 10 Gt CO2e throughout the expansion period, based on different metaverse growth projections in the United States. The metaverse growth accelerates decarbonization and improves air quality, through alleviating air pollutant emissions by 10–23% and saving 10% of nationwide energy use by 2050 compared to the projections without further metaverse sector expansion. Therefore, it is suggested that the environmentally responsible adaptation of the metaverse growth requires transformations of domestic energy supply and benefits implementation of less aggressive climate policies.

Introduction

The metaverse is a seamless convergence of physical and digital worlds that people can access for working, entertainment, relaxing, education, and socializing, and it marks the next stage of human-machine interface in a 3D virtual world by harnessing the technology advances in Web 3.0, blockchain, virtual reality and augmented reality (1-5). The first two decades of the 21st century have witnessed the transformation of the mainstream internet experience from text-based interactions like emails to media-based interactions such as videos and live streams. In the coming decades, metaverse technologies are projected to infiltrate every sector of the economy and grow into a billion-user sector, of which the market opportunity is estimated to be over $1 trillion in global annual revenues (6-8). Furthermore, Big Tech and industrial companies are investing heavily in the metaverse sector, such as NVIDIA, Microsoft, Meta, and Siemens. On the business side, 71% of global executives believe that the metaverse will positively impact their organization, and 42% of them state that such impacts will be breakthroughs or transformational (9).

To provide a smooth, responsive, and immersive virtual experience, the metaverse incorporates a series of supporting technologies, such as the internet, blockchain, virtual reality, and augmented reality. It is worth noting the relationship between the metaverse and its supporting technologies, as the metaverse and these technologies are not independent of each other. On the contrary, it is necessary to harness these supporting technologies for realizing and adopting any metaverse application. Consequently, the vast adoption of metaverse applications can significantly reform various physical-world activities in a digital manner. For instance, the metaverse can conveniently relocate working, learning, and traveling to interconnected virtual worlds, which could be a step further compared to impacts brought by smartphones and the internet, in terms of how technological advances modify and improve experiences and communications. The invention of the smartphone and the internet have revolutionized the lives of billions of people around the world and transformed a wide range of economic activities during the past decades. Similarly, with the recent advances in metaverse-dependent information and communication technologies, it is expected that the metaverse sector is to grow and expand in the following decades, which will replace various physical world activities with digital alternatives in interconnected 3D virtual worlds.

In the context of climate change mitigation (10), the environmentally responsible adaptation of the metaverse industry growth requires understanding the potential climate impacts associated with the emerging metaverse-related technologies and their collateral effects on physical-world activities. The growing metaverse sector can bring revolutionary changes to a wide range of human activities, which are expected to affect the global climate and decarbonization owing to the significant metaverse-induced deviations in energy consumption, greenhouse gas (GHG) emissions, and air pollution. A careful scientific analysis of the energy, environmental, and climate impacts of the metaverse industry

a. Systems Engineering, Cornell University, Ithaca, New York, 14853, USA
b. Robert Frederick Smith School of Chemical and Biomolecular Engineering, Cornell University, Ithaca, New York, 14853, USA
c. Cornell Atkinson Center for Sustainability, 340 Tower Road Cornell University Ithaca, Ithaca, NY, 14853, USA
*Corresponding author. Phone: (607) 255-1162; Fax: (607) 255-9166; E-mail: fengqi.you@cornell.edu

based on its potential growth projections can provide valuable insights into the policy-making process on sustainable development that accommodates the global trend of future metaverse expansion. Cryptocurrency serves as a counterexample for the shortage of studies on energy and emissions projections at the early adoption stage, leading to an energy-intensive industry that consumes over 100 TWh of electricity per year globally, more than the electricity used by the whole of Argentina. Consequently, the greenhouse gas emissions associated with the energy consumption of cryptocurrencies require numerous efforts to offset. For instance, it is estimated that bitcoin mining accounts for around 57 million tons of CO_2 in 2021, which requires planting 300 million new trees to offset (11). On the other hand, incentivizing cryptocurrency mining may be beneficial for the energy systems decarbonization and promoting environmental sustainability by facilitating grid balancing (12), reducing electricity curtailment (13), and enhancing the penetration of renewable energy penetration (14). Furthermore, converting assets to tokens on blockchain platforms, such as non-fungible tokens (NFTs), presents valuable opportunities for increased environmental sustainability (15). NFTs are a distinct form of cryptocurrency that can signify ownership of digital or physical assets. Each NFT is unique and irreplaceable, allowing them to represent items within the metaverse. Utilizing blockchain technology, NFTs provide a secure way of trading virtual assets in the metaverse. However, assessing the energy and environmental impacts associated with NFTs remains a challenge due to their reliance on underlying blockchains remains a challenge.

It could have helped the policymakers to project the impacts of blockchain technology expansion at the early stages, which can lead to more sustainable national long-term strategies to accommodate emerging technologies. Similarly, it would significantly benefit the preparation of metaverse expansion to study and project such growth in terms of the energy, environment, and climate impacts before the rapidly-expanding stage of the metaverse sector. Although the environmental impacts of emerging information and communications technologies (ICTs) and decarbonization technologies have been studied (16-25), the advantages and drawbacks of the metaverse on environmental sustainability have only been discussed separately in the media (26), and no research article has projected the climate impacts of the growing metaverse sector systematically, highlighting the knowledge gap for improving the understanding of how the metaverse boom affects the global climate. To fill the knowledge gap, this study aims to comprehensively investigate the metaverse-induced effects on climate change mitigation, decarbonization, air quality improvement, and energy saving, by incorporating major applications in the metaverse industry and their corresponding physical-world counterparts. We systematically explore the climate impacts of metaverse applications, including metaverse-based remote work, virtual traveling, distance learning, gaming, and NFT, as these applications represent the most prominent use cases in the metaverse sector (7, 27). We also analyze and compare with their physical-world counterpart activities, such as on-site working, in-person learning, tourism in the physical world, and conventional video game, which account for a large share of nationwide energy consumption, greenhouse emissions, and gaseous air pollution. Note that these physical-world counterpart activities can be gradually replaced by virtual alternatives with the growth of the metaverse sector. It is also worth noting that the growth investigated in this study corresponds to the metaverse sector, and no specific product or company is involved in providing services to a metaverse application in the analysis.

Here we study the climate impacts resulted from the growing metaverse sector in the next three decades until 2050 when the metaverse industry is reaching the maximum adoption level based on our projection. In this work, we focus on the metaverse growth in the United States, as it takes the largest share of the metaverse market and provides most of the metaverse development companies among all countries (28). We project three adoption scenarios for the slow, nominal, and fast growth of the metaverse sector, based on the technology diffusion curves of a series of modern relevant technologies. Technologies introduced before the Second World War are not included in projecting the metaverse growing scenarios, because their expansion trajectories show clear differences from that of the modern technologies, indicating that these technologies are unsuitable for representing the adoption trends of modern relevant technologies. The metaverse-induced climate and energy systems impacts are innovatively quantified and aggregated into two categories, namely the extra energy needed for the increasing adoption of the metaverse technologies and the avoided energy consumption associated with the physical-world counterpart activities. The GHG and air pollutant emissions resulted from the metaverse boom are calculated for all types of energy sources and end uses. The climate impacts of the growing metaverse sector are illustrated by the emulation from the Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC), a widely used climate model in various Intergovernmental Panel on Climate Change (IPCC) assessment reports (29) and research articles (30). We analyze the metaverse-induced impacts on climate change mitigation through a series of indicators such as surface temperature, atmospheric carbon dioxide concentration, and effective radiative forcing.

The key findings and novelties of this work include:

- Metaverse growth trajectories for the slow, nominal, and fast expansion of metaverse-based applications are originally projected through 2050, based on the 25^{th}, 50^{th}, and 75^{th} percentile of the adoption data for modern relevant technologies, along with the associated decreasing activity levels of their non-metaverse counterparts, including on-site working, in-person learning, tourism in the physical world, and conventional video game, which stand for the most prominent use cases that the metaverse will significantly transform.
- The growth of the metaverse industry will benefit climate change mitigation and has the potential to reduce the global surface temperature by up to 0.02 °C, lower the atmospheric CO_2 concentration by 4.0

ppm, and decrease the effective radiative forcing by 0.035 W/m^2, as the expanding metaverse sector will reduce the emissions of 570 Mt CO_2e, 505 kt NOx, and 118 kt SOx in the United States by the end of the prospective analysis period.

- The metaverse industry is projected to lower the total domestic energy consumption by 92 EJ during its expansion from 2022 to 2050. This reduction surpasses the annual nationwide energy consumption of all end-use sectors in previous years. Furthermore, swifter adoption of metaverse-based applications may lead to greater energy savings, as determined by quantifying the deviations in climate-related energy consumption induced by the metaverse.

The findings of this work indicate that the vast expansion of the metaverse industry will contribute to climate change mitigation, accelerating decarbonization and energy transition, and reducing gaseous pollutant emissions, which provide insights for the policymakers on actively adapting to the metaverse growth, in order to achieve the climate goals and net-zero targets. The policy implications of this work are listed as follows:

- Climate goals: The metaverse industry growth can accelerate the progress to achieve the net-zero emissions targets, as the growth contributes to the decline of fossil fuel consumption and lowers the annual GHG emissions by around 570 Mt CO_2e before 2050, suggesting that less aggressive climate policies and more flexible decarbonization strategies can be implemented.
- Environmental policy: The increasing adoption of metaverse applications can alleviate air pollutant emissions by 10–23% through reduced transportation and commercial energy usage, suggesting that metaverse-based remote working, distance learning, and virtual traveling can be advocated to improve air quality.
- Energy policy: The energy systems should be transformed to accommodate the energy consumption deviations and the increasing renewable energy shares resulted from the growing metaverse industry, by means of incentivizing distributed renewable energy generation, increasing the energy supply for the residential sector, and reducing the energy provided to the commercial, industrial, and transportation sectors.

Methods

Projection of the metaverse adoption growth

We projected three adoption curves for the slow, nominal, and fast expansion of the metaverse, based on the technology diffusion trends of a series of modern relevant technologies. Specifically, the adoption curves are derived based on 18 post-World War II technologies or information technology (IT) applications that have been invented and commercially utilized, including cellular phones, color TVs, computers, e-book readers, internet, podcasting, smartphones, social media, tablets, debit cards, radio, refrigerators, disk brake, electronic ignition, microwave, power steering, radial tires, shipping container port infrastructure. For each technology, the data for technology diffusion (31, 32) illustrates the percentage of the United States households with access or adoption over a series of years, beginning with the introduction of the technology. The technologies that started their commercial application before the Second World War are not included while projecting the adoption curves for the metaverse industry. This is because the expansion trajectories of these technologies show clear differences from the adoption curves of the modern ones, indicating that the diffusions of technologies introduced before 1945 are not suitable for representing the growth trajectory of the metaverse.

The expansions for applications in the metaverse depict the yearly level of technology adoption that increases with time. The adoption trends are projected based on the adoption data obtained from the modern relevant technologies introduced after the Second World War, following the methodology adopted in a published paper (32). Three types of scenarios are projected according to different metaverse expansion trajectories, namely the slow, nominal, and fast growth. The nominal adoption curve is obtained following the fitted curve with the coefficient of discrimination (R^2) of over 0.99, according to the median adoption levels of the selected reference technologies and IT applications. Similarly, the slow-expanding adoption curve shown on the bottom is projected based on the 25th percentile of the technology diffusion data, and the fast growth trajectory is obtained following the 75th percentile of the adoption data. Following the projected adoption curve, the growing trajectories of metaverse-based working and its non-metaverse counterpart are shown in Fig. 1**d**, while the growth for the other applications within the metaverse sector is presented in Supplementary Fig. 1. Note that a high-speed network is a prerequisite for metaverse adoption, as the metaverse experience generally involves real-time interactions with other participants, which will be infeasible without a reliable network of high bandwidth and low latency (33). To incorporate this factor while projecting the metaverse adoption scenarios, the households and people that have no access to such reliable networks are excluded from the potential diffusion of the metaverse technologies, based on the data from the Federal Communications Commission (34). In terms of coverage, different upper limits are included for different metaverse applications. For instance, the number of workforce, K-12 students, and college students projected from government agencies are considered while projecting the adoption of the metaverse applications for work and education. Furthermore, for certain applications, such as metaverse-based working and education, the trade-offs and replacements of the conventional remote working and distance learning with their alternatives in the metaverse are also considered when we project the growth scenarios, as shown in Supplementary Fig. 1. Besides, devices for virtual reality and augmented reality are utilized for the metaverse-based applications, while they are not required for the conventional remote working and distance learning.

Quantification of metaverse-induced energy systems impacts

The quantification of the metaverse-induced climate-related energy systems impacts can be categorized into two parts, namely the additional energy consumption associated with increasing usages for the applications of the metaverse industry and the energy needed for the physical-world activities that will be replaced by their alternatives in the metaverse.

The first part of energy quantification corresponds to the energy consumption of the additional activities resulted from the expansion of the metaverse, including the energy usage for the metaverse-related devices and for longer hours of staying at the residence. One component of the first part is the energy consumption of the metaverse-dependent equipment, including the additional energy for end-use devices, data centers, and the network infrastructure. The end-use devices include augmented reality and virtual reality headsets, laptop, desktop, and video game consoles, which changes across different metaverse-based applications (35). The energy consumption of the end-user devices is projected based on their power efficiency, annual usage hours, and the market share of each metaverse-dependent device. The extra energy needed for data centers and network infrastructure is estimated according to the additional network traffic volume (36) resulted from the vast expansion of the applications of the metaverse sector, while considering the energy efficiency improvements and the electricity consumption for different types of network traffic (37). For energy efficiency, an annual power efficiency improvement of 3% is applied for the end-user devices, and the network-related equipment is assumed to improve its energy efficiency by 5% every year (38). Another component of the first part is the extra energy consumed due to the long hours of staying at the residency while using metaverse-based applications. The additional energy consumption represented by electricity and fossil fuels can be estimated individually, given the annual extra hours of residential stay and the consumption increase for each energy type (39). Note that energy efficiency improvements are factored into calculating the avoided energy. For instance, electricity-consuming activities at the residence include space cooling, space heating, refrigeration, and lighting, among others. The share of electricity usage for each activity and its projected energy efficiency improvement are estimated based on data and reports from the administrative agency (40, 41). Thus, metaverse-induced electricity increases in residences are calculated while correcting for the deviations from the changes in power efficiency in a bottom-up manner. Similarly, we incorporate the fossil fuel-consuming activities and their individual projected energy efficiency improvements when we estimate the residential fossil fuel consumption increases resulted from the metaverse expansion for the next three decades until 2050.

The second part of estimating the metaverse-induced climate-related energy impacts is to quantify the avoided energy consumption (42) associated with the non-virtual counterpart activities that are replaced by the metaverse-based alternatives. The electricity and fossil fuel consumed by the non-metaverse counterparts in the physical world are projected for each application individually. The energy consumption is calculated across a series of component activities in a slightly different approach compared to what we apply in calculating the first part, as the component activities vary for different non-virtual counterparts in the physical world. For instance, the share of natural gas used for cooking in lodging facilities (counterpart to metaverse-based virtual travels) is around ten times the value of the corresponding share in the offices (counterpart to remote working in the metaverse). Therefore, we estimate the metaverse-induced avoided energy consumption of the non-virtual counterparts using a bottom-up approach that investigates multiple component energy-consuming activities and their efficiency improvements for each metaverse application across the prospective analysis period, leading to energy consumption reductions compared to the business-as-usual scenarios without metaverse growth. The energy consumption data and efficiency projections of the physical-world facilities in which the counterpart activities of the metaverse applications take place are obtained from studies conducted by administrative agencies (40, 43). The avoided energy consumption for transportation is quantified for each application in the metaverse. The conveyance selections and distances for different transportation purposes associated with the non-metaverse counterpart can be calculated from the statistics published by the Department of Transportation (44, 45). The fuel efficiency improvements throughout the prospective analysis periods are incorporated while estimating the energy consumption, following the projections from the Bureau of Transportation Statistics (46). In addition, note that the rebound effects associated with varying energy price and energy production variations are not included (47), as metaverse expansion has direct impacts on the demand side of the energy sector instead of energy production and pricing. In comparison, the displacement impacts of the metaverse growth have been investigated in this study to measure the additional and avoided energy and emissions related to activity changes induced by the metaverse, and involving the rebound effects from energy efficiency improvements and economic behaviors can be a valuable research direction (48).

We investigate the metaverse-induced energy impacts through nine scenarios, based on three different metaverse growth projections of slow, nominal, and fast expansion, and three energy systems projections, namely the reference projection, the projection with low renewable energy cost, and the projection with high renewable energy cost. The baseline projections without the extensive metaverse expansion are sourced from the United States Energy Information Administration (EIA) (40). According to EIA forecasts, the three energy systems projections without the metaverse adoption growth include the reference scenario, low renewable energy cost scenario, and high renewable energy cost scenario. These three business-as-usual scenarios serve as references to highlight the metaverse-induced energy systems variations. In

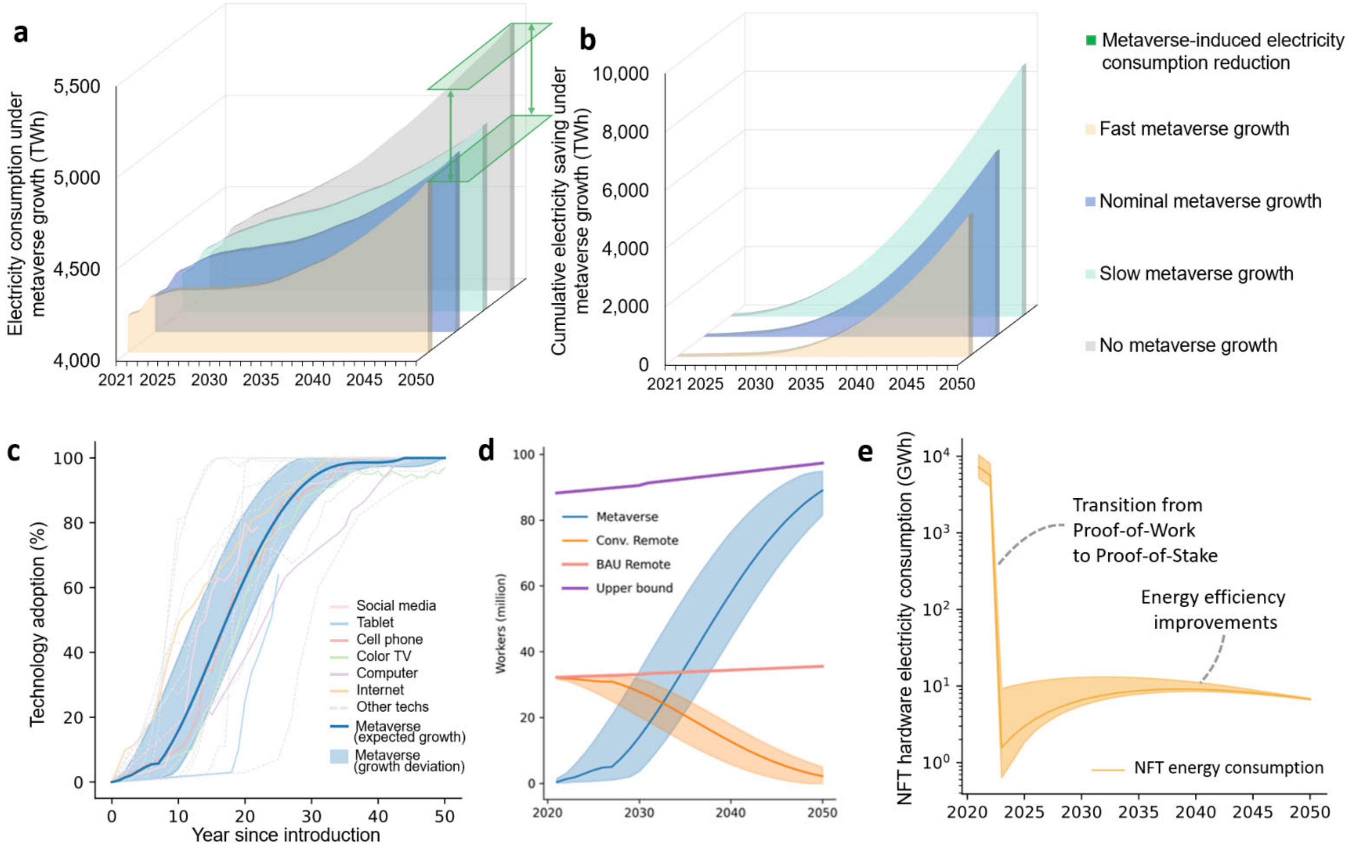

Fig. 1 Impacts from the growing metaverse sector on the electric power systems by year and expansion scenario, adoption curves for the metaverse industry, projected expansion trajectories for metaverse-based working, and the NFT-dependent electricity consumption throughout the prospective analysis period. **a**, Annual electricity consumption induced by different metaverse growth scenarios. **b**, Cumulative electricity consumption reduction resulted from metaverse growth. **c**, Adoption curves for the metaverse sector and for a series of modern relevant technologies. **d**, Projected expansion trajectories for metaverse-based working and its non-metaverse counterparts. **e**, the annual NFT-dependent electricity consumption in the scenarios with metaverse industry growth. In **a**, the grey curve indicates the overall electricity consumption in the United States in the business-as-usual scenarios without metaverse market expansion, and the green arrows on the right of **a** depict the electricity consumption reduction resulted from the increasing metaverse adoption. Each of the thin curves in **c** represents the technology adoption curves for a specific modern technology or IT application that was introduced after the Second World War. The blue curve and blue area in **c** and **d** indicate the nominal expansion trajectory and growth deviations of the metaverse industry, respectively. The nominal adoption curve is obtained following the fitted curve with the coefficient of discrimination (R^2) of over 0.99 according to the median adoption levels of the selected reference technologies and IT applications included in **c**, while the slower and faster growth deviations for the adoption curve are defined by the 25th and 75th percentile of the adoption data. In **e**, the orange curve and orange area correspond to the metaverse sector growth projections with the nominal adoption rate and the deviated expansion rate.

each scenario, the shares of different energy sources of the electric power sector are displayed in Supplementary Fig. 2, while the annual demand of each non-electric energy source is also derived from the EIA forecast (40). It is worth noting that the EIA projections may not reflect the impacts of the recent climate legislation represented by the Inflation Reduction Act. Still, these forecast scenarios from the EIA are presumably the most accurate and reliable energy systems projections that are publicly accessible. Furthermore, in case the metaverse may not grow successfully for some applications, alternative metaverse adoption scenarios are developed and investigated to project the potential energy, emissions, and climate impacts under these cases.

Investigating the environmental sustainability of the metaverse market expansion

The changes in GHG emissions and gaseous air pollution (49) are quantified according to the energy systems deviations resulted from the growing metaverse adoption. The nationwide annual emissions for one type of gas, such as GHG, NOx, and SOx, are calculated as the weighted sum based on the total energy consumption and the unit emission for all types of energy sources. Specifically, the unit GHG emissions for each type of energy source in the electric power sector follow the projections from the EIA (40), and the NOx and SOx emissions for each electricity generation source are obtained from a database of the Environmental Protection Agency (50). The unit emissions for natural gas and petroleum that are not used for electricity generation are obtained from databases of state agencies and research articles (46, 51). Note that the total domestic emissions impacts associated with the metaverse growth are investigated, and scopes 1-3 of GHG emissions are not applicable for this work, as these are used to measure emissions of companies instead of nationwide emissions.

The metaverse-induced climate impacts are examined for a series of shared socioeconomic pathways (SSPs) using the MAGICC v7 climate model (29). The effects of metaverse market expansion on climate change have been studied under three SSPs with low, medium, and high emissions, namely SSP1-1.9, SSP2-4.5, and SSP5-8.5 (52). The SSP1-1.9 scenario reflects the

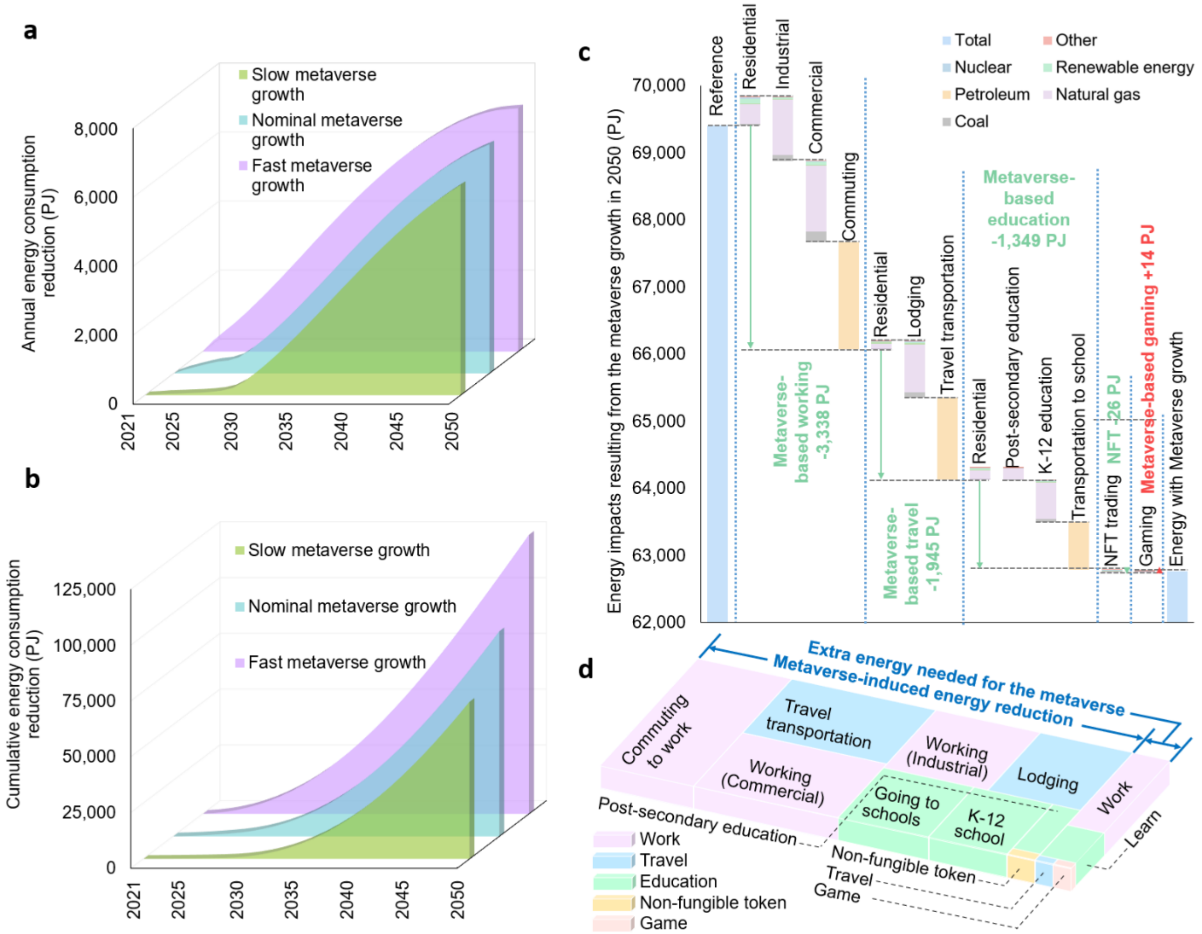

Fig. 2 Metaverse-induced energy consumption changes in 2050 and detailed breakdowns by application and by energy source. **a**, Metaverse-induced annual energy consumption reduction for multiple growing trajectories. **b**, Metaverse-induced cumulative energy consumption reduction for multiple growing trajectories in the coming decades until 2050. **c**, Climate-related energy effect breakdowns by metaverse-based applications and by energy source in 2050. **d**, Shares of component activities in overall energy consumption reduction and increase in 2050. In **c**, the first and last columns display the overall energy consumption for all sectors of the economy under the reference scenario and the scenario with nominal metaverse growth, respectively. Energy impacts related to climate from various metaverse-based applications are separated by blue dashed lines. Increases and decreases in energy consumption attributed to the metaverse are represented by red and green arrows, respectively. The blocks of the same color in **d** indicate activities that fall under the same application in the metaverse sector.

potential transition pathway that is the closest to pursuing the 1.5 °C target under the Paris Agreement (53). The SSP2-4.5 scenario marks the "middle of the road" scenario (54) where the social, economic, and technological trends in the world do not shift considerably from their historical patterns, and it also corresponds to the representative concentration pathway 4.5 that keeps radiative forcing at 4.5 W/m^2 by the end of this century without ever exceeding that value. The SSP5-8.5 is referred to as the pathway with the highest GHG emissions and has high challenges for climate change mitigation. For modeling input, the input parameters for a scenario include annual anthropogenic emissions that impact the climate system, such as greenhouse gases and aerosol precursors. These emissions are projected according to the metaverse-induced emissions impacts in the scenario and the forecasted emissions of the corresponding SSP. As the metaverse sector is projected to reach the maximum adoption level by the middle of this century, the emissions impacts of metaverse growth for GHG, NOx, and SOx are considered to last throughout the second half of the 21st century. The metaverse-induced climate impacts for each scenario are emulated under each pathway, based on 100 Monte Carlo runs using the MAGICC climate model.

Results

Climate-related energy systems impacts resulted from the metaverse sector growth

To investigate the impacts of the metaverse adoption growth on climate change mitigation, decarbonization, air quality improvement, and energy saving in the coming decades, the technology adoption curves for the slow, nominal, and fast growth of the metaverse industry are projected through 2050. In other words, the slow-growing and fast-growing scenarios serve as boundaries of expansion uncertainties of the metaverse sector, depicting the potential deviation range from the nominal metaverse growth scenario. Based on the three projected expansion trajectories and three energy systems projections, nine scenarios are developed for quantification of the metaverse-induced energy deviations for all sectors of the economy. Three business-as-usual scenarios, which follow the three energy systems projections and involve no metaverse expansion, serve as the reference scenarios for quantifying the energy deviations resulted from the metaverse growth. The technology adoption curves for the metaverse are projected based on 18 technologies that were invented and commercially applied after the Second World War, and the metaverse technology growth projections are presented in Fig. 1**c**. The influences on the electric power systems induced by the metaverse industry expansion in the United States are shown in Fig. 1**a**, Fig. 1**b**, and Supplementary Fig. 2. The overall electricity consumption resulted from the expansion of the metaverse sector is projected to decrease by 433–507 TWh by 2050 in the country, which corresponds to 7.9–9.3% of the electricity demand for the baseline scenario without the metaverse market growth. By the end of the analysis period, the shares of renewable electricity are projected to increase by around 8–10%, owing to the growing metaverse industry, while the shares of fossil-based electricity will decrease by 8–19% compared to the business-as-usual scenarios without metaverse expansion. As the metaverse sector growth leads to less electricity consumption, higher shares of renewable power, and lower shares of fossil energy, it can be inferred that advocating metaverse technology adoption will contribute to the decarbonization of electric power systems. The consequent benefits for climate change mitigation and environmental sustainability are further elaborated in the next section. Furthermore, the overall electricity usage deviations from the slower or faster expansion of the metaverse market are insignificant compared to the differences between the business-as-usual scenario and metaverse industry growth scenarios, indicating that different metaverse expansion trends lead to similar impacts on total electricity consumption.

The electricity consumption deviations resulted from the expanding metaverse market are individually quantified for each application in the industry, and an example of NFT is presented in Fig. 1**e**. Although the trading amounts of NFT are projected to boom, as shown in Supplementary Fig. 1, the energy consumption for the NFT-related blockchain in 2050 will be lower than that in 2021. This is because the increasing share of the proof-of-stake mechanism in NFT trading expects to replace the conventional energy-intensive proof-of-work mechanism in the coming decade, as marked by the Merge in September 2022 for Ethereum (55), a major blockchain for NFT trading. The resulting annual electricity consumption for NFT indicates that the blockchain mechanism transfer will lead to significant energy consumption reduction in the coming years. The NFT-related electricity demands will then slightly and gradually increase, as more energy-consuming nodes are needed to deal with the booming NFT trades resulted from the growth of Web 3.0. In the late 2040s, the electricity consumed for NFT slightly decreases, because the energy saved from efficiency improvements becomes larger than the extra electricity needed for the additional nodes, considering that the increasing rates of NFT trades are projected to be substantially lower than those of the previous years.

The metaverse-induced climate-related impacts on energy systems and the associated breakdowns for each application in the metaverse sector are shown in Fig. 2. With the growing metaverse market, the domestic total annual energy consumption is forecasted to reduce by 6,097–7,054 PJ for the projected nominal growth rates of the metaverse sector. The metaverse-induced cumulative energy saving is up to 125 EJ throughout the prospective analysis period, which is more than the current domestic total annual energy consumption. Five applications in the metaverse industry are investigated in this study, namely metaverse-based remote working, virtual traveling, distance learning, NFT, and gaming. Four of the five applications in the metaverse, including remote working, virtual traveling, distance learning, and NFT trading, will result in less energy consumption than their non-metaverse alternatives. The only exception is metaverse-based gaming, as more electricity is required for the devices, the internet infrastructure, and data centers for gaming in the metaverse.

Relocating working from workplaces to the metaverse shows the most significant energy systems impacts, corresponding to 3,337 PJ of total annual energy consumption reduction. Specifically, residential energy consumption is projected to increase, as more electricity is required for the dependent devices for metaverse-based working and longer operational hours of household appliances. Furthermore, the longer staying-at-home time for people to work in the metaverse will lead to more natural gas and other fossil fuel consumed for space heating, water heating, and cooking, among others. As the share of on-site working decreases with the vast expansion of the metaverse industry, the energy consumption in the commercial and industrial sectors is expected to reduce accordingly. Similarly, the declining labor for non-metaverse on-site work is forecasted to decrease the overall commuting needs, resulting in an energy reduction of over 1,500 PJ in 2050 in the transportation sector. The increasing residential energy consumption induced by the growing metaverse-based working can be completely offset by the energy reduced in other end-use sectors, leading to a combined impact of decreasing overall energy demands.

Metaverse-based travel is projected to lower the overall energy consumption by 1,945 PJ in 2050 compared to its physical-world counterpart. However, the residential sector will require over 100 PJ more energy due to the increased electricity demand for the metaverse equipment and the additional energy needed for the extended periods of staying at home. Conversely, energy consumption at lodging facilities is forecasted to decline by approximately 850 PJ, as the number of travel nights is substantially reduced by the growing prevalence of virtual travel. The energy for public and private transportation will naturally decrease with the growing metaverse-based traveling, owing to the decreased demands of physically moving to a traveling destination that is far away from the residence.

Education in the metaverse can save 1,348 PJ of energy in comparison to conventional in-person learning. Similar to the working and traveling applications of the metaverse, residential energy consumption increases with the expansion of metaverse-based education, as a result of the increasing usage of metaverse-dependent devices and longer staying-at-home hours. The projected energy consumption for the K-12 schools and post-secondary education facilities is predicted to decrease by 810 PJ in total by 2050. More energy is lowered by metaverse-based learning for K-12 education than that of post-

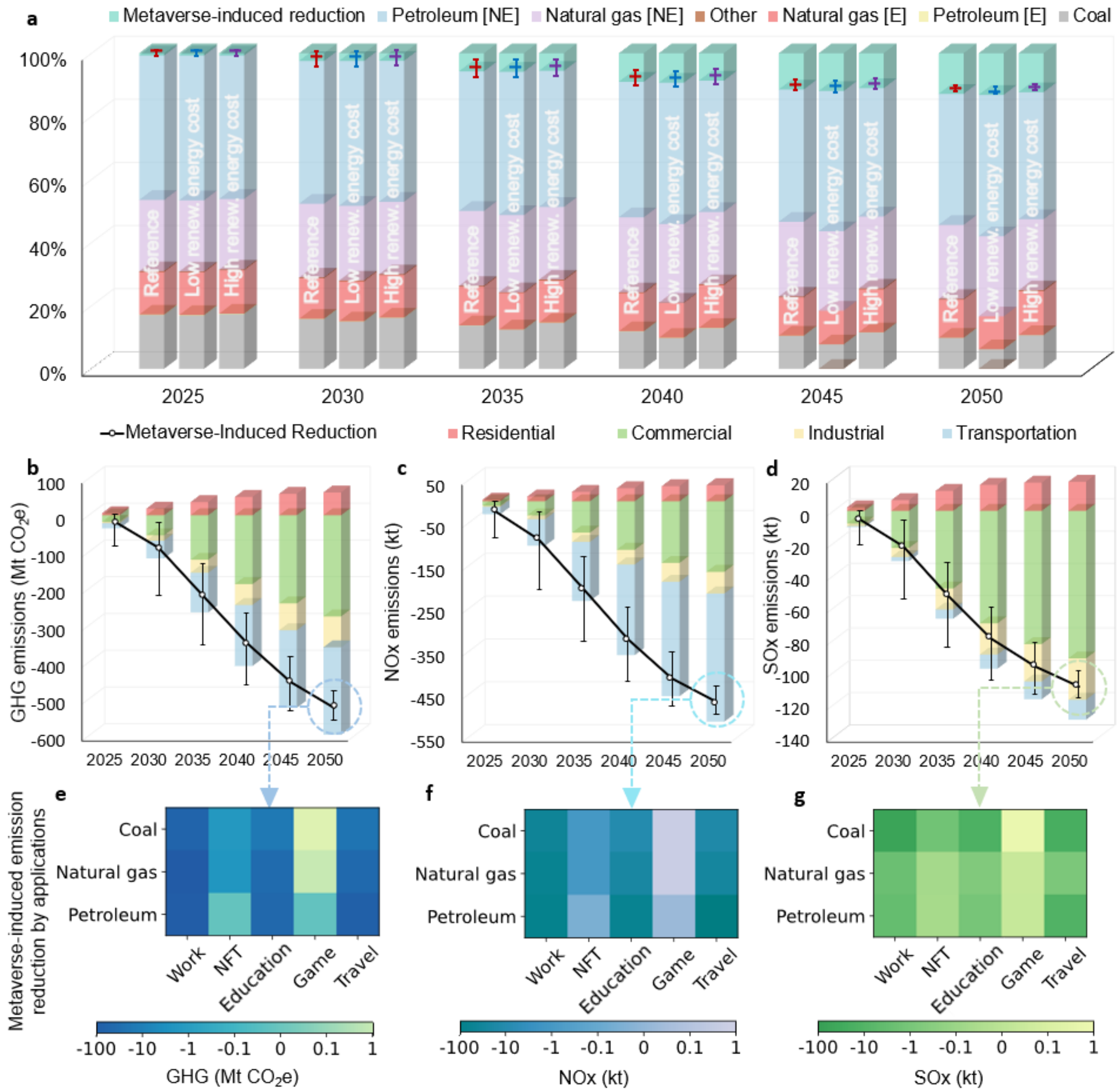

Fig. 3 Metaverse-induced emission changes for greenhouse gas (GHG), NOx, and SOx. **a**, GHG emission reductions resulted from the expanding metaverse sector for the reference scenario, the scenario with low renewable energy cost, and the scenario with high renewable energy cost. **b–d**, Annual emission reductions induced by the metaverse adoption growth for GHG, NOx, and SOx. **e–g**, Emission reduction by application in the metaverse and by energy sources. Error bars in **a–d** depict the deviations from slower or faster metaverse industry growth rates compared to the projected nominal scenarios. E and NE in **a** indicate the emissions from the electric power sector or non-electric energy consumption, respectively.

secondary education, mainly due to the higher total energy demands of instructional buildings in K-12 schools, which leave more potential for energy reduction from transferring to learning in the metaverse. As the students are gradually relocated from schools to the metaverse during the next three decades through 2050, transportation energy demand falls can be naturally expected. In terms of NFT, the energy consumption for NFT trading in 2050 will be lower than its current level, as analyzed previously through Fig. 1**e**.

Metaverse-induced environmental and climate impacts

The emission changes for GHG, NOx, and SOx resulted from the rapid expansion of the metaverse adoption are presented in Fig. 3. The growing metaverse industry will benefit global warming mitigation by reducing GHG emissions. Specifically, the metaverse sector growth is projected to lower the GHG emissions for the energy sector by 11.3–12.3%, 12.4–13.4%, and 13.1–14.3% in 2050 for the slow, nominal, and fast metaverse growth, respectively, corresponding to 476–570 Mt CO_2e by the end of the analysis period. The results indicate that faster adoption of metaverse-based applications can lead to better performances in reducing overall carbon emissions. In Fig. 3**a**-**d**, the deviations resulted from slower or faster metaverse sector expansion projections are represented by the error bars. The deviations from different growth rates tend to be higher in the middle of the analysis period compared to that by the end of the time horizon, because the expanding trajectories for all applications are close to the maximum adoption levels by the end of the analysis period. On the other

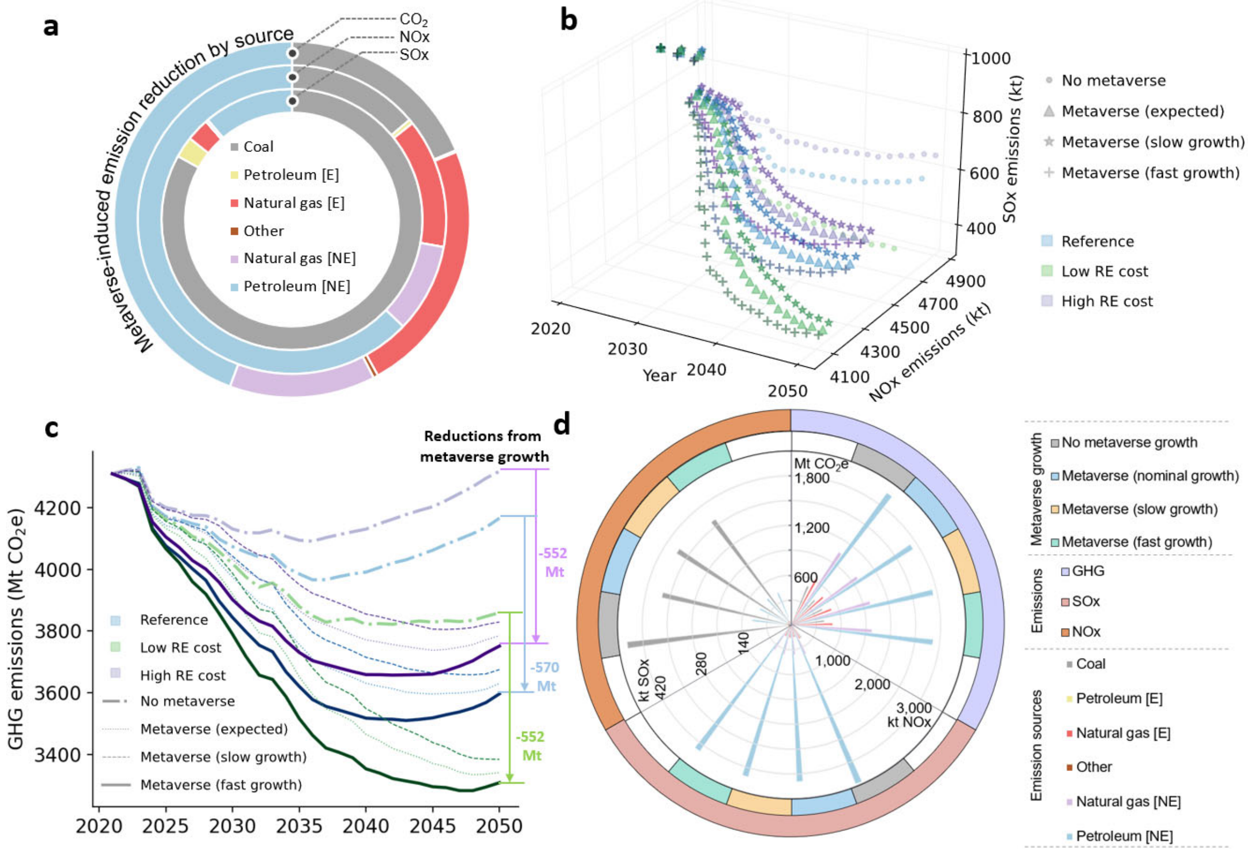

Fig. 4 Share of emission sources and annual emissions for greenhouse gas (GHG), NOx, and SOx for a series of metaverse industry expansion scenarios. **a**, Shares of sources for metaverse-induced GHG, NOx, and SOx emission reductions. **b**, Annual NOx and SOx emissions for the scenarios with various metaverse adoption projections. **c**, Annual GHG emissions for the business-as-usual and the metaverse market growing scenarios throughout the prospective analysis period. **d**, Shares of sources for annual GHG, NOx, and SOx emissions in scenarios with different metaverse sector expansion projections. The annual emission reductions directly resulted from the vast metaverse expansion in 2050 are represented by the arrows in **c**. E, NE, and RE stand for electricity generation, non-electric uses, and renewable energy, respectively.

hand, the variations are more conspicuous in the middle of the transition period for the different metaverse industry growth trends. Scenarios with low forecasted renewable energy costs tend to have low GHG emissions from electricity generation compared to other scenarios with different energy systems projections, owing to their high shares of renewable energy in the electric power sector, as shown in Fig. 1 and Supplementary Fig. 2. For the scenarios with high renewable energy costs, GHG emissions from natural gas in 2050 are higher than the other scenarios with the same metaverse sector growth trajectories, mainly because of using additional natural gas to compensate for their low shares of renewable energy.

The breakdowns for metaverse-induced emissions changes by the economic sector are visualized in Fig. 3**b**–**d**, while the breakdowns for emissions changes in 2050 by application are shown in Fig. 3**e**–**g**. Under the projected nominal growth of the metaverse market, the emissions for GHG, NOx, and SOx are projected to decrease by 536 Mt CO_2e, 476 kt NOx, and 111 kt SOx, respectively, compared to the business-as-usual scenario without the metaverse sector expansion. The GHG, NOx, and SOx emissions in the residential sector will increase with the growing metaverse industry, because of the additional electricity and fossil fuel consumption associated with metaverse-dependent devices and more hours of staying at the residence. In terms of GHG emissions, the commercial and transportation sectors contribute the most to emission reductions, due to the decreases in emissions from metaverse-based working, education, and travel, as can be inferred from Fig. 3**e**. Note that petroleum is mainly used for transportation purposes (40), so most part of the emissions changes from reduced petroleum consumption can be categorized in the transportation sector. NOx emissions, which is primarily resulted from petroleum use in the transportation sector, can also be lowered by the metaverse growth. This is owing to the petroleum consumption reductions resulted from the metaverse-induced decreased transportation demands for commuting to work, visiting schools, and long-distance travels, as visualized in Fig. 3**f**. In terms of SOx emissions, the vast expansion of the metaverse market will lead to significant SOx emission reductions in the commercial sector. As the electric power sector is the main source of domestic SOx pollution, the reductions are primarily achieved by saving the electricity that is originally needed for the physical-world counterpart of the applications in the metaverse sector, such as offices, schools, colleges, and lodging facilities. In addition, the environmental effects of NFT and gaming in the metaverse are not as significant as the other metaverse-based applications in 2050, consistent with the trend of energy consumption deviations shown in Fig. 2.

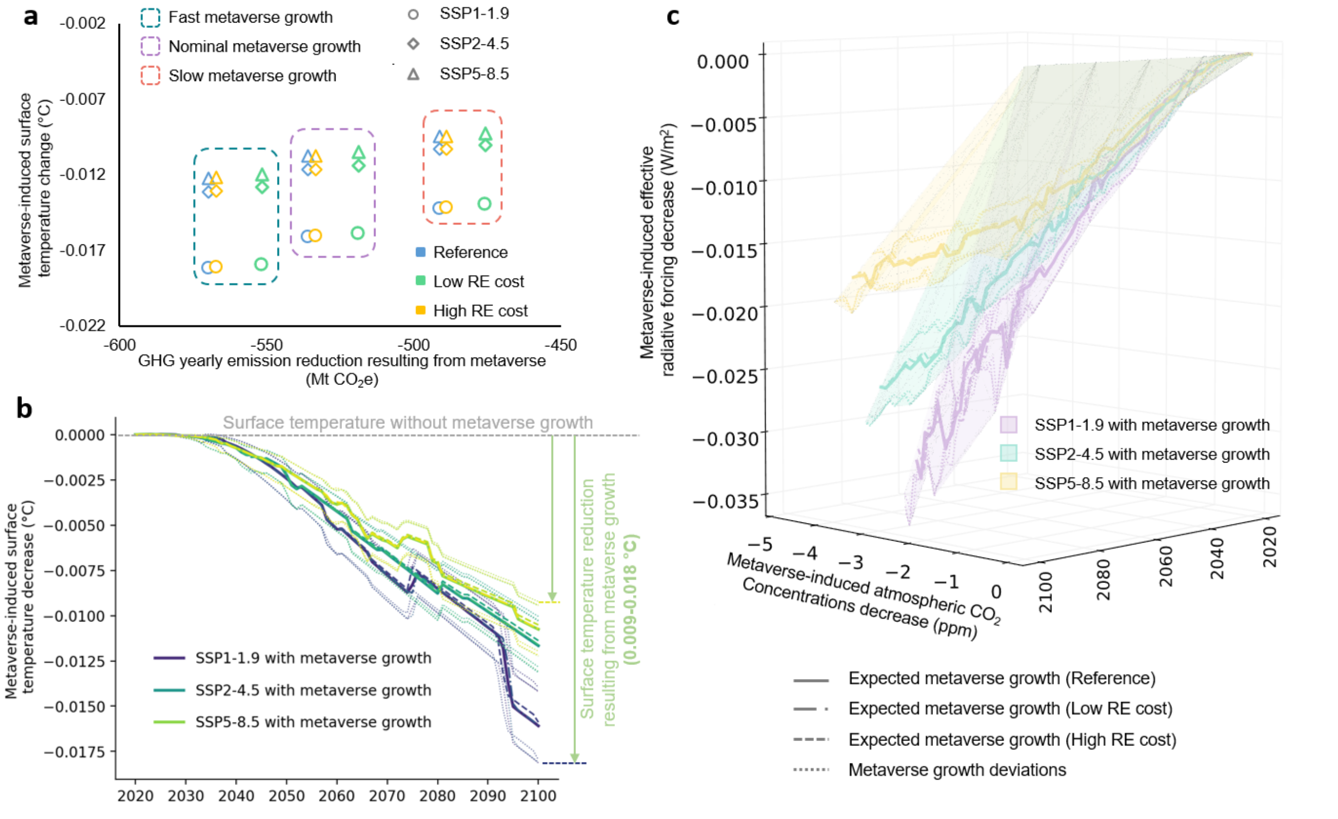

Fig. 5 Metaverse-induced climate impacts represented by decreasing surface temperature, declining atmospheric carbon dioxide concentration, and reducing effective radiative forcing. **a**, Metaverse-induced temperature decreases and annual greenhouse gas emissions by the end of the analysis period, for scenarios with different metaverse adoption trajectories, energy systems projections, and shared socioeconomic pathways (SSPs). **b**, Surface temperature decreases compared to the reference scenario without the rapid growth of the metaverse. **c**, Decreases in atmospheric carbon dioxide concentration and effective radiative forcing reductions resulted from the increasing adoption of the metaverse-based applications. Considering that the metaverse industry is projected to reach the maximum adoption level by the middle of this century, the metaverse-induced emissions impacts for GHG and air pollutants are considered to last throughout the second half of this century. The curves with the same color in **b** and **c** indicate the metaverse-expanding scenarios under the same SSP, and the metaverse adoption projections are differentiated by their line types. The space with the same color in **c** indicates the potential combination of values for atmospheric carbon dioxide concentration and effective radiative forcing reductions with different metaverse industry growing forecasts and different energy systems projections under the same SSP. RE stands for renewable energy in **a**.

Fig. 4 presents the shares of emission sources and the annual metaverse-induced emissions impacts for GHG, NOx, and SOx for all scenarios. Petroleum and natural gas account for most of the GHG emission reductions resulted from the growing metaverse sector, while coal and petroleum are the main sources of metaverse-induced SOx and NOx emission changes, respectively. For different metaverse adoption projections, the scenarios with faster growth tend to result in larger reductions for all types of emissions, because the faster expansion of the metaverse-based applications will save more energy by replacing the non-virtual energy-intensive activities with the energy-efficient metaverse alternatives. As the overall energy usage decreases in scenarios with faster metaverse expansion, less fossil fuel is needed for consumption, which consequently leads to more emission reductions than that of the business-as-usual scenarios without metaverse industry growth. As for different energy systems projections, the scenarios with high renewable energy costs tend to have the highest emission levels among the scenarios with the same metaverse growth expectation, while the scenarios with low renewable energy costs correspond to the least amounts for all three types of emissions. This is mainly attributed to the shares of fossil and renewable energy in these scenarios, considering that fossil fuels represent a dominant source of GHG, NOx, and SOx emissions for the energy sector. As fossil-based energy becomes more economically preferable when the cost of renewable energy increases, the shares of fossil energy in scenarios with more expensive renewable energy will become relatively higher. Therefore, the trend and comparison of annual emissions are consistent with the corresponding shares of fossil and renewable energy presented in Fig. 1 and Supplementary Fig. 2.

The annual emissions in Fig. 4 are not showing trends of monotonically decreasing, and the trend for each type of emissions is different from that of the others. For GHG emissions, the annual GHG emissions tend to stop decreasing and may increase before 2050 for all scenarios, primarily owing to the significant increase of natural gas consumption in the 2040s as projected by administrative agencies (40). Notably, although the annual GHG emissions may increase in the 2040s for most of the scenarios, the metaverse growth will still result in increased GHG emission reductions compared to the business-as-usual scenarios, consistent with the trend in Fig. 3**b**. As for NOx pollution, the emissions are likely to increase at the beginning of the prospective analysis periods and in the 2040s for most scenarios, regardless of metaverse growth projections. The NOx pollution increase before 2025 is mainly attributed to the significant increase in jet fuel and petroleum consumption,

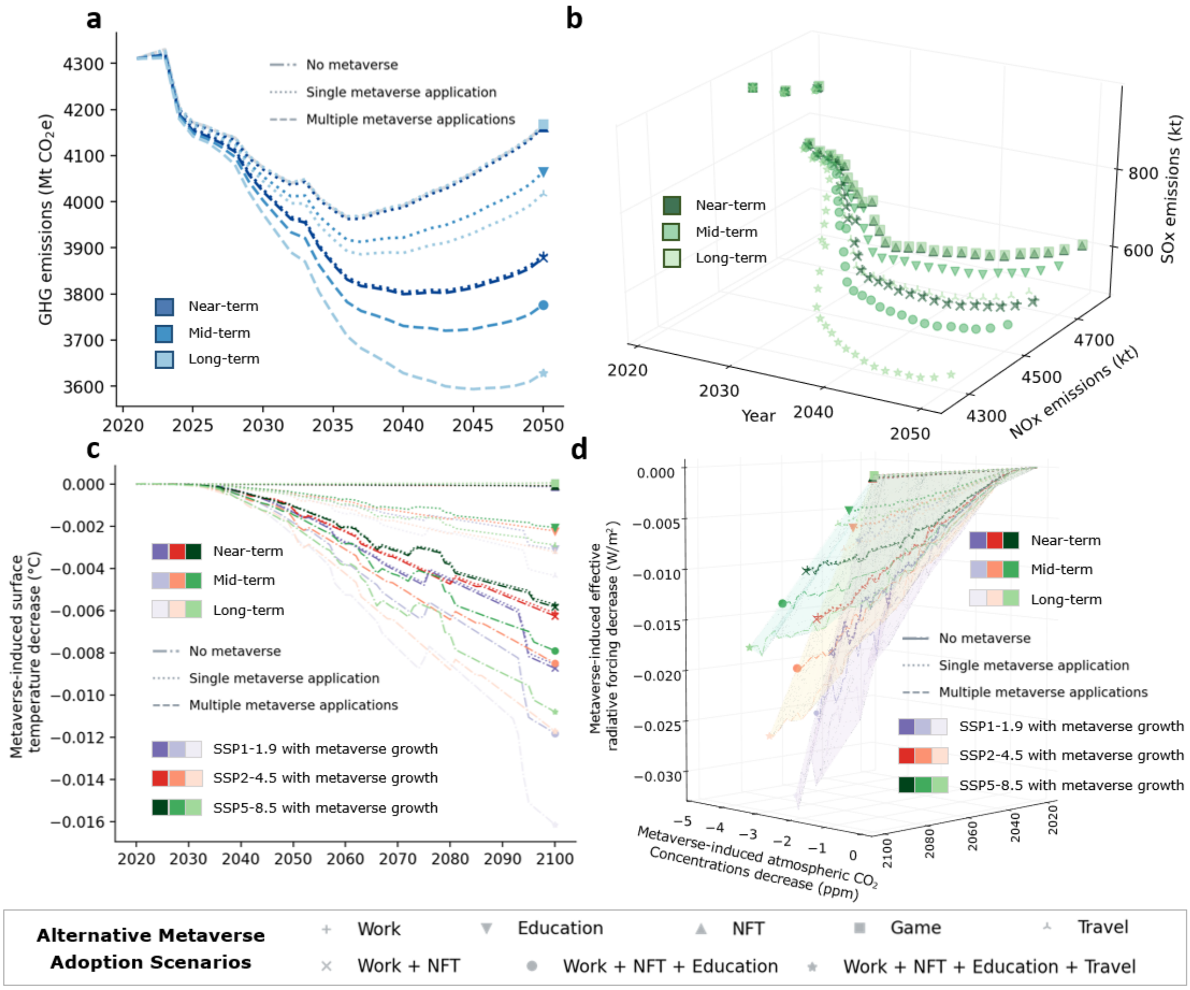

Fig. 6 Emissions and climate impacts of alternative metaverse adoption scenarios that incorporate different potential realization of the metaverse applications. **a,** Annual GHG emissions for the alternative metaverse adoption scenarios with nominal expansion rates throughout the prospective analysis period. **b,** Annual NOx and SOx emissions for the alternative metaverse adoption scenarios with nominal metaverse growth projection. **c**, Surface temperature decreases of the alternative metaverse adoption scenarios compared to the reference scenario without metaverse growth. **d**, Decreases in atmospheric carbon dioxide concentration and effective radiative forcing reductions resulted from the increasing adoption of the metaverse-based applications. The realization potentials of the metaverse adoption scenarios are reflected by the depth of color of the lines in each subgraph, and the darker colors represent the scenarios that are more likely to realize in the nearer term compared to ones in lighter colors. The markers in **b** and at the end of each curve in **a**, **c**, and **d** indicate different metaverse adoption scenarios with different application realizations, and the types of metaverse application realizations are indicated by their line types. The space with the same color in **d** shows the potential values for atmospheric carbon dioxide concentration and effective radiative forcing reductions under the same SSP.

as a result of recovering aviation and travel industries from the COVID-19 pandemic (44). Similar to GHG, the increasing trends of NOx emissions in the late 2040s are attributed to the projected increases in petroleum consumption for road transportation and aviation that are forecasted by the administrative agencies (40). Nevertheless, the NOx reductions induced by the rapidly-growing metaverse market monotonically decrease throughout the prospective analysis period, as can be inferred from Fig. 3**c**. In terms of SOx, the projected increases of natural gas and petroleum have limited influences on the trend of annual SOx emissions, as natural gas and petroleum are not the primary emitting sources. On the contrary, coal accounts for most of the SOx pollution, as indicated by Fig. 4**a** and Fig. 4**d**. Considering that the growing metaverse sector is forecasted to lower the domestic electricity consumption, the electricity generated from coal will consequently reduce, which can lead to the decreasing trends of annual SOx emissions for all metaverse sector expanding scenarios.

The metaverse-induced climate impacts have been investigated using the MAGICC climate model on the basis of a series of SSPs, as the model has been one of the widely used climate models in various assessment reports produced by the IPCC (29). Fig. 5 presents the variations of multiple climate metrics from MAGICC outputs, including surface temperature decrease, atmospheric CO_2 concentration reduction, and effective radiative forcing drop, resulted from the rapid growth of the metaverse industry. Specifically, with the expanding metaverse market, the surface temperature is emulated to decrease by up to 0.02 °C, the atmospheric CO_2 concentration can be reduced by 4.0 ppm, and the reduction of effective radiative forcing is projected to be as high as 0.035 W/m^2. For the scenarios with the nominal metaverse growth and normal renewable energy cost, the surface temperature is projected to decrease by 0.011–0.016 °C, and the increasing metaverse technology adoption tends to lower the atmospheric CO_2 concentration and effective radiative forcing by 2.2–3.5 ppm and 0.017–0.031 W/m^2, respectively. Varying the metaverse sector expansion rates will affect the climate impacts. Faster adoption of the metaverse-based applications compared to the nominal growth rate is emulated to have more significant effects on mitigating climate change, as indicated by the more significant decreases for the three climate metrics. This is because the GHG, NOx, and SOx emission reductions are higher in the fast-growing scenarios than those in the nominal-growing ones, represented by the negative error bars in Fig. 3**b**-**d**. On the contrary, the deviations induced by the expanding metaverse sector tend to be milder for the scenarios with slower expansion rates, owing to their less considerable emissions reduction impacts.

The metaverse-induced climate impacts also differ from the SSPs. The metaverse industry growth is more effective in mitigating climate change for the SSP that is less dependent on fossil fuels. Taking scenarios with the nominal metaverse sector growth rates, for instance, the effective radiative forcing in SSP1-1.9 is projected to decrease by 1.4% compared to the corresponding business-as-usual scenario, while the reductions for SSP2-4.5 and SSP5-8.5 are 1.2% and 0.8%, respectively. A similar trend can also be observed for other metaverse sector projections and climate change metrics. This is because the shares of metaverse-induced emission reductions are higher in the SSP1-1.9 than those in SSP2-4.5 and SSP5-8.5, as SSP1-1.9 consumes less fossil fuel and produces less fossil-associated emissions, such as GHG, NOx, and SOx. Lastly, scenarios with lower renewable energy costs are likely to show more significant climate effects, because of the higher GHG, SOx, and NOx emission reductions in these scenarios, while the scenarios with higher renewable energy costs tend to be less impactful on climate change mitigation.

The climate impacts from various potential realizations of metaverse applications are presented in Fig. 6 through a set of alternative metaverse adoption scenarios, and the emissions of these scenarios are also shown in the figure. Metaverse adoption scenarios with a higher potential to realize in the nearer term are indicated by darker colors in each subgraph. An alternative adoption scenario with a single metaverse application indicates that only one of the metaverse applications may be realized and expanded following the growth projections, while alternative adoption scenarios with multiple metaverse applications consider that more than one of the applications can be realized. Most of the alternative metaverse adoption scenarios show clear emissions reductions and improved climate impacts compared to the reference scenarios without metaverse growth, and such impacts for metaverse adoption scenarios with high confidence levels tend to be comparable to the expected scenarios with all metaverse applications shown in Fig. 4 and Fig. 5. On the other hand, the minority alternative metaverse adoption scenarios that have similar environmental and climate impacts as the business-as-usual scenario are less likely to be realized in the near or medium terms compared to other metaverse adoption scenarios, as a result of the relatively low energy impacts of the specific metaverse applications.

Conclusions and outlook

As the booming metaverse sector is expected to reach billions of users and trillion-dollar global annual revenue in the coming years (6, 7), this study aims to improve the understanding of the climate impacts of the growing metaverse industry. We perform prospective analyses on the metaverse-induced climate impact, environmental sustainability, and energy consumption deviations in the United States through 2050, by incorporating multiple adoption trajectories for the slow, nominal, and fast expansion of the metaverse industry. Our results show that the metaverse market expansion has the potential to reduce the global surface temperature by up to 0.02 °C, lower the atmospheric CO2 concentration by 4.0 ppm, and decrease the effective radiative forcing by 0.035 W/m2. The climate impacts indicate that the increasing adoption of the metaverse technologies will benefit climate change mitigation, and the metaverse sector growth can also facilitate energy saving, GHG emissions reduction, and air quality improvement. Specifically, our analysis indicates that the expanding metaverse industry is projected to reduce the total domestic energy consumption by 92 EJ before 2050. This reduction surpasses the annual nationwide energy consumption of all end-use sectors in previous years. The metaverse growth is projected to reduce the GHG, NOx, and SOx emissions by 5.6–10.3 Gt CO2e, 5.1–9.3 Mt, and 1.1–2.3 Mt, respectively, throughout the expansion period from 2022 to 2050. Therefore, deeply integrating metaverse with various everyday social, business, and personal activities leads to combined positive effects on climate change mitigation, GHG emission reduction, air quality improvement, and energy supply alleviation, contributing to the decarbonization and climate goals. On the other hand, it is essential to recognize that, despite the convenience and transformative effects of the metaverse's expansion, there may be accompanying drawbacks when real-world activities are transitioned to the virtual realm. For instance, in-person collaboration may foster a more nurturing work environment and strengthen connections between colleagues, since communication within the metaverse cannot fully substitute the experience of face-to-face meetings. Besides, metaverse-based education faces challenges, such as the potential for addiction to the virtual world, shifts in social norms, and the decline of social intelligence, due to reduced physical interactions among students. Similarly, virtual travel within the metaverse may struggle to satisfy certain desires, such as savoring foreign cuisine or diving in the ocean.

The increasing adoption of metaverse-based applications can accelerate the progress toward achieving the net-zero GHG emissions target, suggesting that less aggressive climate policies can be implemented for all economic sectors. As the metaverse has the potential to reduce GHG emissions by 10 Gt CO2e throughout the market growth period, the stakeholders will have the flexibility of rearranging the priorities of different decarbonization strategies, as long as the climate goals remain unchanged. For instance, approaches that are economically efficient for reducing the unit amount of GHG emissions can be adopted from the early years. On the other hand, faster metaverse growth is emulated to have more positive effects on mitigating climate change, suggesting that promoting the spread of the metaverse technologies provides a valuable window of opportunity to put more research efforts into less mature carbon reduction technologies and on the last mile of decarbonization. It can be inferred that such flexibility in decarbonization strategy rearrangement will relieve the financial burden on the carbon-neutral transition and climate goal achievement, as the necessity for applying the developing and costly carbon dioxide removal (CDR) technologies can be postponed. From the perspective of energy systems, the expanding metaverse sector contributes to higher shares of renewable energy while reducing fossil fuel consumption compared to the business-as-usual scenario. This finding suggests that, in the context of metaverse growth, the additional energy demands of the metaverse-dependent technologies and infrastructure, such as cryptocurrency and data centers, are lower than the energy saved by avoiding physical-world counterpart activities. From a policy standpoint, the growth of the metaverse sector promotes system-wide energy saving and encourages renewable electricity penetration, which supports the decarbonization goals in most countries.

As for influences on environmental policies, the growing metaverse adoption can alleviate air pollutant emissions by 10–23%, suggesting that the spread of metaverse technologies can be advocated to improve air quality and reduce GHG emissions. The environmental implications of the vast metaverse sector expansion suggest that less stringent implementation approaches are required to meet the same set of environmental standards and climate goals compared to that of the business-as-usual scenarios. We find that petroleum for transportation and coal for electricity generation account for most of the metaverse-induced NOx and SOx emission reductions, respectively. The results suggest that incentivizing the adoption of metaverse technologies will lead to significant decreases in gaseous air pollutant emissions in the transportation and electric power sectors.

The energy systems should be transformed to accommodate the energy consumption deviations resulted from the growing metaverse industry, including increasing the energy supply for the residential sector, incentivizing distributed generation, and reducing the energy provided to the commercial, industrial, and transportation sectors. The metaverse-induced climate-related energy effects vary for different economic sectors. More energy is required for the residential sector, owing to the additional electricity demand of using the metaverse-dependent devices and the extra energy for the increased time of staying at the residence that is associated with household appliances, space heating, water heating, and cooking, among others. Consequently, the supply capability of each form of energy should be re-evaluated for the residential sector, in order to accommodate the rapid and smooth adoption growth of metaverse-based applications. Incentivizing distributed generation can also contribute to addressing the increased residential electricity demands resulted from the expanding metaverse industry. In contrast to the residential sector, metaverse-based work, education, and travel will result in significant energy consumption reduction for the commercial and transportation sectors. This is because the non-metaverse counterpart activities for on-site working, in-person learning, and physical traveling can be replaced by their alternatives in the metaverse, which require no on-site energy usage and no need for long-distance travel. Facilitated by the rapid expansion of Web 3.0, NFT trades are forecasted to boom, while the associated commercial electricity consumption is projected to decrease by the end of the prospective analysis period. This is due to the energy efficiency improvements of the nodes and mechanism transition from the energy-intensive proof-of-work to the more energy-efficient proof-of-stake. Gaming in the metaverse tends to slightly increase residential and commercial energy consumption, because of the additional electricity required for metaverse-dependent gaming devices and data centers. From the perspective of overall energy balances in the context of metaverse sector growth, the increases in residential energy consumption will be offset by the energy reductions in other economic sectors, and the total energy usage consequently becomes lower than that in the business-as-usual scenarios. The implications for energy systems highlight the necessity for re-evaluation and reallocation of multiple forms of energy supply in a systematic manner, in order to accommodate the metaverse-induced energy consumption variations for all economic sectors. Otherwise, the metaverse industry may fail to expand within the coming decades, leading to the loss of all the benefits for climate change mitigation and environmental sustainability that are associated with the metaverse sector growth.

Data Availability

Parameters and data for analysis and climate model for each of the scenarios investigated in this study are publicly available online: https://github.com/PEESEgroup/Metaverse-Climate-Impacts.

Author Contributions

F.Y. and N.Z. contributed to the study design, data collection, data processing, analysis, and result interpretation. Both authors wrote, revised, and reviewed the manuscript.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

This work is based upon work supported by the National Science Foundation (NSF) under Grant No. CBET-1643244 (to F.Y.). We would like to thank the experts from Microsoft and Meta, Amy Luers and Julius Kusuma, for the useful discussions on the prospective analysis assumptions and results visualization.

References

1. Jung YH, Yoo J-Y, Vázquez-Guardado A, Kim J-H, Kim J-T, Luan H, et al. A wireless haptic interface for programmable patterns of touch across large areas of the skin. Nat Electron. 2022;5(6):374-85.
2. Yu X, Xie Z, Yu Y, Lee J, Vazquez-Guardado A, Luan H, et al. Skin-integrated wireless haptic interfaces for virtual and augmented reality. Nature. 2019;575(7783):473-9.
3. Zhu M, Sun Z, Zhang Z, Shi Q, He T, Liu H, et al. Haptic-feedback smart glove as a creative human-machine interface (HMI) for virtual/augmented reality applications. Sci Adv. 2020;6(19):eaaz8693.
4. Park SM, Kim YG. A Metaverse: Taxonomy, Components, Applications, and Open Challenges. IEEE Access. 2022;10:4209-51.
5. Almarzouqi A, Aburayya A, Salloum SA. Prediction of User's Intention to Use Metaverse System in Medical Education: A Hybrid SEM-ML Learning Approach. IEEE Access. 2022;10:43421-34.
6. Ghose R, Surendran N, Bantanidis S, Master K, Shah RS, Singhvi P. Metaverse and Money: Decrypting the Future: Citi Global Perspectives & Solutions; 2022. Available from: https://icg.citi.com/icghome/what-we-think/citigps/insights/metaverse-and-money_20220330.
7. Moy C. Opportunities in the Metaverse: How Businesses Can Explore the Metaverse and Navigate the Hype vs. Reality: J. P. Morgan; 2022. Available from: https://www.jpmorgan.com/content/dam/jpm/treasury-services/documents/opportunities-in-the-metaverse.pdf.
8. Ripert D. The Pathway to the Metaverse Begins With 3D Modelling: Entrepreneur; 2022.
9. Daugherty P, Carrel-Billiard M, Biltz M. Meet Me in the Metaverse: The Continuum of Technology and Experience, Reshaping Business: Accenture; 2022. Available from: https://www.accenture.com/us-en/insights/technology/technology-trends-2022?c=acn_glb_technologyvisiomediarelations_12867298&n=mrl_0322.
10. Abanades JC, Rubin ES, Mazzotti M, Herzog HJ. On the climate change mitigation potential of CO2 conversion to fuels. Energy Environ Sci. 2017;10(12):2491-9.
11. Tully S. Offsetting Bitcoin's Carbon Footprint Would Require Planting 300 Million New Trees: Fortune; 2021. Available from: https://fortune.com/2021/11/06/offsetting-bitcoins-carbon-footprint-would-require-planting-300-million-new-trees/.
12. Velický M. Renewable Energy Transition Facilitated by Bitcoin. ACS Sustainable Chemistry & Engineering. 2023;11(8):3160-9.
13. Niaz H, Liu JJ, You F. Can Texas mitigate wind and solar curtailments by leveraging bitcoin mining? Journal of Cleaner Production. 2022;364:132700.
14. Fridgen G, Körner M-F, Walters S, Weibelzahl M. Not All Doom and Gloom: How Energy-Intensive and Temporally Flexible Data Center Applications May Actually Promote Renewable Energy Sources. Business & Information Systems Engineering. 2021;63(3):243-56.
15. Ahl A, Yarime M, Tanaka K, Sagawa D. Review of blockchain-based distributed energy: Implications for institutional development. Renew Sustain Energy Rev. 2019;107:200-11.
16. Krause MJ, Tolaymat T. Quantification of energy and carbon costs for mining cryptocurrencies. Nat Sustain. 2018;1(11):711-8.
17. Howson P. Tackling climate change with blockchain. Nat Clim Change. 2019;9(9):644-5.
18. Greenblatt JB, Saxena S. Autonomous taxis could greatly reduce greenhouse-gas emissions of US light-duty vehicles. Nat Clim Change. 2015;5(9):860-3.
19. Tian X, Stranks SD, You F. Life cycle assessment of recycling strategies for perovskite photovoltaic modules. Nat Sustain. 2021;4(9):821-9.
20. Kaack LH, Donti PL, Strubell E, Kamiya G, Creutzig F, Rolnick D. Aligning artificial intelligence with climate change mitigation. Nat Clim Change. 2022;12(6):518-27.
21. Niaz H, Shams MH, Liu JJ, You F. Mining bitcoins with carbon capture and renewable energy for carbon neutrality across states in the USA. Energy Environ Sci. 2022;15(9):3551-70.
22. Inderwildi O, Zhang C, Wang X, Kraft M. The impact of intelligent cyber-physical systems on the decarbonization of energy. Energy Environ Sci. 2020;13(3):744-71.
23. Dunn JB, Gaines L, Kelly JC, James C, Gallagher KG. The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling's role in its reduction. Energy Environ Sci. 2015;8(1):158-68.
24. Rosa L, Sanchez DL, Mazzotti M. Assessment of carbon dioxide removal potential via BECCS in a carbon-neutral Europe. Energy Environ Sci. 2021;14(5):3086-97.
25. Fajardy M, Mac Dowell N. Can BECCS deliver sustainable and resource efficient negative emissions? Energy Environ Sci. 2017;10(6):1389-426.
26. Bianzino NM. Metaverse: Could creating a virtual world build a more sustainable one? : Ernst & Young; 2022. Available from: https://www.ey.com/en_gl/digital/metaverse-could-creating-a-virtual-world-build-a-more-sustainable-one.
27. What Are the Most Prominent Metaverse Use Cases and Applications? : PixelPlex; 2022.
28. Metaverse Market Analysis - Global Industry Size, Share, Trends and Forecast 2022 - 2030: Acumen Research and Consulting; 2022.
29. Meinshausen M, Raper SCB, Wigley TML. Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 1: Model description and calibration. Atmos Chem Phys. 2011;11(4):1417-56.
30. Capellán-Pérez I, Arto I, Polanco-Martínez JM, González-Eguino M, Neumann MB. Likelihood of climate change pathways under uncertainty on fossil fuel resource availability. Energy Environ Sci. 2016;9(8):2482-96.
31. Ritchie H, Roser M. Share of US households using specific technologies, 1860 to 2019: Our World in Data; 2019. Available from: https://ourworldindata.org/grapher/technology-adoption-by-households-in-the-united-states.
32. Mora C, Rollins RL, Taladay K, Kantar MB, Chock MK, Shimada M, et al. Bitcoin emissions alone could push global warming above 2°C. Nature Climate Change. 2018;8(11):931-3.
33. Chen SC. Multimedia Research Toward the Metaverse. IEEE MultiMedia. 2022;29(1):125-7.
34. Fixed Broadband Deployment: Federal Communications Commission; 2020. Available from: https://broadbandmap.fcc.gov/#/.
35. Mystakidis S. Metaverse. Encycl. 2022;2(1):486-97.
36. Tao Y, Steckel D, Klemeš JJ, You F. Trend towards virtual and hybrid conferences may be an effective climate change mitigation strategy. Nature Communications. 2021;12(1):7324.
37. Pärssinen M, Kotila M, Cuevas R, Phansalkar A, Manner J. Environmental impact assessment of online advertising. Environ Impact Assess Rev. 2018;73:177-200.

38. Andrae ASG, Edler T. On Global Electricity Usage of Communication Technology: Trends to 2030. Challenges. 2015;6(1):117-57.
39. Cicala S. Powering Work from Home. National Bureau of Economic Research Working Paper Series. 2020;No. 27937.
40. Energy Information Administration. Annual Energy Outlook 2022: U.S. Department of Energy; 2022. Available from: https://www.eia.gov/outlooks/aeo/.
41. Energy Information Administration. Residential Energy Consumption Survey (RECS) in 2015: U.S. Department of Energy; 2018. Available from: https://www.eia.gov/consumption/residential/data/2015/.
42. Shapiro-Bengtsen S, Hamelin L, Bregnbæk L, Zou L, Münster M. Should residual biomass be used for fuels, power and heat, or materials? Assessing costs and environmental impacts for China in 2035. Energy Environ Sci. 2022;15(5):1950-66.
43. Energy Information Administration. Commercial Buildings Energy Consumption Survey (CBECS) in 2012: U.S. Department of Energy; 2016. Available from: https://www.eia.gov/consumption/commercial/data/2012/index.php?view=consumption.
44. Federal Aviation Administration. FAA Aerospace Forecasts: Fiscal Years 2021-2041: United States Department of Transportation; 2022. Available from: https://www.faa.gov/data_research/aviation/aerospace_forecasts.
45. Federal Highway Administration. National Household Travel Survey in 2017: U.S. Department of Transportation; 2019. Available from: https://nhts.ornl.gov/.
46. Bureau of Transportation Statistics. National Transportation Statistics, : U.S. Department of Transportation; 2021. Available from: https://www.bts.gov/product/national-transportation-statistics.
47. Brockway PE, Sorrell S, Semieniuk G, Heun MK, Court V. Energy efficiency and economy-wide rebound effects: A review of the evidence and its implications. Renewable Sustainable Energy Rev. 2021;141:110781.
48. Vázquez-Canteli JR, Nagy Z. Reinforcement learning for demand response: A review of algorithms and modeling techniques. Appl Energy. 2019;235:1072-89.
49. Jacobson MZ. Review of solutions to global warming, air pollution, and energy security. Energy Environ Sci. 2009;2(2):148-73.
50. Emissions & Generation Resource Integrated Database (eGRID): U.S. Environmental Protection Agency; 2022. Available from: https://www.epa.gov/egrid.
51. Winther M, Kousgaard U, Ellermann T, Massling A, Nøjgaard JK, Ketzel M. Emissions of NOx, particle mass and particle numbers from aircraft main engines, APU's and handling equipment at Copenhagen Airport. Atmos Environ. 2015;100:218-29.
52. Meinshausen M, Nicholls ZRJ, Lewis J, Gidden MJ, Vogel E, Freund M, et al. The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. Geosci Model Dev. 2020;13(8):3571-605.
53. Yokoi R, Watari T, Motoshita M. Future greenhouse gas emissions from metal production: gaps and opportunities towards climate goals. Energy Environ Sci. 2022;15(1):146-57.
54. Laine HS, Salpakari J, Looney EE, Savin H, Peters IM, Buonassisi T. Meeting global cooling demand with photovoltaics during the 21st century. Energy Environ Sci. 2019;12(9):2706-16.
55. The Merge: Ethereum; 2022. Available from: https://ethereum.org/en/upgrades/merge/.