Sustainability implications of occupational-dependent hybrid work: overview, research challenges, and outlook

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Submitted to JCLP for the PRES'23 Virtual Special Issue

Abstract

The landscape of employment has been significantly transformed with the rise of hybrid work, allowing teleworkable employees to blend traditional office environments with remote options. As the popularity of hybrid arrangements increases, understanding their effects on environmental and social sustainability becomes crucial. Existing studies have often been narrow in scope, examining only isolated aspects or short- to mid-term consequences, resulting in a lack of comprehensive understanding of the overall system-level environmental impact, including elements such as rebound effects, geospatial inequalities, and long-term implications. This paper offers new perspectives to study the energy and environmental sustainability of hybrid work across temporal scales, including the long-term effects under various socio-economic contexts. Furthermore, the paper delves into the idea of fully immersive hybrid work enabled by the metaverse to augment collaboration and communication. By filling these knowledge gaps, the perspectives presented in this paper aim to guide informed policy decisions and sustainable work practices. It is important to note that the geographical coverage of this study appears to be limited to the major economies, and the findings may not be fully applicable to developing nations. This

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approach helps maximize the environmental advantages of hybrid work while ensuring fair and inclusive work opportunities in diverse geospatial settings.

Keywords

Hybrid work, remote work, prospective life cycle assessment, rebound effects, hybrid paradox, shared socio-economic pathways

Abbreviations

Gbps	Gigabits per second
GHG	Greenhouse gas
HVAC	Heating, ventilation, and air conditioning
IAM	Integrated assessment model
ICT	Information and communication technology
IEA	International energy agency
IPCC	Intergovernmental panel on climate change
kbps	Kilobyte per second
LCA	Life cycle assessment
LCI	Life cycle inventory
NYC	New York City
PM	Particulate matter
PREMISE	Prospective environmental impact assessment
SSP	Shared socioeconomic pathways
UK	United Kingdom
US	United States
WFH	Work from home

1. Introduction

The landscape of work and employment has undergone a profound transformation in recent times, with the global pandemic of COVID-19 acting as a catalyst for significant changes in work arrangements [1-3]. A significant change observed during recent years has been the embrace of hybrid work, allowing employees to blend traditional office settings and remote work from home or other locations. Remote and onsite work can be viewed as the extremes within this continuum, with hybrid work offering a middle ground that promotes balance, flexibility, and adaptability. From 2019 to 2021, the proportion of individuals primarily working from home in the US surged from 5.7% to 17.9%, with the District of Columbia leading at 48.3% [4]. As organizations and individuals adapt to this evolving landscape, it becomes crucial to comprehensively assess the impact of hybrid work on environmental and social sustainability for informing and crafting effective policies that maximize the benefits for individuals, organizations, and society at large.

The sector-specific ramifications and wider effects of hybrid work warrant close scrutiny, especially considering the rebound effects and the so-called "hybrid paradox" [5-7]. Hybrid work is anticipated to offer environmental benefits by reducing commuting and office workspace needs, but the rebound effects inject considerable uncertainty into the overall environmental consequences due to the intricate interactions with the behavioral and economic factors. A thorough review of existing studies on sectors affected by hybrid work, along with an examination of the energy and environmental implications, is thus essential to gain valuable insights into the multifaceted impacts and to identify the potential trade-offs and complexities associated with this new work arrangement. Previous studies on the environmental implications of hybrid work have been limited in scope, focusing on isolated aspects or short- to mid-term consequences, with little exploration of long-term consequences and no consideration of geospatial inequalities, leaving significant knowledge gaps in the comprehensive assessment and understanding of its system-level environmental consequences, including aspects such as rebound effects, geospatial inequalities, and long-term implications. To fill the knowledge gap, we propose perspectives for a holistic examination of the system-level energy and environmental sustainability of hybrid work across immediate, short-term, mid-term, and long-term time frames, and under various plausible future socio-economic scenarios [8-10]. The concept of “hybrid paradox” encapsulates the challenges and contradictions stemming from hybrid work [6, 7, 11], such as issues related to communication, collaboration, and employee well-being, despite its advantages in flexibility. An emerging solution may lie in the concept of fully immersive hybrid work enabled by the metaverse, which promises to mitigate these challenges [12, 13]. With its virtual and interactive nature, the metaverse has the potential to enhance collaboration, communication, and engagement among hybrid workers, seamlessly blending physical and virtual work environments, and amplifying the benefits of both remote and onsite work. In this context, we propose an exploration of the energy and environmental potentials of this futuristic workplace paradigm, establishing it as a vital direction for future research. The rest of this paper is organized as follows. An overview of the potential impacts of hybrid work on the transportation, residential, commercial, industrial, and information and communication technology (ICT) sectors is given in the next section. It is followed by a comprehensive review of existing studies concerning the environmental impacts of hybrid work, identifying significant knowledge gaps. It is worth mentioning that the scope of the overview is constrained by limitations in internet connectivity and the proportion of workers suitable for remote work in many developing countries [14-16]. Consequently, the geographical coverage is focused on major economies, and the findings may not be entirely generalizable to the developing nations. We further delve into the challenges and tentative solutions related to three core areas: (1) examining the immediate, short-term, and mid-term system-level environmental sustainability of hybrid work with a focus on rebound effects and geospatial inequalities; (2) evaluating the long-term system-level climate consequences of hybrid work under the Shared Socioeconomic Pathways (SSP) narratives; and (3) exploring the energy and environmental prospects of fully immersive hybrid work, a concept aimed at enhancing onsite work substitution while minimizing its negative impacts, such as silo-effects, barriers to information exchange, and challenges in nurturing and maintaining social relationships. Concluding remarks are presented in the last section.

2. Sectors affected by hybrid work adoption

In this section, we discuss the sectors most relevant to hybrid work adoption and provide background context for their impact from energy, environmental, and climate perspectives.

2.1. Information and Communication Technology sector

The COVID-19 pandemic led to a significant surge in global internet traffic, with a peak growth rate of 47% in 2020 compared to the forecasted 28%, driven by remote work and learning, causing more reliance on the internet [17, 18]. Existing studies have often overlooked or inadequately evaluated the energy and environmental impacts related to ICT usage, particularly those associated with networks and data centers [19-21]. Recent studies on virtual conferences and hybrid work included ICT devices, networks, and data centers in their system boundaries [22, 23]. However, the primary challenge lies in accurately quantifying and projecting the data traffic associated with teleworking [21]. Surges in data transmission and storage, coupled with the demands for a high-quality internet connection essential for remote work, can exert additional pressure on the power grid and ICT infrastructure. A thorough estimate of the anticipated increase in electricity demand and ICT infrastructure demand is essential for informed planning and effective resource management in the face of these challenges.

Remote work led to persistent changes in employees' communication behavior, with WFH employees increasing individual messaging and group video call communication, even on days they were in the office [24]. Moreover, hybrid work may lead to silo effects for individuals, indicating that employees in such arrangements might experience increased electronic communication within their existing close contacts and team members, potentially limiting their networking and the development of weaker ties with others in the office [24, 25]. The transition to remote work has led to a decrease in synchronous communication (such as scheduled meetings and audio/video calls) and an increase in asynchronous communication (such as emails and instant messages). This shift may potentially make it more challenging for workers to convey and comprehend complex information [25].

Although the current bandwidth is generally adequate for traditional videoconferencing tools, some households still lack access to at least 200 kbps in one direction, falling below the recommended standard of 600 kbps for both upload and download directions in video calling [26, 27]. The metaverse, which blends physical and digital worlds to create a seamless, responsive, and immersive virtual experience for remote work, may alleviate some of the negative impacts of conventional remote work. These include the silo effects, obstacles to informational exchange, and difficulty in building and maintaining social relationships [28, 29]. However, the bandwidth requirements for fully immersive and smooth metaverse applications are considerable, necessitating at least 2.35 Gbps [30].

2.2. Transportation sector

The transportation sector has experienced significant transformations with the widespread adoption of hybrid work, prompting numerous studies to investigate its impact on commuting patterns, travel behavior, and overall transportation demand in different countries. Despite varying methodologies and regional contexts, these studies have revealed similarities and differences in the effects of flexible work.

Telecommuting policies have shown promise in mitigating transportation challenges. First, many studies observe a shift in peak travel hours and changes in mobility patterns due to the flexibility offered by telecommuting [31-33]. A large-scale study in the Chicago region showed that, if 50% of workers have flexible working hours, it can reduce total daily vehicle miles traveled and vehicle hours traveled by up to 0.69% and 2.09%, respectively, underscoring its effectiveness in curbing network congestion and vehicular emissions during rush hours [34]. Teleworking practices in companies in the Brussels Capital Region could lead to substantial savings in external costs of transport, calculated across six categories: climate change, air pollution, upstream and downstream processes, noise, accidents, and congestion. These savings are primarily attributed to the avoidance of commuting by car to the capital city and a reduction in congestion-related costs [31]. Notably, the potential for such cost savings is closely tied to the uncertain proportion of car commuting trips to the company headquarters that may be effectively replaced by teleworking from home or satellite offices [31]. While peak hours on working days have shifted and generally decreased, morning peak travel in Canada was not entirely avoided, partially due to child-related travel [35]. Moreover, weekends in multiple European countries experienced a noticeable uptick in congestion [32].

Second, teleworking can lead to reduced overall travel time and vehicle miles traveled, contributing to potential cost savings and congestion relief [33, 35, 36]. Telecommuters in the US tend to travel more vehicle miles for both work and non-work trips compared to non-telecommuters, leading to higher daily total vehicle miles traveled for households with telecommuters [36]. On average, a telecommuter traveled 38 vehicle miles more per day in 2001 and 45 vehicle miles more per day in 2009 compared to a non-telecommuter, with the impact of telecommuting on daily vehicle miles traveled showing an increasing trend over time [36]. In contrast, some studies found that teleworkers take fewer weekly trips but travel longer distances than traditional workers, and they make more medium and long-distance trips, possibly influenced by their higher income level [37-40]. Non-work-related trips made on teleworking days partially offset the avoided commute, resulting in a 67% reduction in overall distance traveled compared to non-telecommuting days [38]. However, telecommuters travel longer distances over a working week compared to non-teleworkers, and a rebound effect may occur. Also, the International Energy Agency (IEA) reported that the carbon footprint of those driving more than 6 km to work could likely be reduced by switching to remote working, whereas the carbon footprint of those driving less than 6 km or using public transport to work might increase due to higher residential energy consumption [41].

Third, hybrid work is often associated with lower air pollution and carbon footprints due to fewer work-related trips, but they may compensate with more non-work travel. Both a pre-pandemic study in Switzerland and an in-pandemic study in Spain reveal the potential benefits of hybrid work in reducing air pollution, particularly pollutants such as NO_2, SO_2, and PM10 [42, 43]. Workers with multiple workplaces and hybrid workers tend to travel more for both work and non-work purposes, resulting in higher CO_2 emissions. On the other hand, remote workers have lower carbon footprints due to fewer work-related trips, but they compensate with more non-work travel [44]. Although remote workers may travel longer distances, carbon emissions might not increase significantly if telecommuters rely more on public transportation as suggested in a Switzerland-based study [38]. Car ownership and income levels also play significant roles in influencing CO_2 emissions, with the main drivers of cars and high-income workers having higher carbon footprints [44]. Additionally, men tend to have higher CO_2 emissions than women due to longer distances traveled for work, and part-time workers report lower emission levels as they travel shorter distances for work trips [44].

Hybrid work has shown a correlation with the residential location choices of workers. Remote workers tend to live in metropolitan areas and large cities, particularly in the city center, likely due to the concentration of teleworkable employment positions and companies in these areas [37, 45]. Teleworkers in Switzerland live further away from their workplace compared to non-teleworkers, and this difference has been increasing over the years [38]. Teleworking is associated with an increase in tolerance for long-distance commuting [38]. Teleworking weakens the relationship between urban form and travel behavior on workdays [39]. For regular workers in Sweden, commuting to a fixed workplace is a major factor in their travel patterns, but teleworkers, who are anchored only to their residential location, have more flexibility in planning their daily activities and may travel differently. Urban form variables have less impact on travel time and distance for teleworkers compared to non-teleworkers. Car access remains a key determinant of travel distance for both groups. Living in less accessible neighborhoods tends to correlate with higher car ownership rates [40, 46]. This difference may be attributed to income variations, variations in household structure, and potentially location-based factors [46].

The effectiveness of teleworking varies among different worker groups. A UK-based study indicated that higher work-from-home (WFH) frequencies are linked to increased total weekly travel in single-worker households, but this association weakens and becomes insignificant in two-worker households, likely due to more efficient task division and travel redistribution among household members [40]. As a result, the increased travel by teleworkers is partially offset in two-worker households. In Canada, full-time working only from home is associated with a reduction in overall travel time (by 13 minutes on average), higher odds (77%) of meeting physical activity recommendations through non-motorized travel, and a reduced probability of taking trips during afternoon peak travel periods [35]. The Sweden-based study finds that full-day teleworkers make fewer and shorter trips, use active travel modes more frequently, and contribute to less rush-hour traffic, leading to reduced travel demand and congestion relief in the country [33]. However, part-day home working showed weaker relationships with these outcomes, and a rebound effect may be occurring with more non-work travel, though it does not fully offset the reduced work-related travel. The impact of telework on train transport in the Netherlands varies among different types of teleworkers, with the high willingness-to-telework group, consisting of frequent train travelers, experiencing the biggest impact during the pandemic and potentially leading to a decrease in train use in the future [47].

While remote and hybrid work models have shown promise in reducing transportation-related emissions and alleviating congestion, they also present challenges and opportunities for the transportation sector. One notable challenge is the potential decline in public transit revenues due to reduced ridership, which may strain the financial viability of public transportation systems. On the other hand, the rise of hybrid work could lead to increased demand for flexible mobility options, such as shared mobility services and microtransit solutions. These studies underline the importance of considering the interplay between hybrid work and transportation sectors, to inform sustainable policies and infrastructure planning for future urban mobility needs.

2.3. Residential sector

The shift to remote work significantly increased housing demand, leading to sharp increases in house prices and rents [48]. In the US, remote work is estimated to account for at least half of the 24% increase in house prices between December 2019 and November 2021, and migration effects have contributed as well [48]. The future trajectory of housing costs may be influenced by the persistence or reversal of remote work, which could affect inflation and potential policy responses. Panel data from various cities consistently demonstrate a flattening trend in house price CBD-distance gradients [49]. Before the COVID pandemic, US households with at least one remote worker spent a higher percentage of their income on housing compared to similar non-remote households [46]. Specifically, renting households with remote workers spent 6.5% to 7.4% more on housing, while homeowners spent 8.4% to 9.8% more on mortgage payments and property taxes. Remote households also consumed more living space, about 5% to 7% more rooms per dwelling, and lived in higher-quality housing [46]. Remote households tended to live in slightly higher-priced areas, though these differences in location sorting did not offset their higher housing expenditure share. Larger homes were likely chosen by remote households to accommodate the need for home offices, as savings on vehicles did not fully explain the increased housing consumption.

During the second quarter of 2020, residential electricity consumption in the US increased by 10%, while commercial and industrial usage decreased by 12% and 14% respectively [50]. Residential consumption also rose by 16% during work hours compared to normal times [50], mainly due to non-HVAC residential loads [51], and this rise was associated with the share of the labor force working from home [50, 52]. A substantial shift to remote work could move the peak power demand from the evening to the middle of the day, presenting an opportunity for decision-makers to invest in demand-side flexibility resources in the household sector [52]. Lower and higher-income households experienced larger consumption increases in contrast to middle-income groups [51]. US residents who worked from home spent less time working and on personal care but more time on leisure, sleep, and food production and consumption at home [53, 54]. This suggests that working from home may allow for health-promoting dietary behaviors, though the causal relationship is not established [53].

2.4. Commercial sector

Pre-COVID-19, city centers were attractive to commercial tenants, with higher rents associated with proximity to central business districts, transit stations, and higher employment density. But post-COVID-19, the appeal of city centers and density weakened, even though they still retained some level of attractiveness [55]. A study on office markets in the US found a significant 17.54% decrease in lease revenue between January 2020 and May 2022, with a "flight to quality" observed as higher-quality buildings performed better, while lower-quality office stock faced challenges and potential repurposing [56]. Additionally, there was a 44.80% reduction in the value of the entire NYC office stock from 2019 to 2020, and simulations indicated substantial uncertainty about future office values and WFH risk, with values potentially stabilizing around 39.18% below 2019 levels or dropping by 59.86% if the WFH trend persists [56]. Furthermore, if remote workers relocate, retail activities may shift from urban centers to suburbs, a shift that could potentially revitalize struggling suburban malls, and online shopping continues to rise as a habit accelerated during the pandemic [57]. However, a Netherlands-based study suggests only an insignificant causal effect of ICT on commuting distance [58].

Teleworking indirectly increases online shopping and reduces mandatory and maintenance tours, with mandatory tours reducing maintenance tours and online shopping, while maintenance tours positively impact discretionary tours [59]. Moreover, working from home was linked to higher compulsive buying behavior, a link that is mediated by feelings of loneliness among employees during the pandemic [60].

2.5. Industrial sector

The existing evidence regarding the productivity of remote workers compared to on-site workers is limited and inconclusive [57]. The feasibility of remote work is occupation-dependent, and research indicates that up to 37% of jobs in the United States can be fully performed from home, with substantial variation observed across cities and industries [61, 62]. Therefore, our examination of employee productivity in different industries assumes the capability to work remotely as a prerequisite. Appropriate telework hours increase productivity, but excessive telework hours decrease productivity [63]. Telework also increases life satisfaction, which in turn improves productivity, but it also leads to stress in balancing work and domestic chores, thus reducing life satisfaction, although this stress does not directly impact productivity [63]. Life stages and family dynamics are associated with higher work-to-family conflict and family-to-work conflict, while WFH may exacerbate work-related fatigue and worsen work-life balance [64, 65]. The efficiency of telework in improving productivity is higher for workers with longer commutes or crowded rush-hour commutes, and it can help workers avoid trivial duties that may otherwise hinder productivity [63]. Working patterns shifted with more time spent in larger group meetings, less focus time, and narrowed networks [66]. Employees with longer tenure and greater career experience adapted better to remote work, while those with children at home and women experienced greater declines in productivity, possibly due to other domestic demands [66]. Additionally, the shift from WFH to working from anywhere can help improve productivity [67].

There is significant variation across occupations in the share of jobs that can be performed at home, with higher-earning occupations having higher work-from-home potential [61]. Moreover, working outside the office may negatively affect productivity for dull tasks but positively affect productivity for more creative tasks [68]. Flexibility in the workplace may be crucial for enhancing productivity in creative tasks, while peer effects and other factors could also play significant roles in productivity increases [68]. On the contrary, another study indicated that high-skilled employees in cognitively demanding jobs significantly increased their working hours but experienced a decline in productivity, estimating an average decline of 8% to 19% in employee output per hour of work, possibly due to challenges in coordination and communication [66]. More specifically, remote work led to a more static and isolated collaboration network, reducing bridges between different parts of the organization and hindering information sharing due to decreased synchronous communication and increased asynchronous communication [25]. Lastly, a survey in a Japanese institute during the pandemic reveals that teleworking productivity is generally low, with researchers showing higher relative productivity compared to managers and staff but significant variation in productivity even within the same occupation [69].

3. Knowledge gaps on rebound effects, geospatial inequality, and long-term environmental implications of hybrid work

Existing research on the environmental implications of hybrid work has shown a fragmented understanding, with studies often focusing on isolated aspects such as reduced commuting or office energy consumption [20, 21]. While these findings provide valuable insights, there is a critical knowledge gap in systematically and comprehensively assessing the short- and mid-term system-level environmental consequences of hybrid work. Such an analysis should consider all rebound effects, including changes in travel behavior, energy usage, work productivity, and consumption patterns, while also accounting for geospatial inequalities in cost and time savings and variations in occupational distributions. By examining these aspects together, a more holistic understanding of hybrid work's environmental impact can be achieved, enabling informed policy decisions and sustainable work arrangements.

Despite the importance of understanding the long-term environmental implications of hybrid work, few studies have delved into this area. The lack of exploration into the future effects on climate change, energy consumption, and resource utilization is partly due to the uncertain future and limited availability of projection data. Bridging this knowledge gap is crucial for developing strategies that anticipate and address potential long-term environmental challenges associated with the widespread adoption of hybrid work. Investigating the system-level consequences under different SSP scenarios would provide valuable insights into the varying impacts of hybrid work on the environment over time, offering guidance for sustainable work policies and practices in the years to come. Notably, the renewable energy transition can have a significant positive impact on the future environmental footprint of hybrid work. By incorporating more renewables into the power grid and space heating to support communication technology, remote work environments, and electrified transport, the carbon footprint of hybrid work can be substantially reduced, fostering a more sustainable work model. However, climate change mitigation benefits of hybrid work may be weaker, as both the commute and office workplace are being concurrently decarbonized.

Another significant knowledge gap lies in the limited consideration of promising future technologies that could enhance hybrid work experiences and mitigate associated drawbacks. One such technology is the metaverse, which offers fully immersive virtual work environments that could bridge the gap between remote and onsite employees. By integrating metaverse platforms into hybrid work arrangements, individuals can experience a more connected and inclusive work environment, potentially resolving the hybrid paradox of feeling disconnected from the workplace. However, few studies have explored the potential of metaverse technology in enhancing hybrid work experiences and its impact on environmental sustainability [29]. A thorough investigation of this aspect could provide valuable insights into how emerging technologies can shape the future of work and its environmental implications.

While some studies have investigated environmental impacts at the individual and building levels, few have conducted comprehensive geospatial analyses [70]. Understanding the regional-scale consequences of hybrid work is essential for targeted policy formulation and ensuring equitable benefits across different areas. Geospatial disparities, such as variations in access to high-speed digital resources and transport infrastructure, can significantly influence the environmental impact of hybrid work in different regions [71]. Conversely, the adoption of hybrid work may result in increased geographical inequalities in disposable income and time use allocation due to the uneven concentration of certain industries and job sectors. By addressing this knowledge gap and accounting for geospatial disparities, policymakers can design more effective strategies to maximize the environmental benefits of hybrid work and promote sustainable practices across diverse socio-economic contexts.

In summary, addressing the knowledge gaps in previous studies on the environmental implications of hybrid work requires a more systematic and comprehensive approach. Integrating short-, mid-, and long-term perspectives, considering the potential of emerging technologies, and conducting geospatial analysis are all vital steps in advancing our understanding of the environmental consequences of hybrid work. By closing these gaps, policymakers and organizations can make informed decisions to promote sustainable and environmentally friendly work practices in the era of hybrid work.

Table 1 Summary of recent studies on the environmental consequences of hybrid work. Immediate and short-term impacts encompass the direct and near-future consequences of implementing hybrid or remote work arrangements. Mid-term impacts entail sustained changes resulting from ongoing adjustments and adaptations, including delayed responses in human and corporate decisions and changes in congestion. Long-term impacts involve alterations in city structure, socioeconomic characteristics, and the incorporation of various future trajectories and projections.

Scope of impact	Method	Metric	Affected sectors	Rebound effect	Temporal scale	Spatial scale	Country	Note	Reference
Immediate/ short-term	Survey data analysis	Carbon emission	Transport	Concluded from the literature review	Cross-sectional; pre-pandemic	City level	China	Telework penetration among different industries	[70]
Immediate/ short-term	Simulation	Energy use and carbon emission	Residential		Cross-sectional	Household level	UK		[72]
Mid-term	Survey data analysis	Carbon emission	Transport	Non-commute trips and differences in travel patterns and residences	Repeated cross-sectional; pre-pandemic	Individual level	UK		[73]
Mid-term	Survey data analysis	Energy use and greenhouse gas (GHG) emission	Transport, residential, ICT	Non-commute trips	Longitudinal; in-pandemic	Individual level	Canada	A pilot study with a small sample size	[74]
Immediate/ short-term	Simulation	Energy use and GHG emission	Commercial	Partial occupancy, workspace arrangement, and building performance adaptation to variable occupancy		Building and individual level	Canada	Different climate zones and building configurations	[75]
Immediate/ short-term	Scenario analysis	GHG emission	Transport, residential, commercial	Sensitivity analysis on rebound trips and building repurposing	Cross-sectional	Region level	UK		[76]
Mid-term	Scenario analysis	GHG emission	Transport, residential, commercial, ICT	Increase in daily travel distance, larger house size, and increased number of occupants, which are all concluded from the literature review	Cross-sectional; in-pandemic	Country level	Canada		[77]

Mid-term	Scenario analysis	Abiotic depletion, global warming, human toxicity, photochemical oxidation	Transport, residential, commercial, ICT	Non-commute trips and residential appliance use	Cross-sectional	Individual level	Australia		[78]
Immediate/ short-term	Scenario analysis	GHG emission	Transport, ICT		Cross-sectional	Individual level	France		[79]
Immediate/ short-term	Survey data analysis	GHG emission	Transport		Cross-sectional	Individual level	Global		[80]
Immediate/ short-term	Survey data analysis	GHG emission	Transport		Cross-sectional	Individual level	Switzerland	Spatial analysis on the urban-rural differences in coworking	[81]
Mid-term	Scenario analysis	Energy use and GHG emission	Transport, residential, commercial, ICT	Non-commute trips	Cross-sectional	Individual level	US		[19]
Mid-term	Scenario analysis	GHG emission	Transport, residential, commercial, ICT	Non-commute trips and differences in travel patterns for both commute and non-commute trips, variable occupancy and building headcount, time-use based appliance use, changes in the collaboration behaviors of workers	Cross-sectional	Individual level	US	Comprehensive modeling	[23]
Immediate/ short-term	Survey data analysis	GHG emission	Transport, residential		Cross-sectional	Individual level	Ireland	Preference for remote work based on commute distance, land use pattern, public transport, internet	[82]

								infrastructure, occupation, and other socio-demographic characteristics.	
Mid- to long-term	Simulation	Energy use and GHG emission	Transport	Household relocation and congestion mitigation, larger house size, city land area expansion.		City level	US	Urban structure evolution with the remote work adoption	[83]
Immediate/ short-term	Survey data analysis	Energy use	Residential	Office space arrangement and energy efficiency of appliances	Cross-sectional	Individual level	Japan		[84]
Mid-term	Simulation	Energy use	Transport, residential, commercial	Reduced congestion		City level	German		[85]
Mid-term	Simulation and survey data analysis	GHG emission	Transport	Changes in network congestion and vehicular fuel use		City level	US	Preference for remote work	[34]

4. Perspectives

Previous studies have primarily examined the environmental impacts of hybrid work at the individual or company level, yet a comprehensive understanding of the system-level environmental implications of this emerging paradigm remains lacking. To address this knowledge gap, we present a comprehensive multi-term analytics and modeling framework that investigates the environmental consequences of hybrid work across different timeframes, encompassing the short, mid, and long term, and considering the intricate socio-economic dynamics and technological advancements, as depicted in **Fig. 1Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.**.

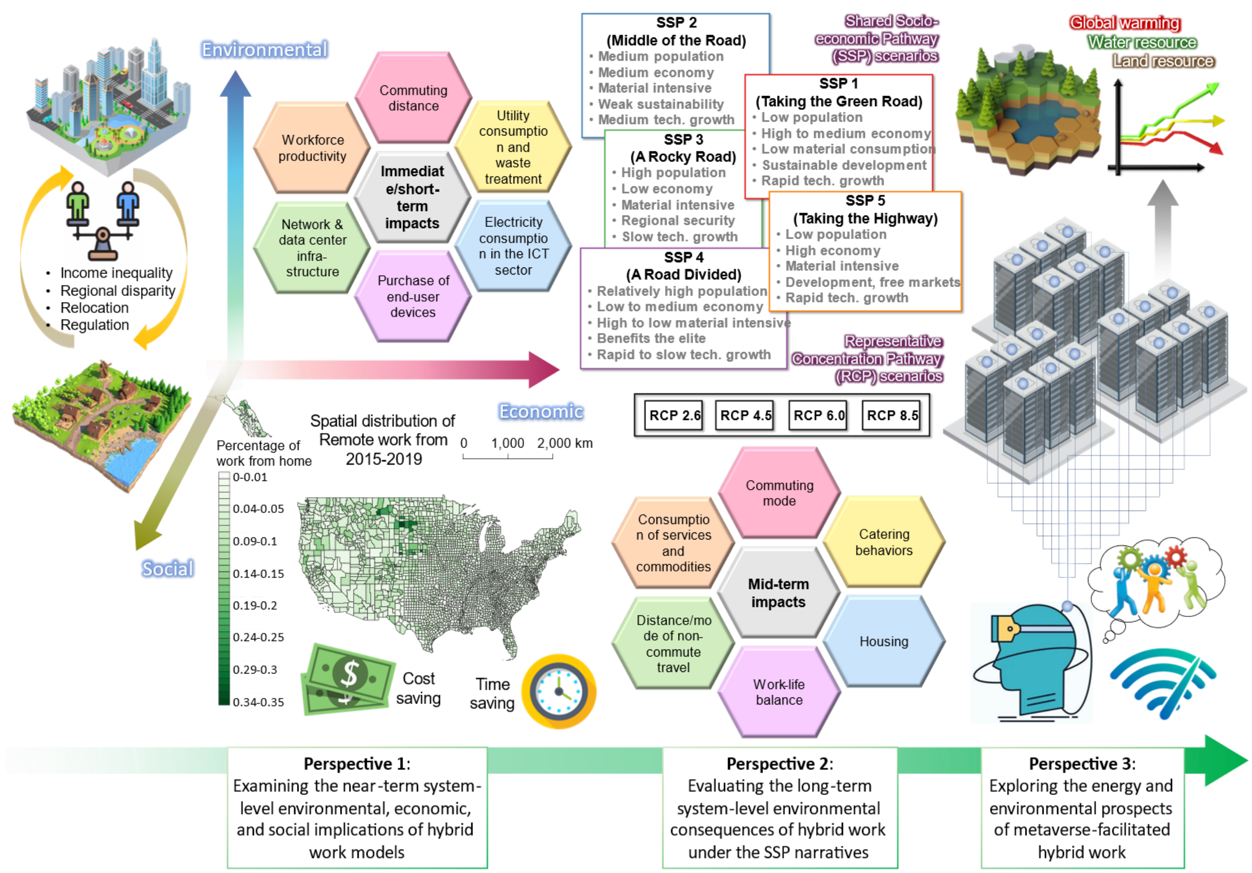

Fig. 1. Schematic of the multi-term analytics and modeling assessment framework for the environmental consequences of hybrid work.

4.1. Examining the near-term system-level environmental sustainability of hybrid work with comprehensive assessment of rebound effects and geospatial inequalities

Hybrid work could offer a higher level of flexibility for work styles and better accommodate people's needs. Hybrid work would not only change when and where to work but also could deeply and structurally reshape the lifestyles of the workforce. Although previous studies have quantified a few aspects of the individual- or organizational-level climate change mitigation potential of hybrid work, the system-level consequences remain unclear, which hinders policymakers from developing effective strategies and guidelines as part of broader sustainability initiatives. To gain insights into the potential nationwide environmental and social benefits and challenges of the hybrid work model by 2030, it is essential to address three key research challenges, each accompanied by tentative solutions. We choose to use the US as an illustrative example because it is the largest economy, extensively studied in the context of remote work, and exhibits a high level of adaptability to remote work practices, along with readily available data.

The first research challenge is to identify the magnitude of GHG emissions reduction achieved through the adoption of hybrid work models in the US compared to traditional office-based work. Consideration should be given to the immediate, short-term, and mid-term impacts of hybrid work in the affected sectors. Immediate and short-term impacts refer to the effects that arise directly or shortly after transitioning from in-person to hybrid or remote work arrangements. It includes changes in (1) commuting distance, (2) consumption of utilities and waste treatment in the residential, industrial, and commercial sectors, (3) electricity consumption in the ICT sector for teleworking-related applications, (4) purchase of end-user devices, (5) demand for network and data center infrastructure, (6) workforce productivity. Mid-term impacts involve more sustained changes or outcomes that reflect the ongoing adjustments, adaptations, and developments within an intermediate timeframe. Mid-term impacts include changes in (1) commuting mode, (2) distance and mode of non-commute travel, (3) consumption of services and commodities, (4) catering behaviors, (5) housing, and (6) work-life balance (time allocation).

There are also challenges associated with investigating the geospatial implications of hybrid work in terms of job distribution, income inequality, and divide in time use allocation in the US [86]. Remote or hybrid work is not a viable choice for all workers. Therefore, to determine the upper bound of the climate change mitigation potential of hybrid work, it is essential to quantify the ratio of workers who are feasible to work remotely. According to the US Bureau of Labor

Statistics, total employment is expected to expand by 5% from 2021 to 2023, with the fastest growth in caregiving, catering, and information technology-related occupations, due to long-term structural changes in consumers' demand for goods and services [87]. Estimating becomes more intricate in developing countries, particularly low-income ones. Limited internet connectivity, constrained by local ICT infrastructure, restricted availability of residential space often lead to an overestimation of remote work feasibility [14]. Moreover, the occupational structure of employment and the fraction of unemployed in the developing countries are largely different from those in the developed countries. Jobs in developed countries often involve a higher degree of cognitive and interpersonal tasks, making them well-suited for remote work. In contrast, jobs in developing countries tend to be more focused on routine, physical, and manual tasks, which are less conducive to remote work [88]. The varying levels of industrialization and technological advancement contribute to significant differences in job requirements for the same occupation across these regions. Future research on sustainable hybrid work should be attentive to technological and social constraints. Emphasis should be placed on exploring how advancements in infrastructure and technology influence the prevalence and dynamics of hybrid work and examining the resilience of socio-economic status in adapting to hybrid work. Counterintuitively, remote work amplifies the existing spatial inequalities in labor markets, with lucrative jobs gravitating towards tech-savvy metropolises and rural areas experiencing disadvantages. These inequalities are further intensified in the platform economy where supply and demand operate without regulatory barriers, resulting in heightened global competition [45]. On the other hand, evidence during the COVID-19 pandemic shows that remote work led to significant outflows of high-skill workers from big cities to less dense areas, impacting consumer service industries in these cities and causing declines in both residential rents and consumer service spending, which highlights the occupational and regional disparities in remote work and raises implications for the future of urban centers [89].

The final challenge lies in interpreting how different policy frameworks, incentives, and support mechanisms would influence the environmental outcomes induced by hybrid work at the country level. The identified environmental hotspots and sensitivity analysis can inform policymakers in developing strategies and guidelines to promote hybrid work models as part of broader sustainability initiatives. Governments may consider implementing incentives or regulations that encourage companies to adopt hybrid work arrangements to reduce commuting-related emissions and resource consumption.

This research aims to bridge the knowledge gap regarding the comprehensive assessment of short- and mid-term system-level environmental consequences of hybrid work, encompassing all rebound effects and addressing geospatial inequalities in cost and time savings, as well as variations in occupational distributions. By addressing these gaps, this first comprehensive and systematic research contributes valuable insights into the multifaceted environmental consequences of hybrid work, aiding in the development of informed policies and sustainable work arrangements for the near future in the US.

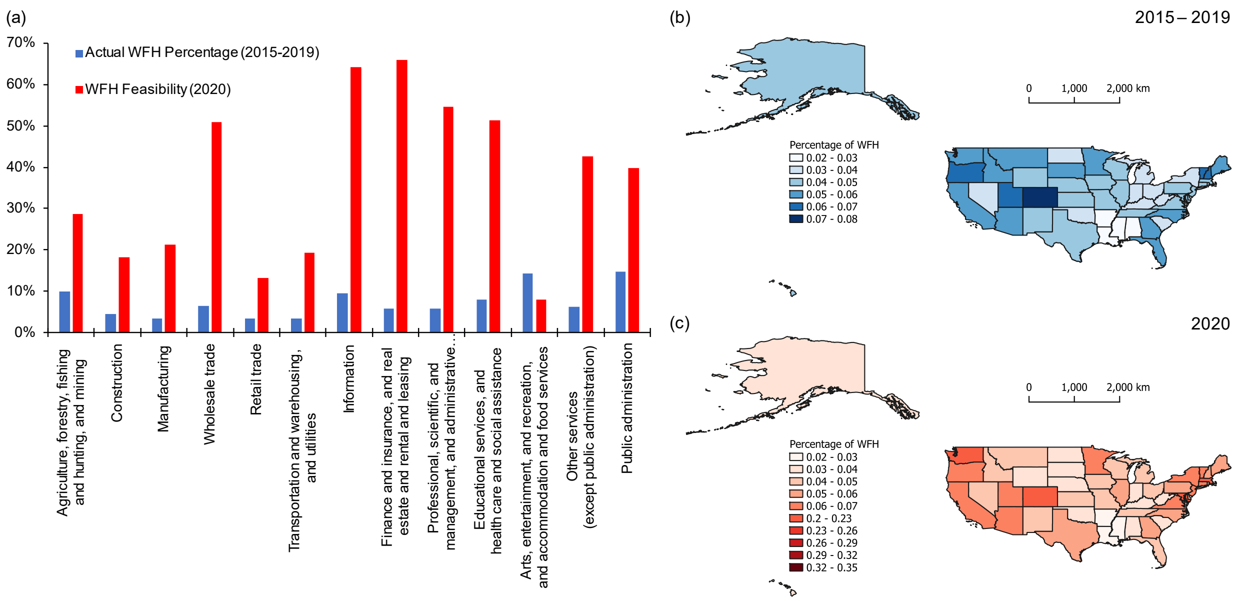

Fig. 2. Historical average percentage and feasibility of WFH by industry and by state in the US. **(a)** Comparison of average percentage of WFH from 2015 to 2019 and feasibility of WFH in 2020 by industry in the US [90, 91], **(b)** Average percentage of WFH by state in the US from 2015 to 2019 [91], **(c)** Average percentage of WFH by state in the US in 2020 [92].

4.2. Evaluating the long-term system-level climate consequences of hybrid work under the SSP narratives

In the previous section, we propose a perspective that fosters a predictive and exploratory approach to investigate the immediate, short-term, and mid-term impacts of hybrid work at the system level. As hybrid work continues to shape the future of work arrangements, it is crucial to examine its long-term macroscopic impacts under different normative scenarios driven by specific policy goals or desired visions for the future [8]. The SSPs serve as a framework developed by the

Intergovernmental Panel on Climate Change (IPCC) to explore different socioeconomic and climate development trajectories [93]. These pathways provide scenarios that consider various factors, such as technological advancements, economic dynamics, demographic changes, and policy frameworks. Examining hybrid work within the context of the SSP narratives allows us to evaluate the alignment of hybrid work with these future trajectories in the US and understand the potential interactions and implications for broader socioeconomic dynamics by 2050.

Systematically evaluating the potential long-term environmental consequences of shifts from in-person to hybrid work under the SSP narratives poses several challenges. The first challenge is associated with gathering comprehensive and reliable data on the long-term temporal and spatial heterogeneity, including variations in population density, infrastructure development, resource availability, energy systems, and climate policy across different regions. The integrated assessment model (IAM) serves as a comprehensive and powerful tool to investigate the long-term system-level environmental consequences of hybrid work as it integrates multiple disciplines and variables to capture the complex interactions and feedback loops between environmental, social, and economic factors, aiding in policy assessment and decision-making [94, 95]. However, research challenges in integrating the changes brought by hybrid work with the IAM model include issues of transparency, interpretability, complexity, uncertainties, and most importantly, model and data availability [96, 97]. Instead, to address the research challenges while also preserving the coherent SSP narratives, the Prospective Environmental Impact Assessment (PREMISE) model that generates prospective life cycle inventory databases based on the ecoinvent database and under the socioeconomic pathways and climate change mitigation targets from the IAM could be considered [96]. This model enables the integration of expected transformations in energy-intensive sectors (power generation, transportation, fuel supply, and cement and steel production), compatibility across different IAMs, and the export of prospective life cycle inventory (LCI) databases to diverse life cycle assessment (LCA) software, offering consistent, transparent, comprehensive and flexible analysis capabilities. As prospective LCI is derived by incorporating the outputs of prospective scenarios of IAM into the currently available static LCI database, this research can provide a more accurate and robust assessment of the environmental consequences of hybrid work, allowing for a comprehensive and realistic representation of the system-level impacts. However, it falls short in capturing the complex interactions and feedback loops inherent in the IAM framework between the adaptation to hybrid work and the environmental, social, and economic factors of different SSP scenarios, prioritizing simplicity instead. The third research challenge is to handle the uncertainty in the long-term adaptation of hybrid work [98]. The level of adaptation to hybrid work is influenced by behavioral changes, technological advancement, organizational and policy changes, as well as socioeconomic and cultural factors. Therefore, it is essential to construct adaptation scenarios that encompass both opportunities for new normality and potential reversion to pre-pandemic levels. Finally, due to the complex nature of the IAM model and SSP narratives, translating complex research outcomes into actionable insights and policy recommendations that align with sustainability goals and inform effective decision-making poses a challenge. This research fills the knowledge gap related to the limited exploration of the long-term environmental implications of hybrid work under various socio-economic scenarios, which has been hindered by uncertainties about the future and data availability.

By employing these normative scenarios of IAMs, the focus shifts from purely predictive analysis to a more purposeful assessment of how different policy interventions and actions can help achieve the desired environmental outcomes with various extents of adaptation to hybrid work by 2050 in the US, ranging from minimal implementation to extensive integration across organizations or individuals. The research can provide evidence-based recommendations for promoting sustainable practices, optimizing resource use, and minimizing environmental footprint in the context of the expansion of hybrid work. Specifically, it can help inform socioeconomic policies related to transport and digital infrastructure that support the transition to hybrid work in the US. Additionally, climate policies can be developed to incentivize the implementation of climate change-mitigating hybrid work practices. The surge in residential energy use due to the widespread adoption of hybrid work, coupled with potential reductions in commercial and industrial energy use, may necessitate a reevaluation of energy planning and renewable energy implementation strategies, as the energy use peak could shift to accommodate the changing work patterns and distribution of energy consumption. This approach can be utilized to evaluate the long-term, system-level climate impacts of hybrid work within the context of the SSP narratives in developing countries. This is particularly relevant since many commonly used IAM have a global perspective, and some lack sufficient geographic resolution at the country level [99].

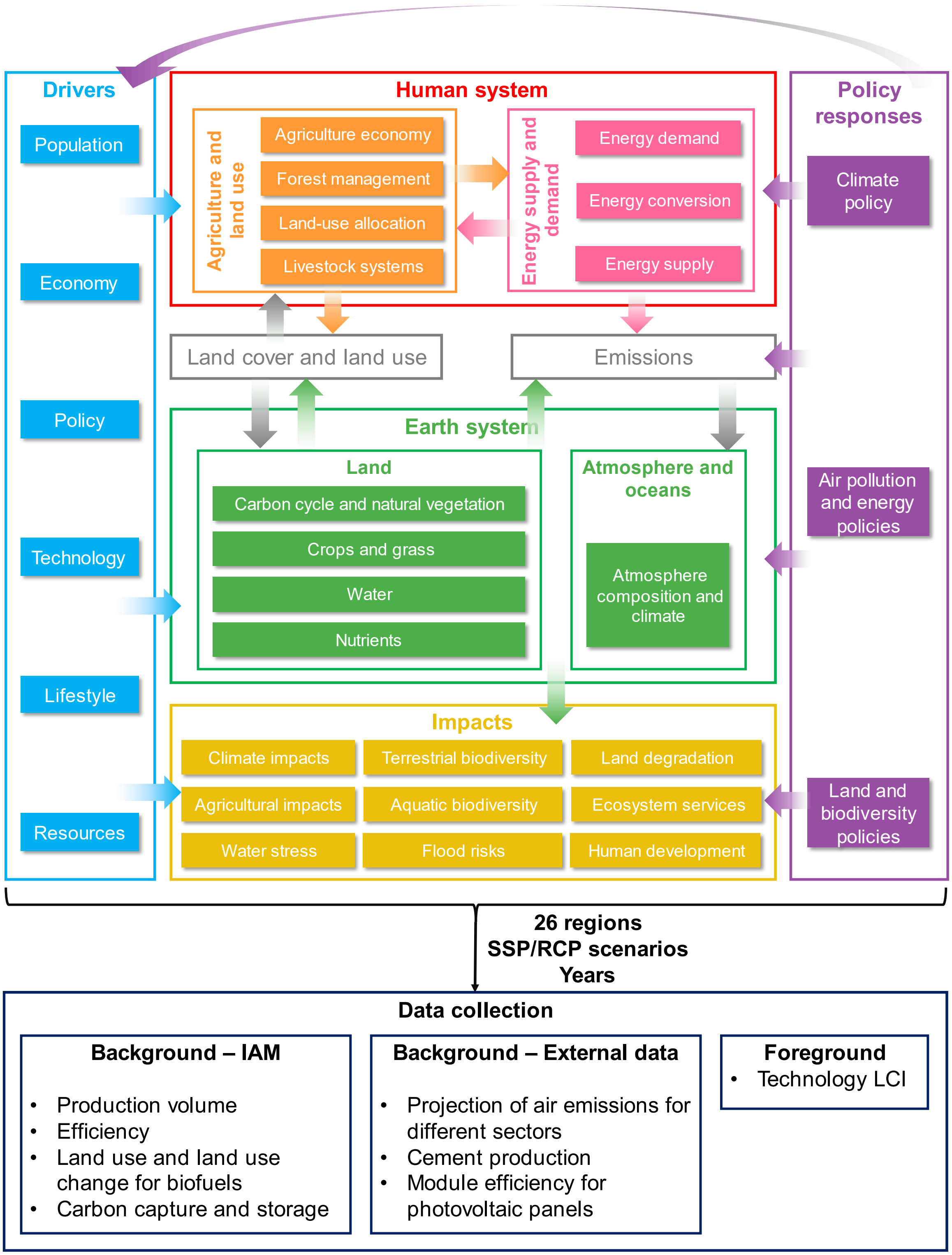

Fig. 3. Overview of the PREMISE model. The background data from IMAGE 3.2 model is used as an illustration to integrate with external background data and foreground technology LCI to perform the IAM-based prospective LCA [100, 101].

4.3. Exploring the energy and environmental prospects of fully immersive hybrid work to address the hybrid paradox

The COVID-19 pandemic has propelled the world towards rapid digital transformation and the adoption of innovative technologies to reshape societal dynamics. Alongside the widespread implementation of conventional virtual conferences and hybrid work models, the industrial sector is projected to embrace robotics, automated systems, and augmented and virtual reality at a rate of approximately 60% by 2025 [102]. High-performance computing is playing a crucial role in facilitating the European Union's green transition through the development of a “digital twin of Earth” [103]. Looking ahead, the convergence of physical and digital realms is expected to flourish in the coming decades, facilitated by digital twins, mixed reality, and metaverse applications, bolstered by the support of Web 3.0.

The Metaverse has the potential to transform remote work by offering a virtual environment that enables seamless collaboration, meeting attendance, and realistic interactions among remote workers, simulating a shared physical space with a heightened sense of presence and immersion beyond what traditional online collaboration tools can provide [104]. However, the widespread adoption of computationally intensive digital transformation for hybrid work has the potential to significantly increase cumulative energy demand, posing a challenge to climate action efforts. It is important to note that the accelerated digital transformation not only leads to a surge in operational electricity consumption but also contributes to embodied emissions and marginal demand for computing hardware and infrastructure [105].

In contrast, virtual conferences, remote working, and the future mainstream realization of digital twins, mixed reality, and metaverse apps hold promise in delivering sustainability benefits through substituting for their counterpart activities in the physical world. The integration of the metaverse with everyday activities shows potential for positive effects on climate change mitigation, GHG emission reduction, air quality improvement, and energy supply alleviation, contributing to decarbonization and climate goals [29]. Furthermore, the implementation of artificial intelligence-based solutions to optimize climate change mitigation and adaptation strategies can yield immediate and system-level mitigation effects on greenhouse gas emissions [105]. The rapid global digital transformation can also induce market- and human behavior-related consequences, as indicated by existing literature, on the energy, climate, and environment profiles

[25, 48]. The net effects of the digital transformation, from conventional hybrid work to the future metaverse-facilitated work, are unclear from the energy and environmental perspective.

There remain multiple research challenges in projecting the net environmental impacts of metaverse-dependent hybrid work. The first challenge lies in predicting the expansion of high-speed networks with high bandwidth and low latency, which is a prerequisite for metaverse-based applications [106]. As of now, there is currently no available forecast of high-speed network coverage. A policy-directed outlook for high-speed network expansion could be informed by the recent commitment of the White House to connect every resident and small business to reliable, affordable high-speed internet by 2030, along with the previous implementation of policies to reduce internet service costs for eligible households [107]. Yet, as of 2021, the average internet penetration rates in lower-middle- and low-income countries stand at only 49% and 20%, respectively, according to the World Bank [108]. Thus, the expansion of metaverse-based applications will be compounded by the limited availability of high-speed networks, posing a significant technical barrier to their development. The second challenge involves estimating the energy and material consumption related to technological advancements in the progressive realization of immersive 3D experiences within the digital world. The third challenge is to understand the potential direct and indirect impacts on physical land resources and water availability due to the infrastructure requirements, energy demands, and cooling systems associated with supporting the metaverse ecosystem [109, 110]. The heightened demand for electricity can impact the resilience of power grids, potentially altering the composition of energy sources and regional strategies aimed at achieving carbon neutrality. This could also serve as a promising avenue for future exploration [29]. These findings can guide policymakers in aligning their climate and environmental goals with the potential opportunities and challenges arising from the integration of the metaverse into hybrid work scenarios.

This research addresses the knowledge gap pertaining to the limited consideration of promising future technologies, such as the metaverse, that have the potential to enhance hybrid work experiences, mitigate associated drawbacks, and resolve the hybrid paradox. Assessing the energy and environmental prospects of adopting fully immersive hybrid work facilitated by the metaverse has the potential to accelerate progress towards climate goals, improve air quality through reduced emissions, and transform energy systems to accommodate changing consumption patterns and increased renewable energy shares.

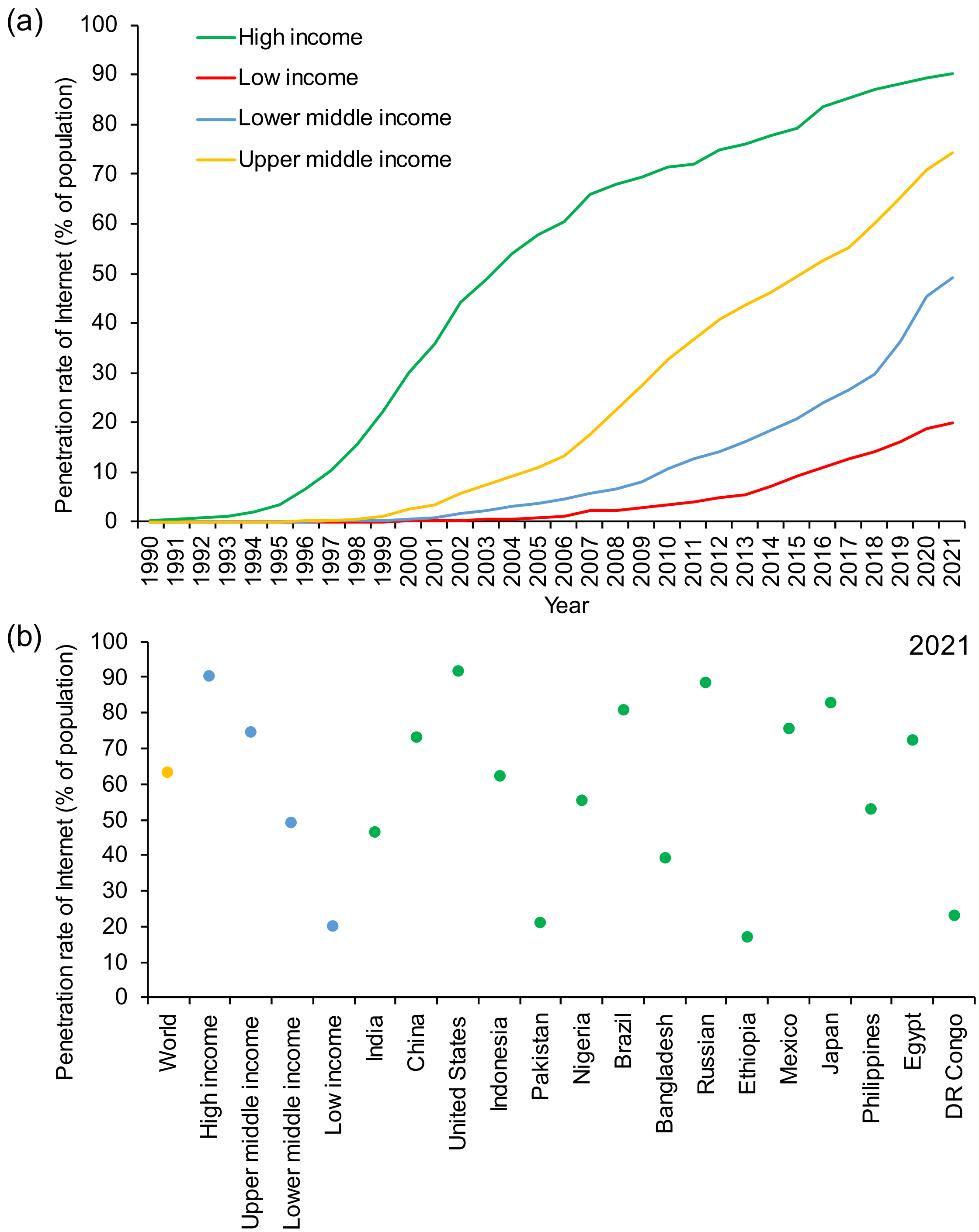

Fig. 4. Overview of penetration rate of Internet by 2021. **(a)** Average generation rate of Internet from 1990 to 2021 in high-, low-, lower-middle-, and upper-middle-income countries [108], **(b)** Generation rate of Internet from in 2021 in countries with population over 100-million people [108].

5. Conclusion

The adoption of hybrid work has revolutionized the traditional work environment, offering employees the flexibility to balance remote and onsite work. However, existing research on its environmental implications has exhibited a fragmented understanding, focusing on isolated aspects and short- to mid-term consequences, leaving critical knowledge gaps. The scope of the overview is constrained by limitations in internet connectivity and the proportion of workers suitable for remote work in many developing countries, focusing the geographical coverage on major economies and potentially limiting the generalizability of the findings to all developing nations. This perspective paper identified three key knowledge gaps: (1) the lack of systematic and comprehensive assessment of short- and mid-term system-level environmental consequences of hybrid work, which include considerations of all rebound effects and geospatial inequalities in cost and time savings and occupational distributions; (2) the limited exploration of the long-term environmental implications of hybrid work under various socio-economic scenarios, impeded by the uncertainty of the future and data availability; and (3) the insufficient consideration of emerging technologies, particularly the potential of the metaverse to resolve the hybrid paradox and enhance collaboration and communication among hybrid workers.

To address these gaps, this perspective paper proposed comprehensive examinations of the system-level energy and environmental sustainability of hybrid work in the US, encompassing immediate, short-term, and mid-term perspectives while also considering the long-term implications under various plausible scenarios by 2050. Additionally, integrating metaverse technology to create fully immersive hybrid work experiences offers a promising solution to address the hybrid paradox and foster a more inclusive and interconnected work environment. By bridging these research gaps, identifying potential research challenges, and offering promising solutions, this work aims to inform policymakers and organizations in making sustainable decisions, fostering a resilient future of work that optimizes environmental impacts while promoting well-being and productivity for employees and the broader society.

Finally, in future research, it is advisable to broaden the scope by investigating the sustainability impacts of hybrid work in upper-middle-income countries, which are less constrained by infrastructure and industrialization limitations. Additionally, researchers should explore incorporating the effects of this evolving workstyle into IAM to comprehensively understand the interactions between this shift, human development, and the natural environment.

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