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Effects of Working from Home on Greenhouse Gas Emissions and the Associated Energy Costs in Six Australian Cities

Satheeskumar Navaratnam [1,*], Amitha Jayalath [2] and Lu Aye [2,*]

[1] School of Engineering, RMIT University, Melbourne 3001, Australia
[2] Renewable Energy and Energy Efficiency Group, Department of Infrastructure Engineering, Faculty of Engineering and Information Technology, The University of Melbourne, Melbourne 3010, Australia; amitha.jayalath@unimelb.edu.au
* Correspondence: sathees.nava@rmit.edu.au (S.N.); lua@unimelb.edu.au (L.A.)

Abstract: Working from home (WFH) has been imposed due to the COVID-19 pandemic. The adoption of WFH impacts energy use in the residential, commercial, and transportation sectors. Consequently, this affects the greenhouse gas emission (GHGE) and the associated energy costs to workers and employers. This study estimates the effects of WFH on the GHGE and energy-related costs in the residential, commercial, and transportation sectors. A simple linear model was used to estimate the changes in the GHGEs and cost by a typical employee when WFH practice is adopted for 1.5 and 4 days per week. The adoption of WFH reduces the operational GHGE accounted for commercial buildings and transport. However, it increases the operational GHGE accounted for residential buildings, which is a maximum of about 6% and 12%, respectively, for WFH 1.5 and 4 days. The reduction of GHGE from transport is significantly higher than that of residential buildings. The GHGE reductions from the transport sector are about 30% and 80%, respectively, for WFH 1.5 days and 4 days per week. WFH for 1.5 and 4 days per week reduces the national annual GHGE by about 1.21 Mt CO_2-e and 5.76 Mt CO_2-e, respectively. Further, the annual transportation cost of an employee is reduced by 30% and 80% in each city when the employee WFH for 1.5 and 4 days per week. The outcomes of this study offer a direction to reduce energy consumption and related costs and potential future research avenues on this topic. Further, the findings also help policymakers develop a hybrid work model for the post-COVID-19 pandemic.

Keywords: building energy; cost data; greenhouse gas emission; office building; residential building; transport emission

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1. Introduction

Technological innovations have reshaped the traditional work practice, enabling flexible working arrangements such as flexibility in work hours (e.g., reduction in hours worked, changes to start/finish times), work practice (e.g., working 'split-shifts' or job-sharing arrangements), and workplaces (e.g., working from home or other locations) [1,2]. Working from home (WFH), also known as telework, can achieve the economic, social, and personal goals of employers, employees, and governments [3,4]. This WFH also helped the business through reduced operating costs and increased productivity, which is 40% higher than the traditional office work practice [4]. The WFH practice reduces transportation costs and travel duration for the employee, enhancing the work-life balance [4,5]. In addition, the WFH also allows the governments and private sectors to run their essential services without disturbance in the event of natural hazards or pandemic lockdown. Due to the numerous benefits of the WFH practice, many countries apply the WFH strategy. For example, in Europe, about 20 million people are practising WFH [6]. A similar number of people WFH in the US, and about 7.5% of the population practice this in the UK [6,7]. In 2018–2019, the Australian Bureau of Statistics (ABS) showed that about 43% of workers engage in WFH, which is expected to increase to 65% by 2020 [8].

Due to the COVID-19 pandemic, the number of people doing WFH increased significantly, in some cases by about 90% [9,10]. Consequently, this reduced the transport energy and related GHGEs [11]. On the other hand, it increased the energy consumption in residential houses. The estimated increase in energy consumption was between 7% and 23% [12]. The energy demand on residential buildings during the workday was higher when people practised WFH. This is because the heating and cooling system remains in operation and requires energy [13,14]. However, greater environmental benefits can be achieved with more energy-efficient houses and switching to cleaner or renewable energy sources at home [10]. Further, WFH generally reduces the energy and associate GHGEs from transport and office buildings [15]. This trend could vary during the COVID-19 pandemic period, as more people are practising WFH during this duration. Jiang, Fan & Klemeš [16] suggested that behaviour and lifestyle changes are also important in assessing net savings from WFH practices. Lister and Kamouri [17] highlighted that current WFH trends induced by the COVID-19 pandemic might be widespread post-COVID-19. Consequently, this will change the energy consumption and associate GHGEs related to the WFH. Therefore, it is necessary to assess the energy impact of WFH to create regulations and policies for developing sustainable cities and society in the post-COVID-19 world.

Previous studies highlighted that WFH means less transport activities consuming fossil energy, and related other emissions are reduced [18,19]. This also helps reduce air pollutants induced by transport, especially in cities, as there is more traffic demand and traffic congestion compared to other areas [18]. The adoption of WFH has a high potential to reduce peak traffic demand, traffic congestion, building space, and operational activities in the workplace [20]. The transport sector in Australia comprises 18.9% of the total GHGE [21]. The GHGE from private transport is higher than from public transport. Philip [22] stated that in Australia, a passenger traveling one km by car produces 171 g of CO_2 emissions, and 41 g when a passenger uses domestic rail. This indicates that reducing commuting can reduce the GHGE significantly. WFH practice may save about 242 kg of CO_2 emissions per person per year, a reduction of 5%. This will reduce GHGE by one million tonnes per year in Australia [23]. Tenailleau et al. [24] highlighted that the total distances travelled by car can reduce by 47,616 km through increasing the WFH population by 5.6%. Consequently, it reduces the GHGEs from a car by 2.6% for a typical medium-sized European city. Thus, WFH practice could be an option to reduce the GHGE from transportation.

Furthermore, many research studies highlighted that buildings and transportation are the main contributors to releasing a higher percentage of GHGEs during their life cycle [25,26]. Therefore, a better understanding of both transport and building energy consumption is needed when assessing urban energy usage, enabling the resource for the policymakers and planners to develop sustainable cities [27]. The buildings in Australia contribute 23% to the national GHGEs [28,29]. It is 43% in the US, and 50% in China and the UK during their life cycle [30]. These figures are higher than GHGEs from other sectors (i.e., industrial, transportation, or agricultural) [18,31,32]. This means there is great potential to reduce the GHGEs in the building sector.

The continued growth of population in the city demands more infrastructure. Consequently, this increases the energy demand and higher energy use compared to other urban areas [31]. This produces a significant amount of GHGEs in the environment. Thus, to enable sustainable cities, governments and the buildings industry should focus on Net Zero Energy Buildings (NZEBs) [32,33]. The primary objectives of the NZEB are to achieve Net-zero: (1) Site energy: producing the least energy as used in a year at the site; (2) Source energy: producing the least energy as used for the source; (3) Energy costs: money paid by the utility is equal to the energy exported to the grid, and (4) Energy emissions: producing at least as much emission-free renewable energy [34,35]. However, building sectors face challenges in adopting this NZEB concept as it requires investments in low-emissions infrastructure and buildings [36,37]. In this case, WFH practice could be a sustainable option to reduce energy consumption. The effect of WFH is more pronounced when employees are located more than 30 km away from the office [10]. Furthermore, the commuting patterns, type of office and home space, and equipment used also contribute to the effect of WFH practice on the environment.

Reducing the operational energy (i.e., heating, ventilation, cooling, lighting, appliances, and vertical transportation) is the first step when designing low-emissions infrastructure and buildings, as about 80% of building energy is used for operational energy [38,39]. The commercial building contributes a higher proportion of operation energy consumption predominantly by heating, cooling, lighting, and equipment use [40]. Generally, operational heating and cooling contribute about 75% of the total operation energy usage, and the rest is used by equipment and lighting [41,42]. The operational energy consumption can be reduced by reducing building space and operational activities. This indicates that WFH practices can reduce operational energy usage and related GHGE from a commercial building as it has the potential to reduce office space and reduce the use of heating, ventilation, cooling, lighting, and appliances. A recent study on the US high-rise office buildings by Corticos and Durate [43] showed that WFH practices with new HVAC settings can still reduce energy intensity in warm and very hot climates. However, this may increase the GHGE from the residential building as WFH practices require additional energy consumption in residential buildings.

Matthews and Williams [7] found that WFH practices reduce national-level energy consumption by 0.01–0.4% and 0.03–0.36% in the US and Japan, respectively. In Australia, the government expects that one in eight Australians will be practising WFH in 2020. An increase in the number of people who spend half their week working from home would cut peak hour traffic by 5%, save 120 mL of fuel and 320 kt of carbon [44]. However, it should be noted that several variables must be considered in determining the actual benefit that arises from WFH practices. A comparative life-cycle assessment undertaken by Guerin [10] showed that some main factors to be considered include commuting distance, energy efficiency in the home and office settings, usage of renewable energy sources, and real estate space savings. Given the complexity of adapting WFH practices, the uncertainties, and different methodologies followed in estimating resulting benefits, and more studies are required during these post-pandemic conditions to determine its benefits [45,46]. However, there is not enough conclusive evidence on the sustainable WFH practice to reduce the GHGE by a typical employee in Australia's dense central business district (CBD) (i.e., Sydney, Melbourne, Brisbane, Perth, Adelaide, and Canberra).

In addition to the employee population, the commuting patterns of each city are different. Car, train, bus, and tram/light rail were the most common transport method in Sydney, Melbourne, and Adelaide. In Brisbane and Perth, employees use similar transport, except for tram/light rail. In Canberra, there is no tram/light rail or train. Further, the numbers of people using various transport methods are also different in each city. Additionally, the ongoing COVID-19 pandemic introduced the hybrid work model (i.e., combined working in office and WFH) for many sectors, and it is expected to be prevalent post-COVID-19. Thus, it requires quantitative analyses of GHGEs and costs for a typical employee who practices WFH in Australia's cities.

This work aims to estimate the GHGEs and costs for a typical employee in six Australian cities (i.e., Sydney, Melbourne, Brisbane, Perth, Adelaide, and Canberra) and their changes when WFH practice is adopted. The changes in the GHGEs from residential houses, commercial buildings (i.e., typical offices), and transportation sectors by an employee are derived when changing the duration of WFH practice applied. Further, this study estimates the total GHGEs reduction when WFH practice is adopted in each city. The outcome will explain the impacts on the GHGEs and related costs when employees practice WFH. This will also help policymakers develop a sustainable hybrid work model for post-COVOD-19.

2. Method

During the current COVID-19 pandemic lockdown, most people practised WFH except the essential workers (e.g., healthcare sector, restaurants, funeral service, supermarkets, grocery stores, etc.). This pandemic lockdown scenario could change energy use and related GHGEs and costs associated with building and transport sectors. This research aims to quantify the energy changes created by the COVID-19 pandemic lockdown-induced WFH practice in six metropolitan cities (Melbourne, Sydney, Brisbane, Perth, Adelaide, and Canberra) in Australia. In addition, this study investigates how energy usage and related GHGE for different WFH scenarios. There is no apparent suitable quantitative model that can produce precise data to achieve the aim of this research. Therefore, a simple linear model estimates the average energy consumption in the typical commercial and residential buildings and transport sectors. It should be noted that a similar approach was employed by Matthews and Williams [7].

The first step in the analysis is estimating how many employed people can work from home in each city. The next step is identifying the typical residential and commercial buildings, the most common transportation used to travel to work, and their average energy consumption. Existing literature and ABS [47] are used to achieve these steps. Assumptions and justifications for the analysis are provided as follows:

- Energy consumption changes through traffic congestion and infrastructure construction are not included. As the aim of this research mainly focused on the energy consumption changes induced by WFH. Therefore, using average energy consumption is sufficient to provide quantitative results to estimate the benefits of WFH.
- The ABS [47] shows that in each city, about 3.4–4.4%, 2.3–2.8%, 2–2.3%, and 5–6% of employed people who are working in the sector of healthcare, restaurants, supermarkets/retailers/grocery stores and machinery operators and drivers, respectively. It was assumed that the people from those sections could not do the WFH practice. Therefore, this study assumed that 90% of employed people in each city could WFH.
- The ABS [47] highlighted that a higher (>90%) percentage of employed people used public (i.e., train, light rail, bus) and private (i.e., car) transport to travel to work. Thus, this analysis used these transport modes to quantify the commuting energy and related GHGE.
- The work hour per employee is assumed to be 8 h [8].

Personal contacts were queried to identify the typical days for WFH has been practised in the current hybrid work model. Based on the information from the universities and construction industry sectors, the typical days for WFH practised for the hybrid work model were 1.5 and 4 days per week. These values were obtained using content validity ratio (CVR) analysis, and the CVR greater than 0.49 was selected [48]. Three WFH scenarios have used this analysis, S_0, S_1, and S_2 (Table 1). The S_0 scenario represents the population already practising WFH in each city. A 4.2%, 4.4%, 4.6%, 3.9%, 3.6%, and 3.4% of employed people in Melbourne, Sydney, Brisbane, Perth, Adelaide, and Canberra, respectively, adopted WFH practice (Australian Bureau of Statistics 2016). Only 90% of employed people in Melbourne (1,792,450), Sydney (1,917,382), Brisbane (906,987), Perth (782,948), Adelaide (501,580), and Canberra (85,481) were used to calculate the energy consumptions and related GHGEs for other scenarios (i.e., S_1 and S_2).

Table 1. WFH scenarios used in this investigation.

Scenario	Days/Week	% of Population Practicing WFH					
		Melbourne	Sydney	Brisbane	Perth	Adelaide	Canberra
S_0	5.0	4.2	4.4	4.6	3.9	3.6	3.4
S_1	1.5	90					
S_2	4.0	90					

2.1. Building GHGE and Cost

WFH practices may imply an increased amount of time spent at home, hence increased energy in the residential building while reducing the energy consumed at the office building. The three main energy uses selected for comparison in this study are heating/cooling, lighting, and equipment energy consumption. It is assumed that a centrally managed HVAC system is being used in a residential building, and the increase in conditioned floor space for a home office is considered when calculating energy consumption. The saving on a commercial building is relevant to floor space savings based on the number of WFH days. Further details on the method used to determine the building energy consumption and related GHGE and the cost are described in the following sub-sections.

2.1.1. Residential Building

The WFH strategies directly affect residential energy consumption, and state-wise differences were considered with an energy mix consisting of electricity and gas for residential buildings. Electricity and gas consumption data based on household occupancy were obtained from Australian government publications [49] for Sydney, Melbourne, Brisbane, Adelaide, and Canberra. The data for Perth was obtained from other sources [50]. Input data in calculating residential energy consumption data for the six cities are shown in Appendix A Table A1. Weighted average methods were used to calculate the residential energy consumption in each city. It was assumed using one WFH worker per household. Thus, energy consumption per household is assumed to be equal to the per worker consumption in each city. In calculating the increased energy consumption due to WFH scenarios, a 3-bedroom house was assumed as a typical residential building in each state based on 2016 Census data [47]. It is assumed that the typical house would have six main areas, including three bedrooms, a living area, a kitchen, a corridor, and others. Thus, additional energy use for home offices was estimated to be one-sixth (17%) of the energy consumption for heating/cooling and lighting. It was assumed that 76% of electricity consumption and 40% of gas consumption accounted for heating/cooling and lighting. Unit prices and GHGE emission factors used in calculations for electricity and gas are shown in Appendix A Table A3 with references for the six cities. Additional daily GHGE per dwelling due to WFH ($\Delta GHGE_{res}$) is calculated as shown in Equation (1), where EC is the daily electricity consumption (kWh), GC is the daily gas consumption (MJ), and EF is GHGE emission factors per representative unit consumption.

$$\Delta GHGE_{res} = (f_{elec}\, EC\, EF_{elec} + f_{gas}\, GC\, EF_{gas})/6 \tag{1}$$

where f_{elec} = fraction of electricity consumption accounted for heating/cooling and lighting and f_{gas} = fraction of electricity consumption accounted for heating/cooling and lighting.

2.1.2. Office Building

Office buildings account for a significant share of total energy consumed in any city, and WFH is assumed to impact its total value directly. It is assumed that energy used in commercial buildings is 100% electricity. A published report from the Department of Industry on measured data of electricity and gas consumption in commercial buildings [51] is the source of the input data for the energy calculations. Stand-alone offices are only considered related to employed people in each state, and energy consumption per worker was estimated. Input data for energy consumption calculations in commercial buildings is shown in Appendix A, Table A2, and the references. HVAC, lighting, and equipment are assumed to be the main energy consumption components in commercial buildings. Computers are considered the variable component in the equipment end-use energy consumption. However, in an office environment, additional monitors are being used; thus, it is assumed as 200% more compared to residential equipment energy consumption. The occupant behaviour in buildings is the main factor affecting energy consumption; it is challenging to obtain accurate information concerning this [52]. Energy consumption for HVAC and lighting is assumed to be proportionate to the building floor space. Further, 1.5 days of WFH is assumed to have no savings on HVAC as such employees are most likely to have dedicated office areas in the building. Employees having 4 days of WFH can be considered flexible with no dedicated office space. It is assumed that floor space for an employee is proportional to the WFH days [53]. Thus, in Scenario 1 (S_1), 90% of employees with a 30% reduction in floor space account for 27% savings, while in Scenario 2 (S_2), 90% of employees with an 80% reduction in floor space will result in 72% savings on floor area served. The annual reduction in GHGE per employee in commercial buildings ($\Delta GHGE_{com}$) is calculated as shown in Equation (2), where $\Delta EC_{HVAC\&light}$ is the annual electricity consumption (kWh) accounted for HVAC and lighting.

$$\Delta GHGE_{com} = (\Delta EC_{app} + \Delta EC_{HVAC\&light})EF_{elec} \tag{2}$$

2.2. Transport GHGE and Cost

Transport energy used by a worker is estimated using annual passenger kilometre travel (PKT) specified in the Bureau of Infrastructure, Transport and Regional Economics (BITRE) [54], and the energy and related GHGE coefficients are specified in Table 2. A total of two modes of transport are used to estimate the transport energy, private transport and public transport. The private transport accounts for the private car as driver and passenger. Public transport considers that the worker used to travel via train, light rail, tram, and bus. Table 3 presents populations [55] and daily passenger kilometre travel per employee. Equation (3) is applied to determine the reduction in transport *GHGE* per worker per day ($\Delta GHGE_{tran}$).

$$\Delta GHGE_{tran} = \sum_{m} \Delta PKT_m \, EF_m \tag{3}$$

where ΔPKT is the reduction in passenger kilometre travel for each mode of travel (Table 2), and *EF* is the GHGEs factor for transport modes (Table 1).

Table A4 in Appendix A shows the commuting energy used per person in a day. This table also illustrates the GHGE per day for each transport mode. The travel expenses for private transport per kilometre is \$0.72, as specified by the Australian taxation office [56]. The public transportation cost is calculated based on the day pass cost specified in each city's public transport (Table A5 in Appendix A).

Table 2. Energy consumptions and GHGE factors for various travel modes.

Travel Mode	Energy (MJ)	GHGE (kg CO_2-e PKT^{-1})	Assumptions
* Private car	3.72	0.260	As driver/passenger, petrol car
** Train	1.47	0.105	-
** Bus	1.30	0.085	-
** Light rail	1.30	0.085	-
** Tram	1.30	0.085	Same as light rail

References: * [57]; ** [58].

Table 3. City populations [55] and daily passenger kilometre travel (km d^{-1}) per employee [54].

City	Population *	Private Car	Train	Bus, Light Rail, and Tram
Sydney	5,312,163	43.09	50.53	46.29
Melbourne	5,078,193	42.69	49.38	42.33
Brisbane	2,514,184	42.98	75.37	33.92
Perth	2,085,973	39.52	81.15	30.30
Adelaide	1,359,760	36.52	0.00	21.75
Canberra	426,704	46.34	0.00	22.47

* Estimated resident population (ERP) at 30 June 2019 [55].

3. Results and Discussion (Effects of WFH)

The effects of WFH in terms of GHGE and cost are presented in the following sub-sections.

3.1. Effects on Employee

The GHGE by a worker per year for each WFH scenario is shown in Table 4. It illustrates that the GHGE from residential buildings increased when employees adopted WFH for 1.5 and 4 days per week. This was due to the increases in residential energy consumption. The GHGE from the transportation reduces significantly when employees practice WFH. This was due to less transport when WFH was adopted by an employee. This GHGE reduction from transportation was higher than the GHGE increase from the residential building. Table 4 also shows the cost saved by an employee through less travel when practising WFH. This table highlighted that an employee practising WFH for 1.5 days per week can save up to $3181, $2682, $2696, $2737, $2504, and $2900 per year through transportation if located in Sydney, Melbourne, Brisbane, Perth, Adelaide, or Canberra, respectively. This cost-saving was increased by 80% per year when employees practised WFH for 4 days per week in all cities due to less transportation in WFH scenario S_2 than in S_1.

Table 4. Annual building and transport-related GHGE and cost per worker.

City	Scenario	GHGE (tCO_2-e)		Cost (AUS $)	
		Building	Transport	Building	Transport
Sydney	S_0	4.69	4.6	1951	10,603
	S_1	5.22	3.2	2048	7422
	S_2	5.64	0.9	2209	2121
Melbourne	S_0	6.00	4.5	1755	8941
	S_1	6.29	3.2	1840	6258
	S_2	6.77	0.9	1884	1788
Brisbane	S_0	3.77	4.9	1166	8988
	S_1	3.97	3.4	1225	6291
	S_2	4.30	0.9	1324	1798
Perth	S_0	3.56	4.8	1774	9124
	S_1	3.75	3.4	1867	6387
	S_2	4.06	1.0	2022	1825
Adelaide	S_0	1.74	2.6	1739	8347
	S_1	1.82	1.8	1823	5843
	S_2	1.96	0.5	1962	1669
Canberra	S_0	8.23	3.1	2884	9667
	S_1	8.49	2.2	3017	6767
	S_2	8.93	0.6	3238	1933

Figures 1 and 2 show the changes in the GHGE per year when an employee was practising WFH. This was derived by reducing the GHGE of the base case scenario (i.e., S_0) from the derived GHGE of other scenarios (i.e., S_1 and S_2). Figure 1 shows that when an employee practised WFH, GHGE from the residential building was increased in each city. When comparing the GHGE of a residential building of S_0, the maximum of about 6% GHGE was increased when employees adopted WFH for 1.5 days per week. This increase is about two times when an employee was practised WFH 4 days per week, while the WFH practice reduced the GHGE via less transport (Figure 2). Efficient energy usage can play a key role in improving these residential energy consumptions and GHGE. Affordable renewable energy sources like solar PV can dramatically reduce energy consumed from fossil fuel sources. It should be noted that similar observations have been made in recent studies [10,46].

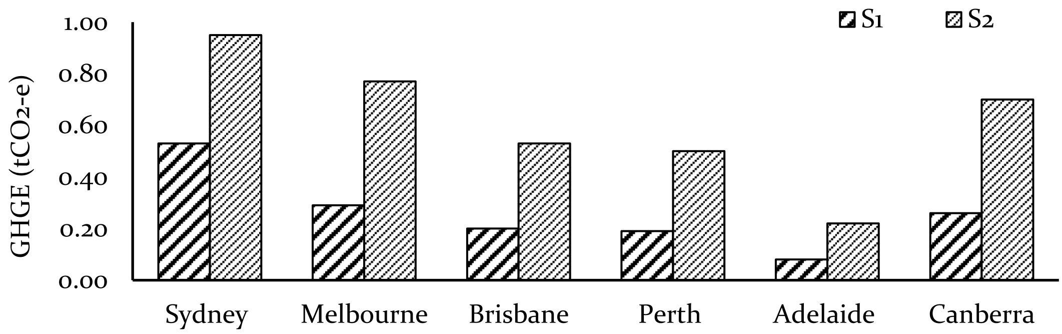

Figure 1. Increases in the GHGE of residential buildings per year when an employee adopts WFH.

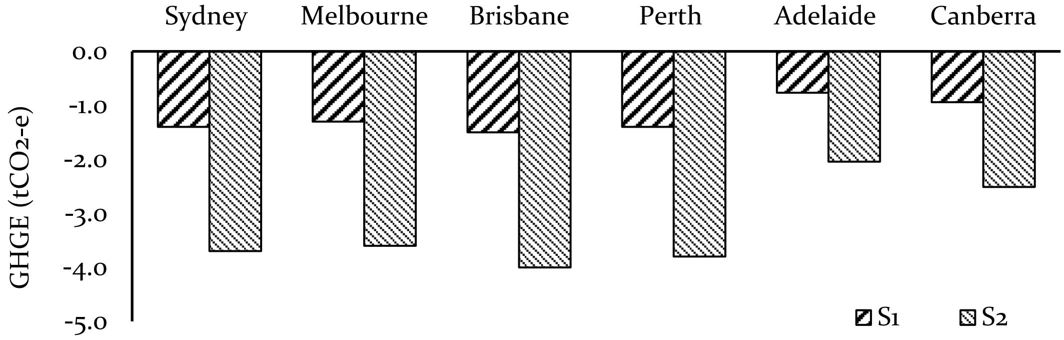

Figure 2. GHGE changes from transportation per year when an employee adopts WFH.

Figure 2 highlighted that about 1.5 tCO_2-e/year GHGE was reduced by an employee from Brisbane when practising WFH for 1.5 days per week. This reduction was about 2% and 1% lower for employees in Melbourne and the other four cities, respectively. While employees adopted WFH for 4 days per week, the GHGE reduction was increased to 80% in all six cities. A similar trend of GHGE reduction from transport was found in previous studies [7,10,48]. Figures 1 and 2 highlight that about 24% and 68% of total GHGE can be reduced by an employee, respectively, whenpractising WFH for 1.5 days and 4 days per week over a year. A recent study by Guerin [10] highlighted that the WFH practice could reduce not only GHGE but also other pollutants which can cause human toxicity, abiotic depletion, and photochemical oxidation.

3.2. Effects on Employer

The GHGE from commercial buildings and related annual costs when an employee adopts WFH are presented in Table 5. This table highlights that compared to the base case scenario, about 8% of GHGE and related costs from commercial buildings were reduced when an employee from Adelaide adopted the WFH for 1.5 days per week. This reduction percentage was about 1%, 3%, 4%, and 2% lower in Perth, Sydney, Canberra, and both Melbourne and Brisbane, respectively. When employees adopted WFH for 4 days per week, the GHGE and related cost reduction was increased to 30% in both Perth and Adelaide and 27% in both Melbourne and Brisbane. The GHGE and cost reduction from an employee in Canberra is 23% when practising WFH 4 days per week. This was due to higher energy consumption for a lower workforce number compared to other cities.

Overall, Table 5 indicates that an employer from Adelaide could save about 8% of their energy cost by allowing an employee to do the WFH for 1.5 days per week. This cost saving was about 1%, 3%, 4%, and 2% lower in Perth, Sydney, Canberra, and both Melbourne and Brisbane, respectively. Further, this cost saving can increase to 30% and 27% in both Perth and Adelaide, 27% in both Melbourne and Brisbane, and 23% in Canberra when employees are allowed WFH for 4 days per week. Similar observations in reducing energy usage in office buildings have been reported in a recent study [48]. However, it should be noted that it is hard to compare these results quantitatively due to different sets of conditions and assumptions made in the analyses.

Table 5. Annual GHGE and cost for an employee.

City	Scenario	Commercial Building	
		GHGE (kg CO_2-e)	Cost (AUS $)
Sydney	S_0	830	361
	S_1	785	342
	S_2	582	254
Melbourne	S_0	718	230
	S_1	674	216
	S_2	490	157
Brisbane	S_0	634	214
	S_1	594	200
	S_2	431	145
Perth	S_0	338	161
	S_1	312	149
	S_2	219	105
Adelaide	S_0	171	223
	S_1	158	207
	S_2	110	144
Canberra	S_0	3157	1077
	S_1	3032	1034
	S_2	2340	798

3.3. Impact on National GHGE

Table 6 shows the impact on the national GHGE when employees work from home in all six cities. This table highlights that GHGE reduction from transportation and commercial buildings is higher than the GHGE increase from residential buildings when employed people from Sydney, Melbourne, Brisbane, Perth, Adelaide, and Canberra practice WFH. Overall, the WFH approach can be adopted to reduce the annual GHGE by 1.21 $MtCO_2$-e when employed people from all six cities practice WFH for 1.5 days per week. This GHGE reduction increased to 5.76 $MtCO_2$-e when employed people practised WFH 4 days per week.

Table 6. Effects of WFH on total GHGE (tCO_2-e) [positive: increase; negative: decrease].

City	Scenario	Residential	Commercial	Transport	Total
Sydney	S_1	+437,293	−92,053	−759,814	−414,574
	S_2	+1,166,114	−503,296	−2,659,350	−1,996,533
Melbourne	S_1	+496,298	−89,219	−684,377	−277,297
	S_2	+1,323,462	−458,428	−2,395,318	−1,530,284
Brisbane	S_1	+161,048	−36,647	−353,046	−228,645
	S_2	+429,460	−186,643	−1,235,662	−992,845
Perth	S_1	+139,785	−21,182	−288,956	−170,354
	S_2	+372,759	−99,831	−1,011,347	−738,419
Adelaide	S_1	+56,386	−9594	−154,785	−107,993
	S_2	+150,363	−44,915	−541,748	−436,300
Canberra	S_1	+23,509	−2106	−32,420	−11,017
	S_2	+62,692	−13,726	−113,470	−64,504

3.4. Limitations

This work assumed that the passenger kilometre travel distance was only for works and single occupancy. This means no other travel activities are included in the WFH practice. This assumption ignored the rebound effect induced by travel to shopping, entertainment trips, and dropping off and picking up children from school on the way home. Ignoring this rebound effect could lead to high GHGE reduction from transport. This could be about a 20% [7,10] variation in the quantified value of GHGE from transport. Further, this work did not consider the car used by rideshare to work. This can also create variations in estimated values of energy and GHGE. Thus, unpredicted human behaviour can create uncertainty when predicting GHGE reduction from WFH.

In this work, a linear model was used to estimate residential energy consumption due to the limitations in the availability of state-wide residential energy consumption data. Some recent studies have highlighted the variations in occupancy behaviour in commercial buildings and the impact on energy calculations [52]. Further, this work assumed that conditioned (i.e., heat and cool) floor space would be reduced based on WFH days. However, floor space savings may not occur immediately. Adoption of WFH practices may apply these strategies in the long run. Furthermore, it should be noted that this study has made a qualitative comparison between the findings of this study and similar literature studies. Given the different conditions and assumptions applied in analysing WFH practices, a direct comparison of the results may not be appropriate.

4. Conclusions and Recommendations

The effects of working from home (WFH) on greenhouse gas emissions (GHGE) and costs in six cities in Australia have been presented.

- Adoptions of WFH for 1.5 days per week reduce the annual operational GHGE of office buildings in Sydney (5%), Melbourne (6%), Brisbane (6%), Perth (7%), Adelaide (8%), and Canberra (4%). On the other hand, they increase the operational GHGE of residential buildings in Sydney (6%), Melbourne (6%), Brisbane (5%), Perth (5%), Adelaide (5%), and Canberra (3%).
- Adoptions of WFH for 4 days per week reduce the annual operational GHGE of commercial buildings in Sydney (26%), Melbourne (27%), Brisbane (27%), Perth (30%), Adelaide (30%), and Canberra (23%). On the other hand, they increase the operational GHGE of residential buildings in Sydney (13%), Melbourne (14%), Brisbane (14%), Perth (14%), Adelaide (13%), and Canberra (9%).
- The reductions of GHGE due to less transport are significant compared to increases due to more time at home. This reduction was about 30% and 80%, respectively, for Scenario S_1 (WFH for 1.5 days per week) and S_2 (WFH for 4 days per week).
- WFH for 1.5 days per week reduced the annual transportation cost of an employee by 30% in each city. This reduction was increased to 80% when an employee adopted to WFH for 4 days per week.
- The total annual GHGE is reduced by 1.21 Mt CO_2-e if employed people from all six cities practice WFH for 1.5 days per week. The annual GHGE can be reduced by 5.76 Mt CO_2-e if employees adopt to WFH for 4 days per week.
- The WFH practice increases the energy cost of residential buildings. This can be reduced by using energy-efficient technologies such as renewable sources (e.g., solar panel systems).

The quantitative analyses of GHGEs and associated costs obtained in this study offer an opportunity to reduce energy consumption and cost via the WFH practice. This would help policymakers develop strategies to combat global warming and climate change in the future. Furthermore, this study's outcomes also help identify the effective WFH days to reduce cost and energy consumption. This helps develop a sustainable hybrid work model for post-COVID-19.

The assumption made in the analyses could be reduced by conducting further research. Further investigations are recommended to assess the influence of working hours, the number of WFH employees in a single house, and the duration of utilising lighting, computers, and heating and cooling systems. Furthermore, workers' behaviour and climate change also create variations in energy consumption and GHGEs. The WFH practices may also have indirect effects not considered in this study, such as increased productivity, lifestyle changes (online shopping, residents moving out of cities), and technology enhancements (energy-efficient homes, faster internet access). Further research is needed to assess these effects to obtain better accuracies of the predictions.

Moreover, the effects of WFH on workplace or office space requirements, initial and operating costs of buildings, and productivity are the major items to be considered from the employers' perspective. If an appropriate optimised number of days of WFH can be identified, the employers could tailor reduced space (e.g., more shared hot desks with less dedicated offices). WFH not only reduces the costs related to commuting but also the commuting time for workers. Reduced commuting results in more free time for other activities such as family time, exercise, and additional work. These could lead to better well-being, better health, and additional income. On the other hand, WFH could also lead to blurring the boundaries between work and home, which may negatively affect well-being. Increased energy consumption due to WFH may lead employees to consider refurbishing homes to improve energy efficiency. A better understanding of these aspects merits further research.

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Nomenclature

Symbols	
EC	Daily electricity consumption per dwelling [kWh]
EF	Greenhouse gas emissions factor [kg CO_2-e kWh^{-1}, kg CO_2-e MJ^{-1}]
GC	Daily gas consumption per dwelling [MJ]
GHGE	Greenhouse gas emission [kg CO_2-e]
PKT	Passenger kilometre travel
S	WFH scenario
Subscripts	
0	base case WFH scenario
1	WFH for 1.5 days per week per year
2	WFH for 4 days per week per year
com	total electricity consumption
elec	electricity
gas	gas
res	residential
tran	Transport

Abbreviations

ABS	Australian Bureau of Statistics
AUS	Australia
BMS	Building Management System
CBD	Central Business District
GHGEs	Greenhouse Gas Emissions
HVAC	Heating, Ventilation, and Air-Conditioning
NZEBs	Net Zero Energy Buildings
WFH	Working From Home

Appendix A

Table A1. Residential building energy consumption data (S_0).

City	No of Residents	No of Dwellings *	Electricity (kWh) +	Gas with Heating (MJ) +
Sydney	5+ people	207,026	7530	29,195
	4 people	293,510	14,162	58,390
	3 people	285,567	5396	24,387
	2 people	486,343	5141	24,387
	1 people	351,418	3388	16,812
	Weighted average	-	6742	29,507
Melbourne	5+ people	166,181	6305	81,607
	4 people	277,013	12,087	156,944
	3 people	271,620	5262	66,145
	2 people	493,659	4526	62,528
	1 people	366,009	3086	39,157
	Weighted average	-	5836	76,344
Brisbane	5+ people	86,353	8150	11,894
	4 people	131,113	6672	10,892
	3 people	135,630	5418	6842
	2 people	262,942	4610	7366
	1 people	173,426	3115	6018
	Weighted average	-	5150	8061
Perth **	5+ people	67,776	10,074	4234
	4 people	117,078	7556	3176
	3 people	116,192	7556	3176
	2 people	230,226	5037	2117
	1 people	159,004	5037	2117
	Weighted average	-	6383	10,322
Adelaide	5+ people	38,727	6356	22,066
	4 people	74,578	6019	26,602
	3 people	78,212	5200	26,602
	2 people	166,105	4514	26,602
	1 people	134,827	3032	16,299
	Weighted average	-	4590	23,424
Canberra	5+ people	12,376	14,347	80,746
	4 people	23,781	11,975	38,451
	3 people	24,174	11,975	38,451
	2 people	46,916	11,840	38,451
	1 people	35,416	9084	35,804
	Weighted average	-	11,419	41,463

References: * [59]; + [49] ** [51,52].

Table A2. Commercial building related data (S_0).

Item	Sydney	Melbourne	Brisbane	Perth	Adelaide	Canberra
Stand-alone offices (m^2) *	13,876,000	9,751,000	4,444,000	3,611,000	1,793,000	2,396,000
Energy Intensity (MJ m^2 a^{-1}) *	546	534	569	429	538	536
Energy consumption (PJ)	7.6	5.2	2.5	1.5	1.0	1.3
Labour force (professionals)	1,917,382	1,792,450	906,987	782,948	501,579	85,481
Energy consumption per worker (MJ a^{-1})	3951	2905	2788	1979	1923	15,024
HVAC 43% * (MJ a^{-1})	1699	1249	1199	851	827	6460
Lighting 26% * (MJ a^{-1})	1027	755	725	514	500	3906
Equipment 20% * (MJ a^{-1})	790	581	558	396	385	3004

Reference: * [51].

Table A3. GHGE factors and unit prices for electricity and gas.

Item	Sydney	Melbourne	Brisbane	Perth	Adelaide	Canberra	Reference
Electricity (kg CO_2-e kWh^{-1})	0.85	1.00	0.92	0.69	0.36	0.85	[57]
Gas (kg CO_2-e GJ^{-1})			51.4				[57]
Residential Electricity (¢ kWh^{-1})	30.69	29.88	25.52	33.19	37.68	27.5	[60]
Residential Gas (¢ MJ^{-1})	3.45	2.35	6.4	4.12	4.53	3	[61]
Business electricity (¢ kWh^{-1})	37	32	31	33	47	27	[62]

Table A4. Daily transport energy consumption and GHGE per employee.

City	Energy (MJ d^{-1})		GHGE (kg CO_2-e d^{-1})	
	Private	Public	Private	Public
Sydney	160.29	134.46	11.20	9.24
Melbourne	158.80	127.61	11.10	8.78
Brisbane	159.88	154.89	11.17	10.80
Perth	147.00	158.67	10.27	11.10
Adelaide	135.87	28.28	9.50	1.85
Canberra	172.39	29.21	12.05	1.91

Table A5. Annual transport energy consumption (PJ) and daily GHGE ($MtCO_2$-e d^{-1}) by employed people.

Scenario	Item	Mode	Sydney	Melbourne	Brisbane	Perth	Adelaide	Canberra
S_1	Energy	Private	12.41	12.32	6.48	5.34	3.24	0.69
		Public	3.97	2.41	1.10	0.86	0.08	0.01
	GHGE	Private	867	861	453	373	227	50
		Public	273	166	77	60	6	1
S_2	Energy	Private	33.08	32.84	17.28	14.23	8.65	1.83
		Public	10.58	6.42	2.93	2.30	0.22	0.03
	GHGE	Private	2312	2295	1208	995	604	13
		Public	727	442	204	161	15	0.2

Table A6. Transportation costs for each WFH scenarios.

Item	Sydney	Melbourne	Brisbane	Perth	Adelaide	Canberra
Population of employed people using private car (%)	59.8	68.1	66.2	68.7	70.5	69.0
Population of employed people using public transport (%)	22.8	15.6	11.6	10.3	8.8	6.0
Daily cost per person for car (Private)	31.02	30.74	30.95	28.45	26.30	33.37
Daily cost per person for public transport (Public)	16.10	9.00	9.00	12.10	10.80	9.6

Table A6. *Cont.*

Item		Sydney	Melbourne	Brisbane	Perth	Adelaide	Canberra
S_0 (Cost M$ a^{-1})	Private car	409	387	224	155	87	443
	Public transport	81	28	11	10	4	11
S_1 (Cost M$ a^{-1})	Private car	2401	2384	1254	1033	628	133
	Public transport	475	170	64	66	32	3
S_2 (Cost M$ a^{-1})	Private car	6403	6357	3344	2755	1674	354
	Public transport	1267	453	170	176	86	9

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