Assessing a Post COVID World: Energy and Emission Impacts of Telecommuting

By

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Abstract

Lockdown and social-distancing policy drove U.S. workers to switch to telecommuting during the pandemic of Covid-19 in 2020. Telecommuting has been widely perceived as a sustainable way of working that reduces energy consumption and greenhouse gas (GHG) emissions. However, existing studies have contradictory results and few of them have a quantitative estimation of individual telecommuting-related activities including transportation, commercial building, residential building and information communication technology (ICT). In our project, we develop a quantitative bottom-up accounting framework to model the energy consumption as well as the GHG emissions of telecommuting. The model integrates the transportation model, commercial building model and residential building model, in which we analyze the energy and emission impact of workers' behavior change due to telecommuting. The results do have a net environmental benefit and show that telecommuting during the outbreak of COVID in 2020 resulted in a 13% (1 quad Btu) reduction in work-related energy consumption and a 7.3%, 11.4%, and 16.9% reduction in our conservative, moderate and aggressive remote work scenarios, respectively. As for GHG emissions, it has a 14% reduction (80 Mt CO2e) in work-related GHG emissions across the U.S. during the outbreak, and a 8.1%, 12.4% and 21.0% reduction in our conservative, moderate and aggressive scenarios, respectively.

Keywords: Covid-19, telecommuting, energy consumption, GHG emissions, transportation, commercial building, residential building, ICT

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1. Introduction

1.1 The Covid-19 Pandemic and the Workplace during the Pandemic

Since the outbreak of Covid-19 over the globe, and the formal declaration of a global pandemic by the World Health Organization on March 11th, 2020, this virus has caused nearly 400 million cases and over 5 million deaths worldwide by Mid-February, 2022 [1]. In order to slow down the spread of this deadly virus, governments all across the world established lockdown measures several times when new waves of outbreaks happened. Even after two years, with more than 60% of the whole population being fully vaccinated in the US [2], the society is still dramatically impacted by ‘social distancing’ policies and regulations that have numerous consequences on the economy, employment and daily life of people. In particular, a big portion of the working population had to shift and carry out their duties and responsibilities away from their physical office to their homes, using information and communications technology (ICT) as an approach to facilitate communication instead of meeting in person. Lockdowns have accelerated the transition of the workplace towards telecommuting, a trend that many expect to last.

Telecommuting can be described as working remotely out of any conventional office by using information and communication technology (ICT) [3]. The official definition of telework can be found in the Telework Enhancement Act of 2010: "the term 'telework' or 'telecommuting' refers to a work flexibility arrangement under which an employee performs the duties and responsibilities of such employee's position, and other authorized activities, from an approved worksite other than the location from which the employee would otherwise work." In addition, the terms “work from home (WFH)” and “flexible workplace” are also used to describe what we define as “telecommuting” above and are treated equally in our scope.

There are also different types of telework: full-time, part-time, and situational [4], and they can affect work-related energy consumptions and emissions. Full-time telecommuting means that the employee performs and completes all or almost all duties outside of a traditional office. In this case, a fixed office space or cubicle assigned to this fully telecommuting employee is not necessary, and providing some shared office space or even no office space seems reasonable for the company. Part-time telework means that the employee performs and completes duties outside of a traditional office on a regularly scheduled basis, but not five days per week. Sometimes even a few hours or half day telecommuting can also be counted as part-time telework. In this case, a permanent office space or shared space both can be reasonable for these employees. Situational telework means that the employee does not telework on a regular basis. This type of telework may happen when there are occasional incidents making employees unable to get to their traditional office. In this case, permanent office space is necessary for these employees.

Many jobs cannot be performed remotely and require that workers be physically present at their worksites. According to a Pew Research Center survey conducted in October, 2020[5], workers' ability to do their job from home varies considerably by industry. For example, a majority of workers in the information and technology sector (84%); banking, finance, accounting, real estate or insurance (84%); education (59%); and professional, scientific and technical services (59%) say their job can mostly be done from home. Among those in government, public administration and military, 46% say their job can be done from home and 54% say it cannot. About three-quarters or more of those employed in retail, trade, and transportation (84%); manufacturing, mining, construction, agriculture, forestry, fishing and hunting (78%); and hospitality, service, arts, entertainment and recreation (77%) say that, for the most part, the responsibilities of their job can't be done from home. Two-thirds of those in the health care and social assistance sector say the same. In a word, the diversified telecommuting potential among industries is an important factor we need to study over the whole working population.

According to the American Time Use Survey conducted by U.S. Bureau of Labor Statistic [6], the percentage of employed persons working at home on days they worked nearly doubled during the COVID-19 pandemic in 2020, rising to 42% [6], with an average of 5.91 hours of working from home on an average workday. Since the Covid outbreak took place in the beginning of 2020 and continued throughout 2020, we can use the labor statistics in 2019 to represent business as usual (BAU) before Covid, and the data in 2020 to represent telecommuting status quo during the Covid. Surveys show that the telecommuting rate over the whole working population in the U.S., has drastically increased during the outbreak of Covid.

1.2 The Energy and Emission Impact of Telecommuting

The primary benefit brought by telecommuting is the reduction in passenger miles traveled (PMT) by any possible transportation modes. Even though each transportation mode has its own environmental impact, given that the majority of those commuting distance savings here in the U.S. are by single-occupancy vehicles, it has a huge impact on energy and emission reductions. Teleworkers can reduce their commute distance to zero on telecommuting days, which seems promising in terms of reduction on their environmental impact. However, it may also cause rebound effects [7] and induce travel at the same time, which may partially offset the potential savings of reduced transportation. We will discuss this in the literature review section.

The second-most potential saving happens in centralized office buildings, since a large portion of the employees work fully from home, those commercial buildings can be operated under a lower energy intensity. In principle, the potential reduction is equal to the percentage of total telecommuting hours of all workers. However, commercial buildings consume energy in a complicated non-linear relation with the number of employees working inside at a given time; they consume a certain amount of HVAC energy even when no one is there. The complexity of commercial building energy consumption patterns needs to be modeled in a proper way to represent the non-linearity, which we will introduce in the method section.

The energy and emission impact of telecommuting on home offices is the biggest downside of telecommuting, with some of the office equipment energy directly transferred to home. Similar to commercial buildings, home offices also present a non-linear energy consumption pattern, which is difficult to capture. Moreover, aside from the lighting, heating, ventilation and air conditioning that are used by both commercial buildings and residential buildings, household appliances such as refrigerators and stoves add challenges of accurate modeling, since they will consume more electricity on telecommuting days than they usually do on non-telecommuting days.

Information and communication technology, which enable a smooth and efficient telecommuting transition, also plays an important role in this process. The devices used for video-conferencing, file transferring and storage, as well as the underlying internet infrastructure, all have a huge energy impact. Thus, the likely increased ICT energy consumption caused by telecommuting, should also be taken into consideration. However, the energy consumption and corresponding emission of ICT are part of the total energy consumption of commercial and residential buildings, so we do not need a separate model for estimation.

In conclusion, the overall impact brought by telecommuting could be expressed as the overall net savings of the listing above, which is depicted by the figure below:

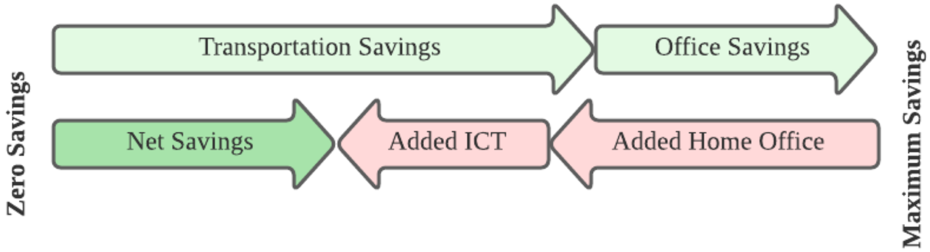

Figure 1. Overall impact brought by telecommuting.

1.3 Functional Unit, Research Goal and Scope

Given the broad spectrum of teleworkers and limited data regarding the telecommuting related activity, great care must be taken defining our research goal, the functional unit, our research scope and the idealizations and assumptions of our model in representing the complex telecommuting reality.

Firstly, which portion of the population are involved in our accounting? As we mentioned in the previous section, there are jobs that can be done entirely from home, while others can only be done partly from home, with workers still needing to be physically present in the workplace. Therefore, our research is focused on the environmental impacts of workers who would normally work at a central office, but instead are spending more of their working hours working from home due to Covid. This distinction is very important since a broader or narrower definition for telecommuting may dilute or exaggerate the environmental impact of telecommuting.

Secondly, what telecommuting-related activities are we modeling? One's activities in a day can all somewhat be affected by telecommuting, but that is impossible for our scope of study. Apart from that, their activities vary from day to day. Therefore, we only focus on modeling activities related to transportation, commercial and residential building and ICT, which are directly affected by a higher frequency of telecommuting and we assume there are no other direct or indirect influences brought by telecommuting just for simplicity. The functional unit for our modeling is the average work-related energy consumption and corresponding emissions per worker per week in transportation, residential building and commercial building. By modeling the impact per worker per week, we can then scale it up to estimate the total impact of all US workers.

Moreover, what environmental impact are we looking for? The energy impact of telecommuting in terms of net energy saving per capita per week is derived from our model, as well as the related GHG emission impact (CO2-e). The energy and emission in our model are use-phase only, since we are only accounting for short-term changes. For example, we do not consider the life-cycle energy and emission impact of the building that is associated with the construction or demolition process, since most companies will not consider building new offices to fit the short-term impact of a higher telecommuting rate of their employees. The details will be further discussed in the method section.

Our model focuses on the overall impact brought by telecommuting in the U.S., using the data mainly from government agencies such as EIA and BLS. Since the subsequent impact of Covid on telecommuting is still unclear, we assume that telecommuting will continue as a trend even in a post-covid world. Given the variability and uncertainty of telecommuting over time, we could only explore a few scenarios regarding the circumstances of telecommuting in the very near future (less than 5 years).

2. Literature Review

Compared with traditional office work, telecommuting is a new type of office method for collaborative work outside the scope of traditional office locations, which replaces the daily commute to the traditional office location with some hardware or software tools. Broadly speaking, it refers to replacing work-related travel with remote communications, thus removing the limitations of distance to work remotely. The development of modern technology and artificial intelligence technology has made telecommuting easier for people to work. The pandemic resulted in a large increase in telecommuting, with 33% of US workers reporting that they had teleworked because of the coronavirus pandemic in May - June 2020 before the percentage declined to a still substantial 22% in the fourth quarter [8]. The suitability of occupations for telework is, unsurprisingly, an important determinant of this rate. Although falling from their peak at the start of the pandemic, telecommuting rates are still considerably higher than before the pandemic. It seems likely that some of the increase in telecommuting will be permanent as workers and employers gain experience with telecommuting arrangements and with the information technology that helps facilitate telecommuting [8]. In the Netherlands, around 80% of the population reduced activities due to the pandemic, resulting in a 55% reduction in the number of trips and a 68% reduction in the distance traveled in April, 2020. Percentage of people working from home increased from 6% to 39%, compared to conditions of 2019 [18]. Shamshiripour et al. conducted a revealing preference survey in Chicago and found that not only online shopping but telecommuting activities are also increasing [19].

The potential for telecommuting to save on transportation and building energy was the predominant focus of similar studies. For example, Atkyns et al. surveyed 1238 AT&T managers and concluded that telecommuting could reduce transport-related carbon emission by 0.65 tonnes CO_2/employee/year [9]. Dissanayake and Morikawa concluded through modeling of Bangkok and five hypothetical telecommuting centers that telecommuting can decrease overall air pollutant emissions from transportation by 18 – 26% [10]. Mokhtarian and Varma used a combination of surveys and calculations for 72 center-based (A telecommuting center is a site, other than the home, from which the employee works instead of traveling to a more distant central work location) telecommuters in California. The result shows when weighted by telecommuting frequency, average reductions of 11.9% in PMT and 11.5% in VMT were found over a five-day work week [11]. The above studies only focused on measuring the impact of commuting on energy consumption and emissions in the transportation sector. However, the impact of commuting on energy is driven by a comprehensive set of processes from transportation, offices, home buildings, and corresponding equipment. Matthews and Williams estimated a decrease of 42 GJ/ teleworker in the US using a bottom-up model based on national averages and considering the impact of commuting on transportation, home buildings, and offices [14]. Roth et al. used life cycle assessment to evaluate how Telecommuting (TC) alters transportation, residential building, and commercial building energy consumption patterns. By using a simplified model of 4-million teleworkers telecommuting 5-day/week in the US, results indicated a reduction of 0.13 - 0.18% of total US primary energy or 9 MJ/year. [12]. There has also been recent work examining the costs associated with the shift of energy use from commercial to residential buildings. Kawka and Cetin examined a data set from 225 housing units primarily located in the state of Texas, where energy use data was directly captured using a home energy monitoring system [17]. Their analysis revealed that the largest percentage increase in non-HVAC loads were apparent between the hours of 10am and 4pm, reflecting the increased demand due to workers staying in their personal residence. Deiss et al. compares the energy burden of New York City office buildings versus personal residences before and during the stay-at-home period of the COVID-19 pandemic. The scope is composed of employees that, prior to the stay-at-home order, underwent a daily commute to and from a representative midtown Manhattan office building. The results of this study demonstrated that remote working conditions consume 39.7% less energy [13].

However, many other studies focusing on telecommuting transportation have reported conflicting results, as transportation mode, vehicle efficiency, and telecommuter behavior play a role in the savings achieved through telecommuting [10]. Likewise, device efficiency, ICT-related energy consumption, and teleworker behavior at home are all important aspects of evaluating the environmental impact of telework [15]. Therefore, Kharvari et al. suggest that the impact of telecommuting can be assessed through scenario analysis and modeling the energy consumption through different activities [16].

3. Methodology

3.1 Data Collection

3.1.1 Transportation

The data collection for the transportation model of this study is mainly from the latest 2019 U.S. Census data, the U.S. Bureau of Labor Statistics data, the U.S. Department of Transportation, literature reviews, and some official reports and guidelines. The specific data sources are as follows:

Telecommuting (TC) frequency (days per week) is based on statistics from the U.S. Bureau of Labor. The data mainly shows the average hours per day of employees (hours per day) and the proportion of employees (%) in their home and workplace in 2019 and 2020.

The data for the average one-way commute distance comes from a comprehensive statistical report released by the U.S. Department of Transportation in 2003. The report states that the average one-way commute distance for commuters across the country is 15 miles.

Rebound Effect induces work or non-work travel due to reduced commute travel. For example, TC could increase the number of weekend trips (Short-term effect); TC could enable people to live further from their workplace, effectively increasing distance to work and potentially of all other trips (Long-term effect). That is to say, although telecommuting will reduce the VMT for weekly commute distance, it will correspondingly increase the VMT for other purposes. The Rebound Effect on VMT/day considered in this study is based on the comprehensive considerations of three papers - Hopkinson (2003), Reitan (2014) and Henderson (1996). Most of the methods for calculating the rebound effect include case studies [30], building a simulation model or simulation framework [31] and using survey data [32]. According to the results of the above literature, we found the range of the rebound effect to be between 19% and 27%. We chose the data of the most cited article, which is 25%, as the rebound effect on a commute day for our study.

In this study, we also considered six different commuting modes, including Car, Truck, Bus, Rail, Walked, and Bicycle. The data for the commuting patterns of car, truck, walked, and bicycle are from the 2019 U.S. Census data; for the commuting patterns of bus and rail, the data comes from monthly traffic monitoring data of the U.S. Department of Transportation.

We also calculated the energy consumption factor and the GHG emission factor (in terms of the equivalent amount of carbon dioxide) for various commuting modes, assuming that walking and cycling commuting consumes no energy and emits no GHGs, so both energy and emission factors are 0. The amortized embodied energy and emission factors of the car and truck are from the energy use and emissions of Well-to-Pump, Vehicle Cycle and Vehicle Operation of Gasoline Vehicle: CG and RFG, Conventional Material section of the GREET model in 2021. It is worth noting that the original data sources are all calculated according to VMT, and our research is to use passenger mile traveled (PMT), so the concept of occupancy rate which depends on trip type of commuting is introduced, that is, the number of passengers in each vehicle. Calculated based on the U.S. Department of Transportation statistics and U.S. Census data. PMT is obtained by multiplying VMT by occupancy rate. The energy factor data for bus and rail is from the transportation energy data book, and the GHG emission factor data is from the report published in 2019 by the Climate Change Standard Working Group, SUDS Policy and Planning Committee.

Population data for different industries comes from 2019 U.S. Census data and the U.S. Bureau of Labor.

3.1.2 Residential and Commercial Building

The data for the residential building model of our study was collected primarily from the U.S. Energy Information Administration (EIA), the U.S. Bureau of Labor, the U.S. Department of Transportation, peer-reviewed journal articles and official guidelines. Due to the limitations of the long time interval between the publication of official data, some assumptions were required to conduct this analysis.

The 2015 Residential Energy Consumption Survey (RECS) published by the EIA provides data on the number of national residents and the annual site consumption of each type of energy source (e.g., natural gas, electricity fuel oil/kerosene, propane, etc.) for different uses (e.g., room heating, water heating, lighting, etc.) in residential buildings [20]. The

2012 Commercial Buildings Energy Consumption Survey (CBECS) published by the EIA provides data on the number of national employees and the annual site consumption of each type of energy source for different uses in commercial buildings [21].

The U.S. Bureau of Labor Statistics provides the number of national employees, the average hours of work per day in different industries, and the comparison of hours of work at home/workplace in 2019 versus 2020.

To meet consistency with the transportation section assessment, employees nationwide were reclassified in accordance with the industry classifications provided by the U.S. Department of Transportation.

The paper by Dixit (2014) provides the primary energy factor (PEF), carbon emission factor and energy conversion efficiency of each type of energy source [22].

3.2 Assumptions

There are a few fundamental assumptions we made to accommodate data limitations.

Firstly, the telecommuting frequency data from BLS [6] tracks workers working at workplace and working at home separately, which result in a summation of frequency larger than 100% due to the fact that people may work both at workplace and home on the same day. We assume that those days will not be counted as telecommuting days. It makes sense for transportation since commuting happens as long as workers show up at their physical office. However, for both commercial buildings, residential buildings ICT, we assume that working at different places in a single day has identical energy consumption and emission impact as working at office solely.

Secondly, we assume constant energy and emission intensities in future scenarios. The intensities are sensitive to how people commute, what appliances they adopt, which grid are located in, etc. Tracking those intensities in real time is unrealistic. Based on existing data we could calculate the energy and emission intensities of several telecommuting related activities such as commuting, we then apply the same intensities to future scenarios with different telecommuting frequency, so the underlying assumption here is that energy and emission intensities remain constant regardless of telecommuting frequency changes and technology innovation in the future.

Thirdly, when investigating the impact of telecommuting on building energy consumption and emissions, we consider people who previously worked onsite in offices. For the baseline values of residential building energy consumption and emissions, we assume that there is no difference between those who work in offices and the remaining workers. For the baseline values of commercial buildings, we equally allocate the energy consumption and emissions corresponding to the office buildings to each study subject. We assume that the energy consumption and emissions caused by people who do not work in the office will not change significantly because of the pandemic.

Finally, we assume an unchanged working population in different future scenarios. That is, to be more specific, neglecting the effect of fluctuation and dynamics in the whole U.S. job market.

3.3. Method

Since the Covid outbreak took place in the beginning of 2020 and continued throughout 2020, we use the labor statistics in 2019 as business as usual (BAU) before Covid, and data in 2020 as telecommuting status quo during the Covid. Surveys show that the telecommuting rate over the whole working population in the U.S., as a matter of fact, has drastically increased during the outbreak of Covid.

In our study, as shown in Figure 2, in order to calculate the results under different scenarios based on the energy consumption and greenhouse gas emissions caused by transportation commuting and telecommuting, we separately calculated the total annual energy consumption and GHG emissions of the transportation, commercial and residential buildings sectors before and after the pandemic, and then combined the results to evaluate net impacts.. It is worth noting that ICT-related energy and emissions are already accounted for in the commercial and residential model.

$$E_{Total} = E_{Transportation} + E_{Home} + E_{Office}$$

Figure 2. The calculation equation for the full model.

Where:

E_{Total} : Total energy consumption or GHG emissions of the telework system;

$E_{Transportation}$: Total energy consumption or GHG emissions of transportation;

E_{office} : Total energy consumption or GHG emissions of commercial building;

E_{home} : Total energy consumption or GHG emissions of residential buildings.

3.3.1 Transportation

In the transportation model of our study, we firstly applied the bottom-up analysis method to analysis throughout, and also used the related methods of literature review and data analysis to systematically analyze, calculate and compare.

Specifically, on the national average scale, the transportation model is divided into four parts: Commuting Frequency, VMT, Commute Mode, and Energy Consumption/GHG Emission Factor, as shown in Figure 3. The final energy consumption and GHG emission results are the product of these four parts. Where $E_{Transportation}$ refers to total energy consumption or GHG emissions of transportation per person per week; Commuting Frequency refers to commuting days per week for different scenarios; VMT refers to average travel distance considering rebound effect (allocating the weekly rebound effect to each working day); Commute Mode refers to different trip types of commuting for automobile (including car, truck, bus, rail, bicycle and walk etc.); Energy Factor/Emission Factor refers to the amount of energy (Btu) or emission (g) per passenger mile traveled (PMT).

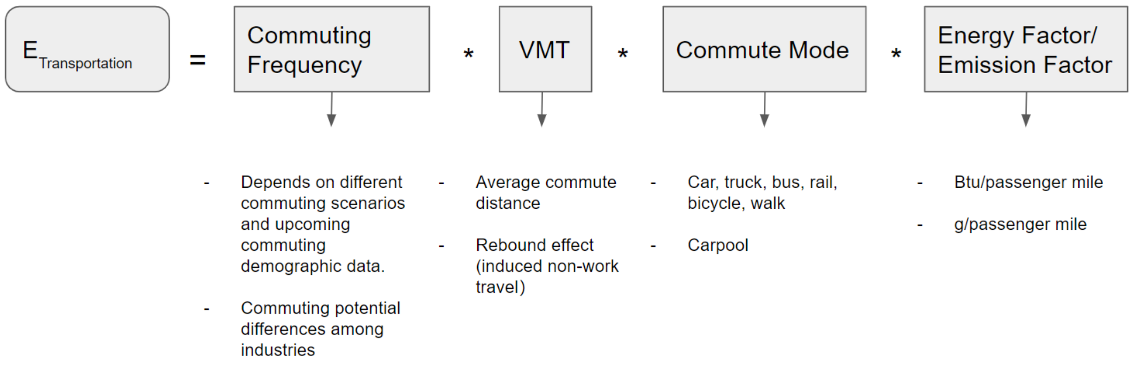

Figure 3. The calculation equation for the transportation model.

As shown in Figure 4, the calculation flow chart of the transportation model, we calculate the proportion of commuters in different commuting modes and the VMT using the commuting mode according to the collected data. Our research uses passenger mile traveled (PMT), which is calculated based on the U.S. Department of Transportation statistics and U.S. Census data. To obtain the PMT-based energy consumption factor and GHG emission factor, we multiply the initial VMT-based energy and emission factor by the occupancy rate.

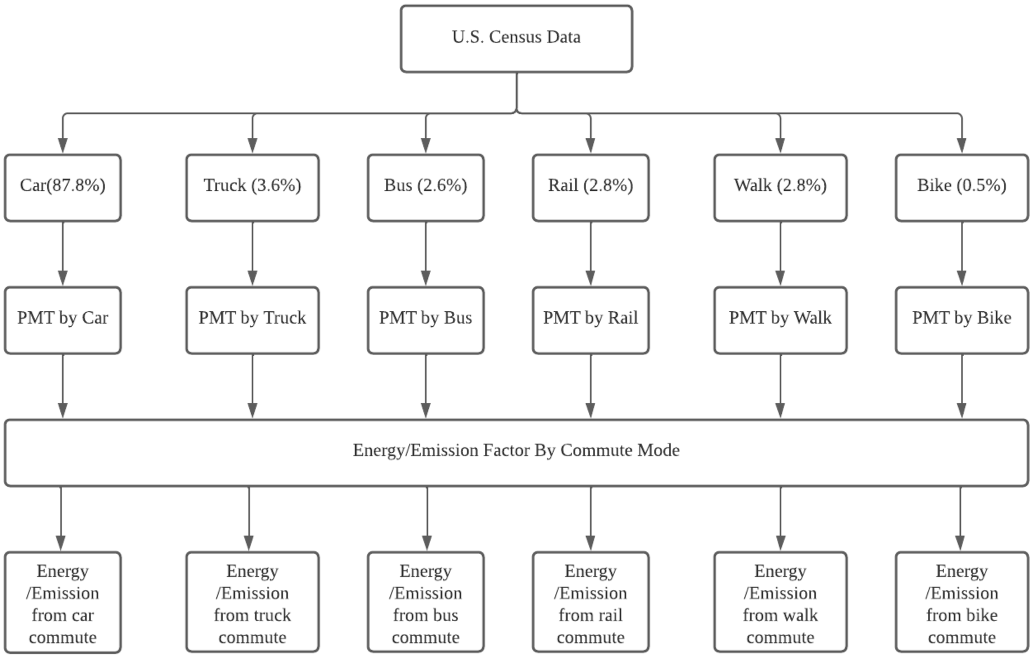

Figure 4. Transportation model calculation flow chart.

When calculating the average commuting distance, we determined the distance increment due to the rebound effect of telecommuting days per week plus the mileage of normal commuting days to get the total VMT for a week (we assume that commuting is required on five days a week, each additional day of telecommuting will cause a rebound effect). The method shown in Figure 5 can calculate the total commuting distance of the national average commuter under the influence of the different telecommuting days and rebound effect which is assumed to occur proportionally across all modes.

$$\boxed{\text{VMT}} = \boxed{\text{One-way Commute distance}} * \boxed{2} * \boxed{(\text{Commtue days} + (5 - \text{Commute days}) * \text{Rebound Effect})}$$

Figure 5. The calculation equation of VMT per person per week.

When calculating commuting frequency, we assume that as long as a commuter commutes to and from the workplace once during the day, it is considered a commute on that day, that is, it does not belong to telecommuting. That is to say, in the transportation model, no matter what the time of working from home or working at the workplace, as long as there is a round-trip commute, it is not regarded as telecommuting. According to the data in Table A 2 and Table A 3, the sum of the proportion of people who choose to work at home and the proportion of people who choose to work in the workplace every day is greater than 100%, which means that some workers choose to work both in the workplace and at home on the same day. On a national scale, through the previous assumptions, we only selected the proportion of people who work at home and subtracted this data from 100% to get the proportion of daily commuters, that is, the proportion of weekly commuters. For individuals, that proportion is the frequency of telecommuting and commuting per person per week.

For each industry analysis, we used U.S. Census and Bureau of Labor Statistics data on the working population of each industry and the percentage of people working in the workplace each day to calculate the frequency of telecommuting by industry. We then used the data obtained on the national scale of the changes in energy consumption and GHG emissions brought about by the transition from commute work to telecommuting in a single day, so as to calculate the total energy consumption and GHG emissions of the work-related transportation in 2019 and 2020, respectively.

3.3.2 Residential and Commercial Building

Assessing the impact of telecommuting on the life cycle assessment of a building requires consideration of both the changes in people's daily activities (the operation component) and the construction of the building (the construction component). The energy consumption of the construction component can be represented as a specific percentage of the entire life cycle consumption. For short-term comparisons, the focus should be on the use phase as the energy consumption and corresponding emissions of the construction component can be neglected. For long-term (e.g., decades) calculations involving building demolition and reconstruction, the post-pandemic energy consumption attributable to the buildings can be deduced from the results of short-term comparisons, the total pre-pandemic energy consumption of buildings and the corresponding proportion of the construction component in the energy consumption.

In order to obtain a baseline for comparison (i.e., pre-pandemic energy consumption and emission levels) ， the national energy consumption data for each building activity is obtained from the EIA report and multiplied by emission factors to derive the corresponding emission data. However, EIA only provides total annual energy data for the commercial building sector and residential building sector while energy consumption intensity varies from day to day. Therefore, granular data characterizing different energy consumption intensity (e.g. weekday vs. weekend energy consumption for commercial building) must be further derived to support future scenario analyses. By introducing an assumed energy intensity ratio, post-pandemic energy consumption and emissions can be estimated. The analysis of the operation component can be characterized by the following outline.

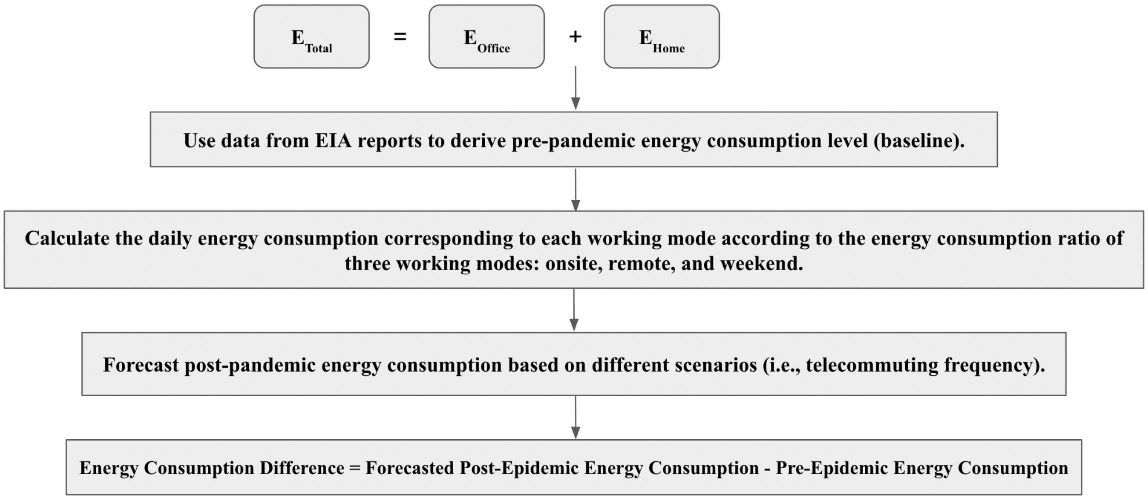

Figure 6. Structure for residential/commercial building energy consumption.

The 2015 RECS and 2012 CBECS respectively provide data on the numbers of national residents and employees and the annual site consumption of each type of energy source for different uses in residential and commercial buildings. The 2018 Commercial Buildings Energy Consumption Survey published by EIA provides the proportion of offices in commercial buildings, national office floorspace and average floor space per office worker, from which the national number of office workers can be extrapolated [23]. Since office area accounts for only 17% of the total commercial building area, it is assumed that its energy consumption occupies the same proportion of the total energy consumption of commercial buildings for the purpose of calculation. The following table shows the annual energy consumption for space heating and the corresponding population data.

Table 1. National annual energy consumption for space heating and the corresponding population data

Main heating fuel	Residential Space Heating (TBtu)	Commercial Space Heating (TBtu)	Number of Residents (million)	Number of Office Workers (million)
Natural gas	2,677.60	1,339.00	300.77	32.39
Electricity	637.73	85		
Fuel oil/kerosene	400	92.5		
Propane	232.8	0		
District Heating	0	240		

The operation component is divided into five sections for assessment: Space Heating, Water Heating, Air Conditioning, Refrigerators and Others. According to the PEF and carbon emission factor of each type of energy source [22], the primary energy consumption and corresponding GHG emissions of each section of the operation component for both residential and commercial buildings can be derived. The table below shows the annual energy consumption and GHG emissions per capita of residential buildings before the pandemic.

Table 2. Annual energy consumption and GHG emissions per capita of residential buildings before the pandemic.

Space Heating Fuel	Site Energy Consumption (MBtu)	Emission Factor (kg/MBtu) [22]	Emission (kg)
Natural Gas	9.17	23.46	215.13
Electricity	2.12	80.76	171.21
Fuel Oil/Kerosene	1.27	26.14	33.20
Propane	0.78	63.05	49.18
Water Heating Fuel	**Site Energy Consumption (MBtu)**	**Emission Factor (kg/MBtu) [22]**	**Emission (kg)**
Natural Gas	3.49	23.46	81.88
Electricity	1.96	80.76	158.29
Fuel Oil/Kerosene	0.19	26.14	4.97
Propane	0.25	63.05	15.76
Air Conditioning	**Site Energy Consumption (MBtu)**	**Emission Factor (kg/MBtu) [22]**	**Emission (kg)**
Electricity	2.43	80.76	196.25
Refrigerators	**Site Energy Consumption (MBtu)**	**Emission Factor (kg/MBtu) [22]**	**Emission (kg)**
Electricity	1.01	80.76	81.57
Others	**Site Energy Consumption (MBtu)**	**Emission Factor (kg/MBtu) [22]**	**Emission (kg)**
Natural Gas	0.91	23.46	21.35
Electricity	6.85	80.76	553.21
Fuel Oil/Kerosene	0.02	26.14	0.52
Propane	0.17	63.05	10.72

As post-pandemic data remains unavailable and existing pre-covid data measures total building energy consumption is broken down by different energy types and there are no data characterizing the difference in building energy consumption under different working modes (e.g. onsite or teleworking), therefore the energy intensity ratio is introduced to address this issue. There are three working modes in our scope, as shown in table 3. Onsite refers to normal weekdays when employees work at the office and leave their home vacant, remote refers to weekdays when employees work from home while some of the equipment in the office is still operating to support their remote work, and weekend stands for a normal weekend when most people spend their time at home. Each of the modes has a different energy consumption intensity at the workplace (commercial building) or at home (residential building). The energy intensity ratio represents the relative intensity between these three modes. Since teleworking already took up certain portions of the total workdays, the pre-covid data is composed of certain proportions of each mode. We can then apply the energy intensity ratios and the percentage of each mode to the pre-covid data to calculate the energy consumption of each work mode. By assuming a constant energy consumption for each work mode, we can then estimate the total energy consumption under different post-covid teleworking scenarios by combining the frequency of each mode and its energy consumption intensity. The value of the ratios comes from literature that analyzes energy consumption intensity variation over time for residential and commercial buildings [41][42].

Table 3. Energy intensity ratio of working modes in residential and commercial building

	Onsite	Remote	Weekend
Residential	1	1.17	1.17
Commecial	1	0.8	0.8

By applying these energy intensity ratios and pre-covid telecommuting frequency data on the total energy consumption data, we can calculate the average energy consumption per day per capita under each working mode for both residential and commercial buildings. We assume a constant energy consumption intensity for each mode, and then we combine them with post-covid telecommuting frequency to estimate the commercial building and residential building total energy consumption under different post-covid telecommuting scenarios.

3.4 Scenario

In order to estimate the status of telecommuting in the post-covid future, we use telecommuting frequency data of 2019 and 2020 published by Bureau of Labor Statistics [6] to assume the conservative, moderate and aggressive future scenarios based on how well the trend of telecommuting is going to last in the U.S. after the pandemic. A higher telecommuting frequency scenario with reduced environmental impact is considered the ‘aggressive’ case in the context of our research. Based on these three different scenarios, we could then estimate the changes in energy consumption and emissions that would result from different frequency in telecommuting among the working population. Given that 19.4% of workers in the US already worked at least partially from home before the pandemic, according to the Bureau of Labor Statistics, we assume a baseline of 16.3% telework. A 35.5% telecommuting rate in 2020-roughly 20% increase from 2019, which reflects the impact brought by the pandemic and social distancing policy.

Table 4 presents the post-covid telecommuting scenarios. The scenarios are developed under different perspectives on how people look upon telecommuting as a new form of working. Under the most aggressive perspective, which refers to our aggressive scenario, 6.8% more workers will switch to telecommuting compared to 2020 (during the pandemic). In this scenario, people simply regard telecommuting as beneficial to both employers and employees, so more workers with telecommuting capability adopt telecommuting. Under the moderate scenarios where 6% less of workers will remain telecommuting compared to 2020 status, some workers will return to work in their physical office after the pandemic, because their jobs are not suitable for telecommuting, but they were doing so during the pandemic just for safety reasons. Under our conservative scenarios, where only 10.7% increase compared to 2019, most people will go back to their office, indicating that the booming of telecommuting in 2020 was almost driven by the pandemic, companies still prefer business as usual over telecommuting due to diverse reasons.

Table 4. Description of different telecommuting scenarios.

COVID Scenarios	Teleworking rate	Net Increase	Description	Source
2019 (Baseline)	16.30%	-	Teleworking status quo before the pandemic, representing business as usual (BAU)	BLS
2020	35.5%	19.20%	Teleworking frequency during pandemic under strict social-distancing policy.	BLS
Post-COVID Telework Scenarios	Teleworking rate	Net Increase	Description	Source
Conservative Scenario	27%	10.70%	A 10.7% net increase from 2019 and a 8.5% drop from 2020, indicating that most employees or employers still prefer working at a physical office rather than teleworking.	Assumed
Moderate Scenario	33%	16.70%	A 16.7% net increase from 2019 and a 2.5% drop of the growth in 2020, indicating some workers return to their physical office after the pandemic while the majority of them keep working from home.	Assumed
Aggressive Scenario	45%	28.70%	An aggressive projection with 9.5% more workers switching to teleworking compared to 2020, indicating that teleworking will become a trend in the post-covid world.	Assumed

4. Results and Discussion

4.1 Transportation

Our project used the data of 2019 as a baseline to compare and analyze total amount and change of the energy consumption and greenhouse gas emissions of commuters across the U.S. in 2020, which is the year of the pandemic outbreak. For these two different years, we assume that the changes brought about by the pandemic to the transportation sector are driven by changes in the weekly telecommuting frequency. The rest of the parameters, such as the number of commuters and behavior patterns, has not changed in all scenarios. `

According to the results of Baseline (2019) and 2020 in Table 5, the average number of telecommuting days per week for commuters across the U.S. was about 0.82 days in 2019 (pre-Covid-19). This figure rose to 1.78 days per week in 2020 after the pandemic outbreak. Under the influence of the rebound effect, we first calculated the average weekly energy consumption and greenhouse gas (GHG) emissions of each commuter. In 2019, the energy consumption and GHG emissions based on the average of all trip types of commuting by automobile (as shown in Table D 1) were 724 MJ and 51.2 kg per week before the pandemic. By 2020 (during Covid-19), weekly energy consumption decreased by 119 MJ, and GHG emissions decreased by 8 kg per week, which represents a reduction of 16%.

Table 5. Calculated energy consumptions and GHG emissions for each scenario for the transportation sector.

Different Scenarios	TC Frequency (days/week)	Energy (MJ/person week)	Emission (kg/person week)	Total Energy Consumption (Quadrillion Btu)	National Total Emission (Mt CO2e)	Percentage (%) of Changed Energy	Percentage (%) of Changed Emission
Baseline	0.82	724	51.2	5.956	444.44		
COVID-19	1.78	605	42.8	4.979	371.53	-16.4%	-16.4%
Conservative	1.35	658	46.5	5.412	403.81	-9.1%	-9.1%
Moderate	1.65	621	43.9	5.106	381.02	-14.3%	-14.3%
Aggressive	2.25	546	38.6	4.495	335.45	-24.5%	-24.5%

Total national results are also shown in Table 5. The total annual energy consumption by commuters in the U.S. in 2020 (during Covid-19) was 5.0 quadrillion Btu which is about 18% of total U.S. energy consumption provided by the EIA for the annual transportation sector [38], accompanied by a total of 372 Mt CO2e of GHG emissions. Compared with the 2019 data, energy consumption decreased by about 0.97 quadrillion Btu from 5.96

quadrillion Btu in 2019, and total GHG emissions decreased by about 72 Mt CO2e from 444 Mt CO2e in 2019, both accounted for a 16% reduction relative to 2019 levels.

Based on the 3 different predictive scenarios (Conservative, Moderate, Aggressive) in Table 4, the results obtained by the U.S. under different forecast scenarios are that the annual energy consumption in the aggressive scenario is 4.5 quadrillion Btu, in the moderate scenario is 5.11 quadrillion Btu, and in the conservative scenario is 5.41 quadrillion Btu. The corresponding GHG emissions are 335 Mt CO2e, 381 Mt CO2e and 404 Mt CO2e per year, which decreased by 24.5%, 14.3% and 9.1% respectively compared with the data of the base year of 2019.

The results of different industries are shown in Table 6. Except for some industries where the data is incomplete and cannot be calculated, industries have increased the number of days of telecommuting from 2019 to 2020, especially the four industries of Manufacturing, Wholesale and Retail trade, Transportation and Utilities, and Office. Among these industries, the number of telecommuting days more than doubled, especially in the Transportation and Utilities sector, which saw an increase of around 110% from 0.55 days per week to 1.14 days per day previously. Among all sectors, the frequency of remote work in the Office sector is the greatest before and after the pandemic, 1.35 days per week before Covid-19 and 2.81 days per week during Covid-19, which means that more than half of the working hours in a week are working from home. The education and health services industry has the largest number of people in a single industry, and its frequency of telecommuting is second only to Office, increasing from 1.12 days a week in 2019 to 2.11 days a day in 2020, a growth rate of 88%. As the two industries with the largest population base, Education and Health Services and Office, their energy consumption and GHG emission reductions achieved due to the pandemic are of great significance. Among them, for people in the Education and health services industry, the pandemic has reduced their energy consumption by 122 MJ per person per week, and the corresponding GHG emission has been reduced by 8.6 kg per person per week; for the Office industry, because the pandemic has reduced their energy consumption by a reduction of 180 MJ per person per week and a corresponding reduction in GHG emissions of 12.8 kg per person per week.

Table 6. Calculated weekly energy consumptions and GHG emissions for different industries for the transportation sector.

Industry	Transportation								
	TC Frequency Days			Energy Impact (MJ / person week)			Emission Impact (kg / person week)		
	Baseline	COVID-19	Changed %	Baseline	COVID-19	ΔEnergy	Baseline	COVID-19	ΔEmission
1. Agriculture, forestry, fishing, and hunting		NA			NA			NA	
2. Mining, quarrying, and oil and gas extraction		NA			NA			NA	
3. Construction	0.57	1.02	78%	752	697	-55	53	49	-3.9
4. Manufacturing	0.57	1.20	110%	752	675	-77	53	48	-5.4
5.Wholesale and retail trade	0.52	1.05	104%	759	693	-66	53	49	-4.6
6. Transportation and utilities	0.55	1.14	109%	755	682	-73	53	48	-5.2
7. Office	1.35	2.81	108%	656	476	-180	46	34	-12.7
8. Education and health services	1.12	2.11	88%	684	563	-121	48	40	-8.6
9. Leisure and hospitality	0.50	0.96	92%	761	704	-57	54	50	-4.0
10. Other services		NA			NA			NA	
11. Public administration	0.39	NA	NA		NA			NA	

4.2 Building

Before COVID-19, 32.39 million employees commuted to representative office buildings from home, residential and commuter areas. The pre-COVID-19 case simulates all employees working in an office building, while the post-COVID-19 case simulates the energy consumption of all employees under various remote working hours. Table 7 shows the energy burden of residential buildings due to workplace shifts and observes an increase in energy consumption from 0.68 quadrillion Btu/year before COVID-19 to 0.70 quadrillion Btu/year during COVID-19 (an increase of 3.2%). Table 8 shows that the energy consumption of commercial buildings decreased from 0.92 quadrillion Btu/year before COVID-19 to 0.89 quadrillion Btu/year during COVID-19 (a decrease of 4%). Overall, residential energy and office energy consumption are calculated using a summation of energy-consumed activities at different operating conditions. Staff energy consumption in the building sector decreased by a total of 0.9% during the pandemic.

The total emissions for residential and commercial buildings are calculated in Mt CO2e as shown in table 9. Compared with available data from the U.S. EIA shows a nominal 6% reduction in total greenhouse gas emissions from buildings, our calculations also show a 3.8% decrease in GHG emissions. In the conservative case, a 0.5% drop in total energy consumption is observed, with 2.2% saved in energy consumption for the building. This is due to commercial buildings having larger energy savings during the pandemic, although the rise of energy consumption and induced GHG emission is observed in residential buildings. In contrast, the aggressive-case scenario yields larger savings (4.4%) in GHG emissions. It should be noted that the lower share of greenhouse gas emissions in buildings is due to the fact that we calculated only the commuter portion (32.39 million commuters).

Table 7. Calculated energy consumptions and GHG emissions for each scenario for residential buildings.

Different Scenarios	TC Frequency (days/week)	Energy (MJ/person week)	Emission (kg/person week)	Total Energy Consumption (Quadrillion Btu)	National Total Emission (Mt CO2e)	Percentage (%) of Changed Energy	Percentage (%) of Changed Emission
Baseline	0.82	427	21.1	0.682	35.48		
COVID-19	1.78	441	21.7	0.703	36.60	3.2%	3.2%
Conservative	1.35	435	21.4	0.694	36.10	1.8%	1.7%
Moderate	1.65	439	21.6	0.701	36.45	2.7%	2.7%
Aggressive	2.25	447	22.1	0.714	37.15	4.7%	4.7%

Table 8. Calculated energy consumptions and GHG emissions for each scenario for commercial buildings.

Different Scenarios	TC Frequency (days/week)	Energy (MJ/person week)	Emission (kg/person week)	Total Energy Consumption (Quadrillion Btu)	National Total Emission (Mt CO2e)	Percentage (%) of Changed Energy	Percentage (%) of Changed Emission
Baseline	0.82	578	35.8	0.923	60.27		
COVID-19	1.78	555	33.0	0.886	55.52	-4.0%	-7.9%
Conservative	1.35	565	33.6	0.903	56.55	-2.2%	-6.2%
Moderate	1.65	558	33.1	0.891	55.83	-3.4%	-7.4%
Aggressive	2.25	544	32.3	0.868	54.40	-5.9%	-9.7%

Table 9. Calculated energy consumptions and GHG emissions for each scenario for total buildings.

Different Scenarios	TC Frequency (days/week)	Energy (MJ/person week)	Emission (kg/person week)	Total Energy Consumption (Quadrillion Btu)	National Total Emission (Mt CO2e)	Percentage (%) of Changed Energy	Percentage (%) of Changed Emission
Baseline	0.82	1005	56.8	1.605	95.75		
COVID-19	1.78	996	54.7	1.590	92.12	-0.9%	-3.8%
Conservative	1.35	1000	55.0	1.596	92.65	-0.5%	-3.2%
Moderate	1.65	997	54.8	1.592	92.28	-0.8%	-3.6%
Aggressive	2.25	991	54.3	1.582	91.55	-1.4%	-4.4%

4.3 Overall impact

This study compares and analyzes the total energy consumption of commuters in the United States in 2020 (during Covid-19) and three different assumed scenarios (Conservative, Moderate, aggressive) using data from 2019 (pre-Covid-19) as a benchmark and total greenhouse gas emissions and their changes from the base year. In general, the energy consumption and greenhouse gas emissions of the transportation and commercial buildings in all scenarios decreased to varying degrees from the base year (2019), with only a slight increase in the residential sector.

As shown in Figure 7 and Figure 8, the total energy consumption based on telecommuting in 2019 was 7.56 quadrillion Btu. In 2020, due to COVID-19, a decrease of approximately 1.00 quadrillion Btu was estimated representing a 13.1% reduction compared to the previous year. Transportation has the greatest change, dropping from the previous 5.96 to 4.98 quadrillion Btu, a drop of nearly 16%. The changes in building energy are relatively small, less than 5%, of which commercial building energy decreased by 2.2% and residential building energy increased by 1.8%. It is worth noting that the total energy consumption of transportation in different scenarios is the highest among the three sectors, all around 5 quadrillion Btu or higher. Correspondingly, total energy consumption reductions in the order of Conservative to Moderate to Aggressive are 7.3%, 11.4%, and 16.9% in the three forecast scenarios compared to the Baseline. The transportation sector still dominated the decline ranging from 9.1% to 24.5%, with the remaining two sectors showing smaller percentage changes, not exceeding 3%.

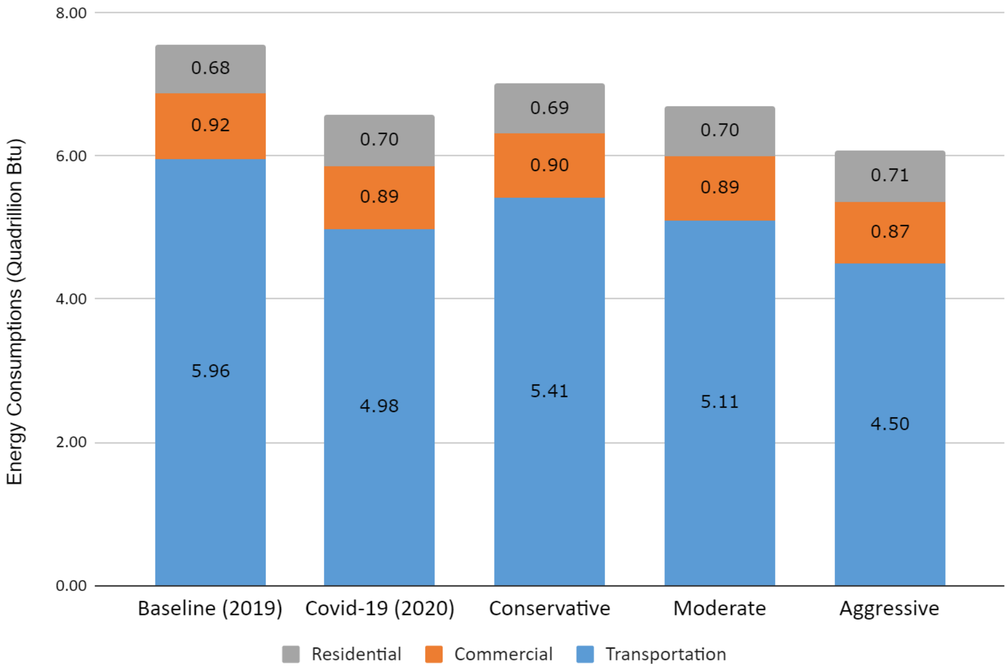

Figure 7. Total annual U.S. telecommuting related energy consumptions in different scenarios.

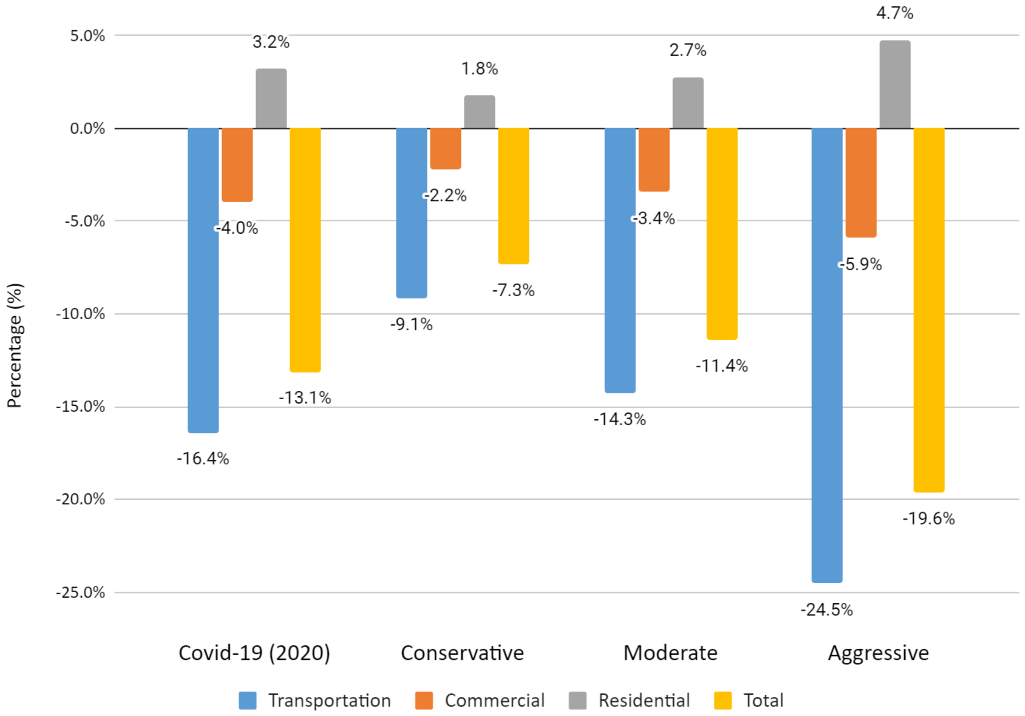

Figure 8. Annual percentage changed U.S. telecommuting related energy consumptions in different scenarios based on baseline (2019).

Then, as shown in Figure 9, for annual greenhouse gas emissions based on telecommuting, we use CO2-equivalent calculations. The results are similar to energy consumption. The total GHG emissions in 2019 were 539 Mt CO2e and 465 Mt CO2e in 2020, a reduction of 74 Mt CO2e accounting for about 14.2% of 2019. Total emissions from the transportation sector still account for the largest proportion of all sectors, around 400 Mt CO2e before and after the pandemic. And the transportation sector continues to see the most dramatic changes, down about 16.4% in 2020 compared to 2019. Correspondingly, the total GHG emissions based on the base year in the order of Conservative to Moderate to Aggressive are 8.1%, 12.4% and 21.0% in the three forecast scenarios, respectively, as shown in Figure 10.

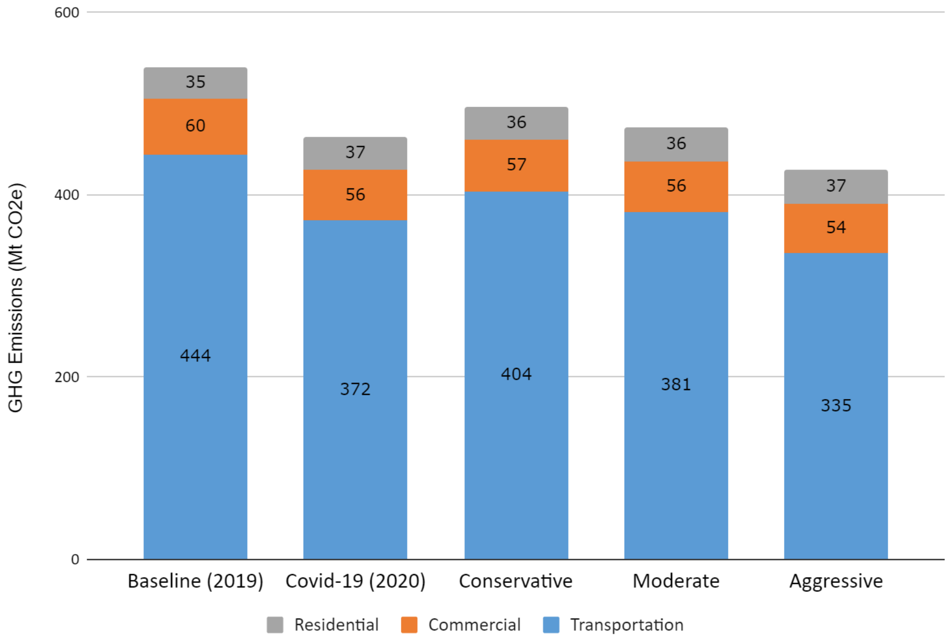

Figure 9. Total annual U.S. telecommuting related GHG emissions in different scenarios.

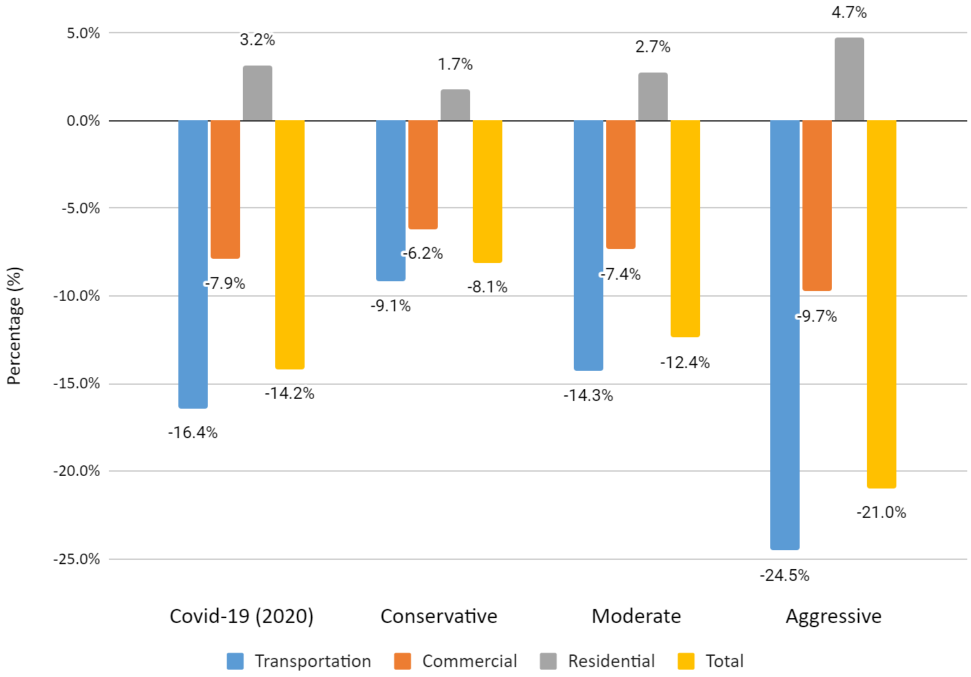

Figure 10. Annual percentage changed U.S. telecommuting related GHG emissions in different scenarios based on baseline (2019).

4.4 Discussion

Energy savings from remote work are generally considered to be primarily in the area of commuting, and this was the focus of most literature studies [24]. The impact of the pandemic on employee commuting is mainly reflected in two aspects: changes in commuting methods and commuting frequency. On the one hand, due to remote work, people can greatly reduce the frequency and distance of commuting, thereby reducing energy consumption; on the other hand, the operation of public transportation will be greatly affected, and people are more willing to choose isolated private cars to travel. Also, while working from home reduces commute distance, other trips due to this behavior can reduce energy savings. Kitou and Horvath have studied the rebound effect of telecommuting [40]. The main rebound effect is divided into two parts: one is non-work-related travel (such as increased VMT miles due to increased shopping); the other is increased household energy use (such as longer lighting hours due to working and more home heating, etc.). According to statistics, traffic volume dropped sharply during the COVID-19 pandemic which was associated with significant drop in RTCs globally and a reduction of road deaths in 32 out of 36 countries in April 2020 compared with April 2019, with a decrease of 50% or more in 12 countries, 25 to 49% in 14 countries, and by less than 25% in six countries [29]. Existing studies on energy consumption in the transportation industry during the pandemic have come to similar conclusions to varying degrees: daily energy demand plummeted due to city lockdowns. Suehiro and Koyama of Japan's Institute of Energy Economics estimated that oil demand, especially for transportation, will decrease by as much as 20% [36]. Zhang et al. estimated that China's gasoline and diesel consumption for fuel vehicles in February 2020 was -46.99% and -46.12% respectively, and the change in CO2 emissions was -46.45% [37]. Our study was limited to people in the office who commute to work rather than the entire transportation industry. Therefore, we calculated the energy consumption due to changes in commuting frequency, assuming the same commuting distance and mode. The results show that, in different scenarios, the transportation sector is the most energy-saving sector compared to the building sector. This result is different from the study by Kharvari et al. [16]. In their analysis, the carbon emissions of the transportation sector were smaller than the carbon emissions of the building sector for all assumed scenarios. This is likely due to two reasons: First, their study took an extreme hypothetical approach, that is, in their aggressive scenario, which is consistent with our study, the commuting-related transportation was assumed to be completely stopped, so the associated carbon emissions were zero. It is also possible that they did not take into account different modes of transportation to calculate the detailed energy change and just assumed the energy and emission for the transportation sector remained unchanged or decreased to zero. Second, our transportation model studies all commuting employees, while the building model studies only those who work in offices and need to commute. In Kharvari et al.'s study, the subjects of the two sectors were national workers. The study of Diess et al. [13] on Manhattan and its surrounding areas in New York City yielded similar conclusions to our results. This is because we used an approximate research method, that is, calculating the number of commuters and the average commute mileage, taking into account different modes of transportation. In addition, both of our studies calculated the result as energy consumption per unit distance per worker. For the building sector, we also used energy change in type to model the process. The only difference is we used the national average data to do the estimation and they limited the study object to New York City.

The energy consumption profile of the building sector has also changed during the Covid-19 pandemic, as movement restrictions have prompted mass telecommuting and e-learning, shifting activities and energy use to the residential sub-sector. For example, increased ICT use has a potential impact on energy consumption in homes (connected devices) as well as in data centers and networks, with global internet traffic surging nearly 40% between February and mid-April, 2020 [25]. Commercial and residential buildings combined are the third-largest source of greenhouse gas emissions, after transportation and industry. According to the Monthly Energy Review report from EIA, in 2020, these two industries alone generated 1.6 billion metric tons of CO2 direct emissions, or about 36% of total U.S. emissions [26]. In 2020, electric power generation accounted for 64% of residential CO2 emissions, and direct consumption of natural gas accounted for 29%, while the associated data for commercials are 69% and 24% [26]. However, compared with the same period last year, the US Residential energy consumption is estimated to have decreased by 6-8% [26]. This may have been caused by the reduced activity of residents due to Covid-19. However, in our study, we assumed that the 32.39 million people work remotely and home activities are not affected. Besides, we introduced an energy consumption ratio for remote working and onsite working for each home activity to represent the change in per capita energy consumption due to remote work. However, due to the limited study and data on the home and office activities, we can only use the total consumption in different types of energy rather than the consumption for qualified activities to model the change. The result is a 3.2% increase in energy consumption due to home consumption for this segment of the population.

In addition, many non-residential buildings, especially commercial buildings, will need to adjust operating plans, including space and energy use, and the impact of these unprecedented changes on energy – and whether they will persist after the crisis – remains to be determined. Unlike the transport sector, greenhouse gas emissions from commercial buildings during lockdown are harder to evaluate. When telecommuting became normal during the pandemic, energy consumption in commercial buildings stayed the same when it could have fallen, and in other cases, energy consumption even rose. In addition, the decline in energy and the use of floor space are disproportionate. Despite 50% of the U.S. working population working from home, office buildings that were vacant during the lockdown continued to consume between 40% and 100% of their energy for normal operations [27]. According to Kastle Systems, Office occupancy dropped to 10% to 20% from nearly 100% in March 2020, depending on the city. Since then, this occupancy has struggled to break the 40% rate [28]. The Kastle Systems data measures the occupancy of individual buildings, not the percentage of workers returning to offices nationwide. This means that while office occupancy rates have been historically low last year, the reductions in office energy use have not been matched. While building employees no longer turn on nearby lights, many commercial buildings continue to heat, cool, and ventilate. That's why we want to explore the ratio for detailed activities rather than just focus on the total energy change at first. The energy consumption of the latter two building modes is reflected in heating, cooling and a series of other energy changes compared with normal commuting. Therefore, the energy consumption of a building, whether it is a residential area or a commercial building, is divided into these three work modes (normal on-site, remote and weekend) in a week as illustrated before. In our hypothetical scenarios, different commuting frequencies will in turn cause differences in time and energy consumption between different modes. It can be seen that due to the change of commuting frequency, the energy consumption is also different in different scenarios. Commercial buildings experienced a 4% reduction in energy consumption during Covid-19 compared to 2019.

There have been similar studies that have examined the effects of the pandemic on building energy consumption. Kawka and Cetin examined a data set from 225 housing units primarily located in the state of Texas, where energy use data was directly captured using a home energy monitoring system [33]. Their analysis revealed that the largest percentage increase in non-HVAC loads were apparent between the hours of 10am and 4pm, reflecting the increased demand due to workers staying in their personal residence. Furthermore, the group also discovered that households earning 50,000 USD or less and those earning 150,000 to 299,999 USD exhibited the largest energy demands (66.9% and 50.5% increase respectively). Another study by Abdeen and colleagues report a significant increase (from 16.3 to 29.1%) in daily electricity demand after COVID-19 in the province of Ontario, Canada [34].

Our research method considers the energy composition of different activities in the building to calculate the final energy consumption of the building, however, most literature studies have focused on energy. In addition, most research evaluated changes in electricity consumption and ignored energy sources, such as natural gas and propane. Furthermore, the proportion of energy consumption and the types of activities vary between different buildings. For example, a study of university buildings by Gaspar et al. shows that between the beginning of the pandemic and the resumption of teaching, the energy consumption of buildings changed over time by 42%-87% compared with those before the pandemic [35]. The data may be different for other types of buildings. This makes it difficult to make accurate assumptions about the energy consumption ratio for different work states (onsite or telecommuting) , i.e., we cannot resolve how the energy consumption of different building activities has changed during the pandemic relative to the pre-pandemic period. Furthermore, it is difficult to compare data because of different energy costs between regions, as well as a different methodology of acquiring data (direct measurement versus publicly available data). Therefore, during the actual calculation, we used the energy consumption ratio between different work modes (onsite and telecommuting). If more reliable data on the energy consumption of detailed activities are available, our model will be more accurate because we can directly calculate the energy consumption change among different scenarios rather than using the ratio to estimate.

5. Conclusion

The COVID-19 pandemic is undoubtedly a great challenge to human society, but it also reveals to the world a new opportunity of energy saving and emission reduction. The main output of this study is the evaluation of telecommuting's effect on energy savings and emission reductions in transportation, commercial building and residential building components respectively under different scenarios. As work patterns were forced to shift to telecommuting, people used significantly less energy in commuting. In the assessment of the building component for office workers, the energy savings in commercial buildings were steadily offset by an increase in residential buildings. This study suggests that maintaining or even further promoting telecommuting will have significant energy saving and emission reduction effects.

For the transportation sector, the focus of future research should be on how to characterize the differences more accurately in travel patterns of people with different demographic characteristics such as age and profession, which would enable a more precise assessment of the energy consumption and emissions associated with travel for a specific population. For the building component, the next step should be to investigate the extent of change in energy consumption and emission changes for each building activity (e.g., space heating, water heating, lighting, etc.) before and after the pandemic, which would allow a more accurate prediction of the pandemic impact. When a new EIA report is available, the projections in this study can be compared with actual data to further adjust the model and tune the parameters.

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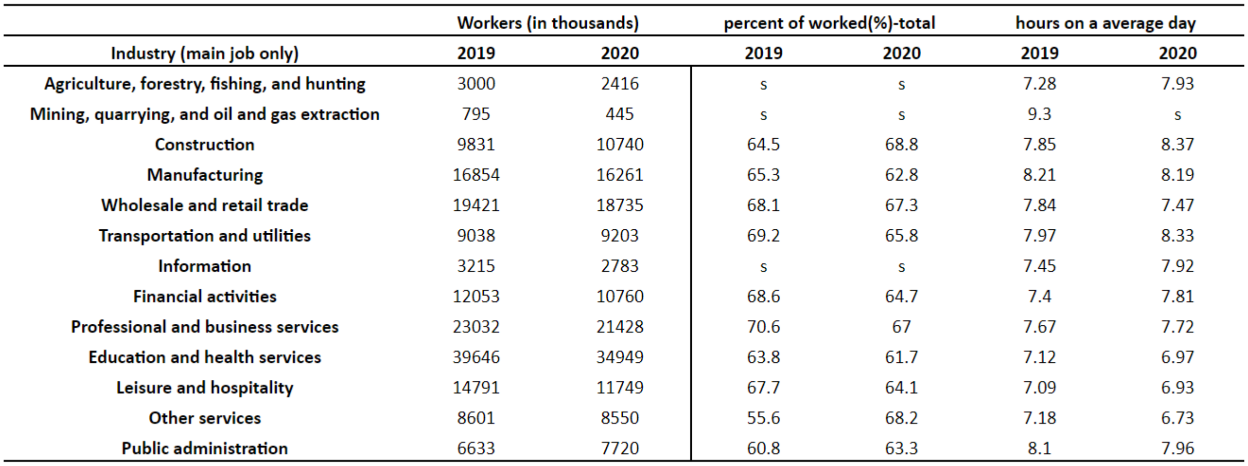
Appendix

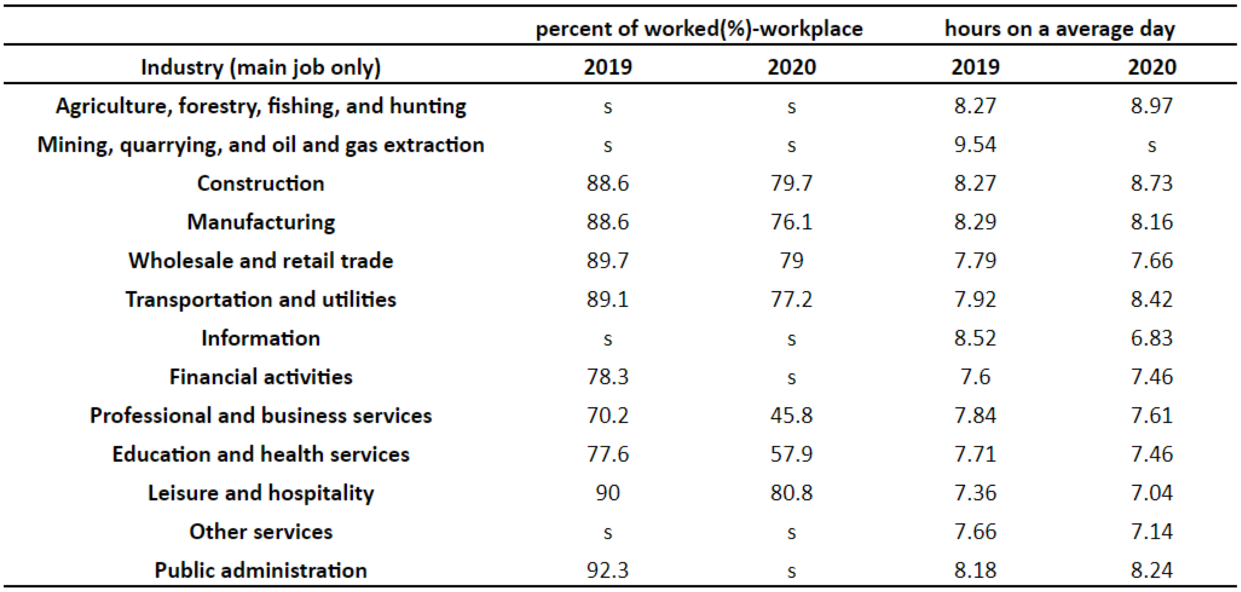
A. Number of workers, venues and hours of work in various industries across the country in 2019 and 2020

Table A 1. The total number of workers by industries across the country and the number of workers per day and hours worked in 2019 and 2020



	Workers (in thousands)		percent of worked(%)-total		hours on a average day	
Industry (main job only)	**2019**	**2020**	**2019**	**2020**	**2019**	**2020**
Agriculture, forestry, fishing, and hunting	3000	2416	s	s	7.28	7.93
Mining, quarrying, and oil and gas extraction	795	445	s	s	9.3	s
Construction	9831	10740	64.5	68.8	7.85	8.37
Manufacturing	16854	16261	65.3	62.8	8.21	8.19
Wholesale and retail trade	19421	18735	68.1	67.3	7.84	7.47
Transportation and utilities	9038	9203	69.2	65.8	7.97	8.33
Information	3215	2783	s	s	7.45	7.92
Financial activities	12053	10760	68.6	64.7	7.4	7.81
Professional and business services	23032	21428	70.6	67	7.67	7.72
Education and health services	39646	34949	63.8	61.7	7.12	6.97
Leisure and hospitality	14791	11749	67.7	64.1	7.09	6.93
Other services	8601	8550	55.6	68.2	7.18	6.73
Public administration	6633	7720	60.8	63.3	8.1	7.96

Table A 2. Percentage of people and daily hours of working in workplaces by industries across the country in 2019 and 2020



	percent of worked(%)-workplace		hours on a average day	
Industry (main job only)	**2019**	**2020**	**2019**	**2020**
Agriculture, forestry, fishing, and hunting	s	s	8.27	8.97
Mining, quarrying, and oil and gas extraction	s	s	9.54	s
Construction	88.6	79.7	8.27	8.73
Manufacturing	88.6	76.1	8.29	8.16
Wholesale and retail trade	89.7	79	7.79	7.66
Transportation and utilities	89.1	77.2	7.92	8.42
Information	s	s	8.52	6.83
Financial activities	78.3	s	7.6	7.46
Professional and business services	70.2	45.8	7.84	7.61
Education and health services	77.6	57.9	7.71	7.46
Leisure and hospitality	90	80.8	7.36	7.04
Other services	s	s	7.66	7.14
Public administration	92.3	s	8.18	8.24

Table A 3. Percentage of people and daily hours of working from home by industries across the country in 2019 and 2020

	percent of worked(%)-home		hours on a average day	
Industry (main job only)	**2019**	**2020**	**2019**	**2020**
Agriculture, forestry, fishing, and hunting	s	s	s	4.63
Mining, quarrying, and oil and gas extraction	s	s	s	s
Construction	17.2	24.3	2.62	4.97
Manufacturing	18.9	29.9	4.03	6.18
Wholesale and retail trade	12.4	22.7	3.91	5.24
Transportation and utilities	10.8	20.2	2.08	6.62
Information	s	s	4.75	7.71
Financial activities	30	69.7	4.31	7.1
Professional and business services	34.1	59.5	4.94	6.62
Education and health services	26.1	49.3	2.61	4.64
Leisure and hospitality	11	19.2	3.18	5.47
Other services	s	s	3.3	4.63
Public administration	7.1	s	s	6.82

B. Commuter-based energy consumption in various scenarios

Table B 1. Total annual energy consumption in various scenarios

Total Annual Energy Consumptions (Quadrillion Btu)	Baseline (2019)	Covid-19 (2020)	Conservative	Moderate	Aggressive
Transportation	5.96	4.98	5.41	5.11	4.50
Commercial	0.92	0.89	0.90	0.89	0.87
Residential	0.68	0.70	0.69	0.70	0.71
Total	7.56	6.57	7.01	6.70	6.08

Table B 2. Net changes in annual energy consumption based on baseline in various scenarios

Net Annual Energy Consumptions (Quadrillion Btu)	Covid-19 (2020)	Worst	Conservative	Aggressive
Transportation	-0.98	-0.54	-0.85	-1.46
Commercial	-0.04	-0.02	-0.03	-0.05
Residential	0.02	0.01	0.02	0.03
Total	-0.99	-0.55	-0.86	-1.48

Table B 3. Percentage of net changes in annual energy consumption based on baseline in various scenarios

Net Annual Energy Consumptions (%)	Covid-19 (2020)	Conservative	Moderate	Aggressive
Transportation	-16.4%	-9.1%	-14.3%	-24.5%
Commercial	-4.0%	-2.2%	-3.4%	-5.9%
Residential	3.2%	1.8%	2.7%	4.7%
Total	-13.1%	-7.3%	-11.4%	-19.6%

C. Commuter-based greenhouse gas emissions in various scenarios

Table C 1. Total annual GHG emissions in various scenarios

Total Annual GHG Emissions (Mt CO2e)	Baseline (2019)	Covid-19 (2020)	Conservative	Moderate	Aggressive
Transportation	444	372	404	381	335
Commercial	60	56	57	56	54
Residential	35	37	36	36	37
Total	540	464	496	473	427

Table C 2. Net changes in annual GHG emissions based on baseline in various scenarios

Net Annual GHG Emissions (Mt CO2e)	Covid-19 (2020)	Conservative	Moderate	Aggressive
Transportation	-73	-41	-63	-109
Commercial	-4.8	-3.7	-4.4	-5.9
Residential	1.1	0.6	1.0	1.7
Total	-77	-44	-67	-113

Table C 3. Percentage of net changes in annual GHG emissions based on baseline in various scenarios

Net Annual GHG Emissions (%)	Covid-19 (2020)	Conservative	Moderate	Aggressive
Transportation	-16.4%	-9.1%	-14.3%	-24.5%
Commercial	-7.9%	-6.2%	-7.4%	-9.7%
Residential	3.2%	1.7%	2.7%	4.7%
Total	-14.2%	-8.1%	-12.4%	-21.0%

D. Parameters, values, data sources and descriptions

Table D 1. Parameters, values, data sources and descriptions for transportation sector

Parameters	Value	Source	Description
Average One-way Commute Distance	15 miles	U.S. Department of Transportation 2003	The average one-way commute distance of American workers
Rebound Effect on VMT/day	25 %	Hopkinson (2003), Reitan (2014) and Henderson (1996)	The averaged overall rebound effect of possibly increased travel due to reduced commute travel (e.g. grocery shopping on the way back to home after work)
Use-phase Energy Factor(car)	5461.00 Btu/passenger mile	Greet model 2021	The embodied energy of vehicle, amortized to Btu/mile
Use-phase Emission Factor(car)	408.00 g/passenger mile	Greet model 2021	The embodied emission of vehicle, amortized to g/mile
Use-phase Energy Factor(light duty truck)	7122.00 Btu/passenger mile	Greet model 2021	The embodied energy of vehicle, amortized to Btu/mile
Use-phase Emission Factor(light duty truck)	532.00 g/passenger mile	Greet model 2021	The embodied emission of vehicle, amortized to g/mile
Energy Factor(bus)	4560.00 Btu/passenger mile	Transportation energy data book edition39:2-13	The embodied energy of vehicle, amortized to Btu/mile
Emission Factor(bus)	291.66 g/passenger mile	Climate Change Standard Working Group, SUDS Policy and Planning Committeeommittee	The embodied emission of vehicle, amortized to g/mile
Energy Factor(rail)	1603.00 Btu/passenger mile	Transportation energy data book edition39:2-13	The embodied energy of vehicle, amortized to Btu/mile
Emission Factor(rail)	147.87 g/passenger mile	Climate Change Standard Working Group, SUDS Policy and Planning Committeeommittee	The embodied emission of vehicle, amortized to g/mile
Energy Factor(bicycle)	0 Btu/passenger mile	Assumed	Assumed
Emission Factor(bicycle)	0 g/passenger mile	Assumed	Assumed
Energy Factor(walk)	0 Btu/passenger mile	Assumed	Assumed
Emission Factor(walk)	0 g/passenger mile	Assumed	Assumed
Commute Mode:			
Car	87.8 %	US Census	The percentage of all commute types
truck	3.6 %	US Census	The percentage of all commute types
Bus	2.5 %	Monthly traffic monitoring data of U.S. Department of Transportation	The percentage of all commute types
Rail	2.7 %	Monthly traffic monitoring data of U.S. Department of Transportation	The percentage of all commute types
Walked	2.7 %	US Census	The percentage of all commute types
Bicycle	0.5 %	US Census	The percentage of all commute types

Table D 2. Parameters, values, data sources and descriptions for building sectors

Parameters	Value	Unit	Source	Description
Residential Building Energy Consumption - Space Heating - Natural gas	2,678	TBtu	EIA 2015 RECS	Site energy consumption for space heating in residential buildings where the energy source is natural gas.
Residential Building Energy Consumption - Space Heating - Electricity	187	TBtu	EIA 2015 RECS	Site energy consumption for space heating in residential buildings where the energy source is electricity.
Residential Building Energy Consumption - Space Heating - Fuel Oil/Kerosene	2,891	TBtu	EIA 2015 RECS	Site energy consumption for space heating in residential buildings where the energy source is fuel oil/kerosene.
Residential Building Energy Consumption - Space Heating - Propane	2,549	TBtu	EIA 2015 RECS	Site energy consumption for space heating in residential buildings where the energy source is propane.
Commercial Building Energy Consumption - Space Heating - Natural gas	1,339	TBtu	EIA 2012 CBECS	Site energy consumption for space heating in commercial buildings where the energy source is natural gas.
Commercial Building Energy Consumption - Space Heating - Electricity	85	TBtu	EIA 2012 CBECS	Site energy consumption for space heating in commercial buildings where the energy source is electricity.
Commercial Building Energy Consumption - Space Heating - Fuel Oil/Kerosene	93	TBtu	EIA 2012 CBECS	Site energy consumption for space heating in commercial buildings where the energy source is fuel oil/kerosene.
Commercial Building Energy Consumption- Space Heating - District Heating	240	TBtu	EIA 2012 CBECS	Site energy consumption for space heating in commercial buildings where the energy source is district heating.
Residential Building Energy Consumption - Water Heating - Natural gas	1,019	TBtu	EIA 2015 RECS	Site energy consumption for water heating in residential buildings where the energy source is natural gas.
Residential Building Energy Consumption - Water Heating - Electricity	173	TBtu	EIA 2015 RECS	Site energy consumption for water heating in residential buildings where the energy source is electricity.
Residential Building Energy Consumption - Water Heating - Fuel Oil/Kerosene	432	TBtu	EIA 2015 RECS	Site energy consumption for water heating in residential buildings where the energy source is fuel oil/kerosene.
Residential Building Energy Consumption - Water Heating - Propane	835	TBtu	EIA 2015 RECS	Site energy consumption for water heating in residential buildings where the energy source is propane.
Commercial Building Energy Consumption - Water Heating - Natural gas	424	TBtu	EIA 2012 CBECS	Site energy consumption for water heating in commercial buildings where the energy source is natural gas.
Commercial Building Energy Consumption - Water Heating - Electricity	22	TBtu	EIA 2012 CBECS	Site energy consumption for water heating in commercial buildings where the energy source is electricity.
Commercial Building Energy Consumption - Water Heating - Fuel Oil/Kerosene	0.8	TBtu	EIA 2012 CBECS	Site energy consumption for water heating in commercial buildings where the energy source is fuel oil/kerosene.
Commercial Building Energy Consumption- Water Heating - District Heating	60	TBtu	EIA 2012 CBECS	Site energy consumption for water heating in commercial buildings where the energy source is district heating.
Residential Building Energy Consumption - Air Conditioning - Electricity	214	TBtu	EIA 2015 RECS	Site energy consumption for air conditioning in residential buildings where the energy source is electricity.
Commercial Building Energy Consumption - Air Conditioning - Electricity	633	TBtu	EIA 2012 CBECS	Site energy consumption for air conditioning in commercial buildings where the energy source is electricity.
Residential Building Energy Consumption - Refrigerators - Electricity	89	TBtu	EIA 2015 RECS	Site energy consumption for refrigerators in residential buildings where the energy source is electricity.
Commercial Building Energy Consumption - Refrigerators - Electricity	670	TBtu	EIA 2012 CBECS	Site energy consumption for refrigerators in commercial buildings where the energy source is electricity.
Residential Building Energy Consumption - Others - Natural gas	266	TBtu	EIA 2015 RECS	Site energy consumption for other uses in residential buildings where the energy source is natural gas.
Residential Building Energy Consumption - Others - Electricity	604	TBtu	EIA 2015 RECS	Site energy consumption for other uses in residential buildings where the energy source is electricity.
Residential Building Energy Consumption - Others - Fuel Oil/Kerosene	57	TBtu	EIA 2015 RECS	Site energy consumption for other uses in residential buildings where the energy source is fuel oil/kerosene.
Residential Building Energy Consumption - Others - Propane	567	TBtu	EIA 2015 RECS	Site energy consumption for other uses in residential buildings where the energy source is propane.
Commercial Building Energy Consumption - Others - Natural gas	485	TBtu	EIA 2012 CBECS	Site energy consumption for other uses in commercial buildings where the energy source is natural gas.
Commercial Building Energy Consumption - Others - Electricity	2,831	TBtu	EIA 2012 CBECS	Site energy consumption for other uses in commercial buildings where the energy source is electricity.
Commercial Building Energy Consumption - Others - Fuel Oil/Kerosene	41.4	TBtu	EIA 2012 CBECS	Site energy consumption for other uses in commercial buildings where the energy source is fuel oil/kerosene.
Commercial Building Energy Consumption- Others - District Heating	12	TBtu	EIA 2012 CBECS	Site energy consumption for other uses in commercial buildings where the energy source is district heating.
Emission Factor - Natural gas	23.46	kg/Mbtu	Dixit, Culp & Fernandez-Solis (2014)	The emission factor of natural gas.
Emission Factor - Electricity	80.76	kg/Mbtu	Dixit, Culp & Fernandez-Solis (2014)	The emission factor of electricity.
Emission Factor - Fuel Oil/Kerosene	26.14	kg/Mbtu	Dixit, Culp & Fernandez-Solis (2014)	The emission factor of fuel oil/kerosene.
Emission Factor - Propane	63.05	kg/Mbtu	Dixit, Culp & Fernandez-Solis (2014)	The emission factor of propane.
Emission Factor - District Heating	0.15	kg/Mbtu	Neirotti et al. (2020)	The emission factor of district heating.
Residential Change Factor - Space Heating - Remote	+ 10	%	Assumed	Assumed
Residential Change Factor - Water Heating - Remote	+ 10	%	Assumed	Assumed
Residential Change Factor - Air Conditioning - Remote	+ 10	%	Assumed	Assumed
Residential Change Factor - Refrigerators - Remote	+ 10	%	Assumed	Assumed
Residential Change Factor - Others - Remote	+ 10	%	Assumed	Assumed
Residential Change Factor - Space Heating - Weekend	+ 5	%	Assumed	Assumed
Residential Change Factor - Water Heating - Weekend	+ 5	%	Assumed	Assumed
Residential Change Factor - Air Conditioning - Weekend	+ 5	%	Assumed	Assumed
Residential Change Factor - Refrigerators - Weekend	+ 5	%	Assumed	Assumed
Residential Change Factor - Others - Weekend	+ 5	%	Assumed	Assumed
Commercial Change Factor - Space Heating - Remote	-15	%	Assumed	Assumed
Commercial Change Factor - Water Heating - Remote	-15	%	Assumed	Assumed
Commercial Change Factor - Air Conditioning - Remote	-15	%	Assumed	Assumed
Commercial Change Factor - Refrigerators - Remote	-15	%	Assumed	Assumed
Commercial Change Factor - Others - Remote	-15	%	Assumed	Assumed
Commercial Change Factor - Space Heating - Weekend	-25	%	Assumed	Assumed
Commercial Change Factor - Water Heating - Weekend	-25	%	Assumed	Assumed
Commercial Change Factor - Air Conditioning - Weekend	-25	%	Assumed	Assumed
Commercial Change Factor - Refrigerators - Weekend	-25	%	Assumed	Assumed
Commercial Change Factor - Others - Weekend	-25	%	Assumed	Assumed