Impact of Changes in Lifestyle due to Digitalization on Urban Energy Consumption

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ABSTRACT

The impact of digitalization, particularly telecommuting and ride-sharing, on urban energy consumption is estimated in this study. In the short term, telecommuting can alter energy consumption patterns. Over the long term, these innovations have the potential to affect preferences for residential environments. This study used a variety of simulation models to estimate the impact of telecommuting and ride-sharing on urban energy demand in the residential, commercial, and transportation sectors. Residential energy demand was estimated using a detailed bottom-up simulation that considers heterogeneity of household energy use, simulates appliance operations based on occupant behaviour, and aggregates these energy use. For commercial energy demand, commercial buildings were categorized based on their purpose, size, and floor area, and representative models of each category were created to estimate the energy demand intensity. In the transportation sector, energy demand was estimated based on a travel survey that recorded the origin and destination, purpose, and mode of transport. The results showed that telecommuting leads to substantial energy savings in the commercial sector. Further, while relocating to larger detached houses increases household energy consumption, this is offset by power generation from photovoltaic (PV) systems. Under a social change scenario, the potential reduction in annual primary energy demand was of 18%.

Keywords: Digitalization, Energy, Net-zero, Urban sprawl, Bottom-up simulation model

INTRODUCTION

Digitalization, which can be defined as the process of enhancing the value of products and services using digital technologies, represents one of the most important societal shifts in recent years. To effectively achieve net-zero, quantifying the impact of digitalization on urban energy demand is considered critical. For example, in the short term, telecommuting alters workers' behaviour and influences urban energy consumption. At the same time as telecommuting becomes more prevalent, household energy consumption is increasing, especially for heating and cooling, and energy demand is expected to decrease in office buildings and transportation. In addition, if ride-sharing services become more widespread, then energy use for transportation is expected to be reduced due to higher car occupancy rates. Over the long term, the growth of telecommuting, e-commerce, and ride-sharing will change living environment preferences. Telecommuters will not need to live in small apartments near stations to make commuting more convenient. With increased adoption of ride-sharing, the necessity and benefits associated with living near stations will decrease as people will be able to access any area by car without relying on public transportation. Furthermore, as people spend more time at home, there will be a growing demand for new household features such as improvements in the natural environment and rooms dedicated to telecommuting. These changes due to digitalization may lead to relocation from small

apartments near stations to large houses in suburban areas blessed with natural environment.

Many studies in recent years have focused on the impact of digitalization on energy consumption. For example, Shimoda et al. (2007) used simulation models to estimate the changes in energy consumption induced by telecommuting in both residential and office buildings in Osaka City. However, these studies have focussed solely on the short-term impacts of telecommuting. To accurately evaluate the changes in urban energy demand due to digitalization, it is necessary to consider the long-term impact of digitalization, such as changes in living environment preferences.

This study first examines the current state of telecommuting and ride-sharing in Japan. Based on surveys by public institutions and previous research, the potential impact of telecommuting and ride-sharing on energy consumption in the residential, commercial, and transportation sectors is estimated for Ibaraki City, Osaka, Japan. The southern part of Ibaraki City has a concentration of major train stations, while residential areas have been developed in the northern part of the city. In order to conduct a detailed analysis, a micro-scale estimation was carried out in Ibaraki City, in which relocation scenarios can be created. Figure 1 shows the analytical objectives of this study.

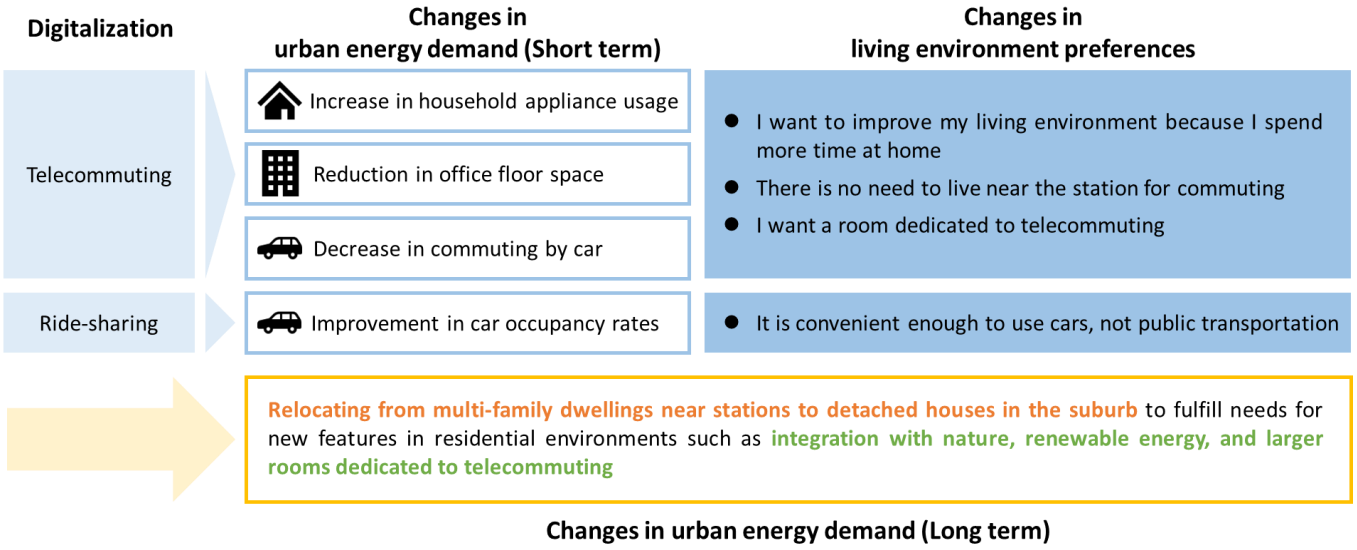

Figure 1: Key influences of telecommuting and ride-sharing on residential choices and energy demand

SURVEY ON TELECOMMUTING AND RIDE-SHARING IN JAPAN

According to a national survey, approximately 80% of telecommuters expressed their desire to continue telecommuting even after the end of the COVID-19 pandemic (Ministry of Land, Infrastructure and Transport (MLIT), 2022). The findings imply that the practice of telecommuting is likely to further spread in the future. The survey also showed that the feasibility of telecommuting is affected by occupation. Kotera (2020) quantified the feasibility of telecommuting as a percentage for various types of occupations. Subsequently, Endo and Egawa (2020) aggregated these percentages for major occupations based on Kotera's (2020) study, as shown in Table 1. The results of surveys of relocation intention are shown in Figure 2 (MLIT, 2022). Additionally, Table 2 shows the top two reasons for relocation based on the survey. It can be inferred from the figure and the table that desire to relocate to live in larger houses in suburban areas with richer natural environments is stronger among telecommuters than it is among non-telecommuters.

As for ride-sharing, demonstration started in April 2024 with the purpose of supplementing shortages of taxis in specific regions, times, and hours. The MLIT (2024) has announced its policy to expand the areas where ride-sharing services will be provided in the future.

Table 1: Telecommuting feasibility percentages by occupation (Endo and Egawa, 2020)

Occupational Classification	Percentage
Administrative	86.8 %
Professional and technical	49.6 %
Clerical	49.0 %
Sales	59.3 %
Service	7.3 %
Security	0.7 %
Agricultural, forestry, and fisheries	0.5 %
Production	2.9 %
Transportation and machinery operation	0.0 %
Construction and mining	1.5 %
Transportation, cleaning, and packaging	0.0 %

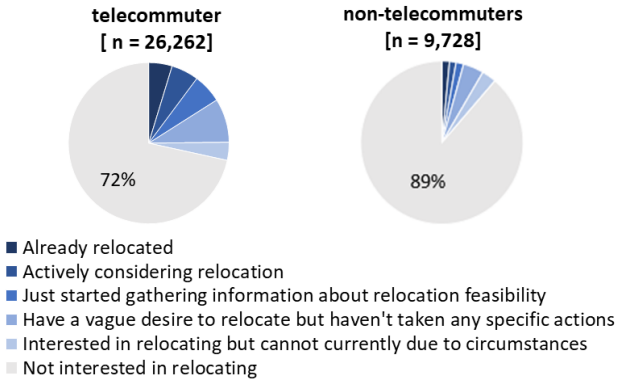

Figure 2: Relocation intentions of telecommuters versus non-telecommuters (MLIT, 2022)

Table 2: Main reasons for wanting to relocate among telecommuters and non-telecommuters (MLIT, 2022)

telecommuters	non-telecommuters
to live in a large house (40.6 %)	To relocate to a place where rent or living expenses are lower, in order to reduce living cost (27.8 %)
To have a relaxed, stress-free, and healthier lifestyle in local cities or rich natural environment (24.9 %)	to live in a large house (22.4 %)

METHODS

Residential Sector: Simulation Model

The Total Residential End-use Energy Simulation (TREES) model was used to estimate energy demand in the residential sector (Taniguchi-Matsuoka, 2020). An overview of the model is shown in Figure 3. First, for the target area, household attributes such as family composition, gender, employment status and occupation of household members, type of housing, and floor area are probabilistically determined based on statistics. Using these household attributes, Data Preparation models are used to set each household's determinants of energy demand, such as occupants' behavior (Okada, 2019), the number of appliances and efficiency of equipment. Next, the Energy End-Use Model estimate the energy consumption of each household by simulating appliance operations based on occupant behaviour. Finally, by summing the results of all households, the residential sector energy consumption for the target area can be calculated. The TREES model accounts for the heterogeneity in household energy use characteristics. Additionally, the energy demand for heating and cooling is estimated using dynamic thermal load calculations with input conditions, such as weather data, housing layout, and exterior wall specifications. In this way, the TREES model can faithfully reproduce the energy consumption in actual households, accurately evaluate the impact of the increase in time spent at home due to telecommuting, and changes in housing specifications due to relocation on energy demand.

Residential Sector: Calculation

To estimate the impact of digitalization on the residential energy demand, three scenarios were established: the Business as Usual (BAU) scenario, the Telecommuting scenario and the Relocation scenario.

1. The BAU scenario

Telecommuting and ride-sharing are not prevalent.

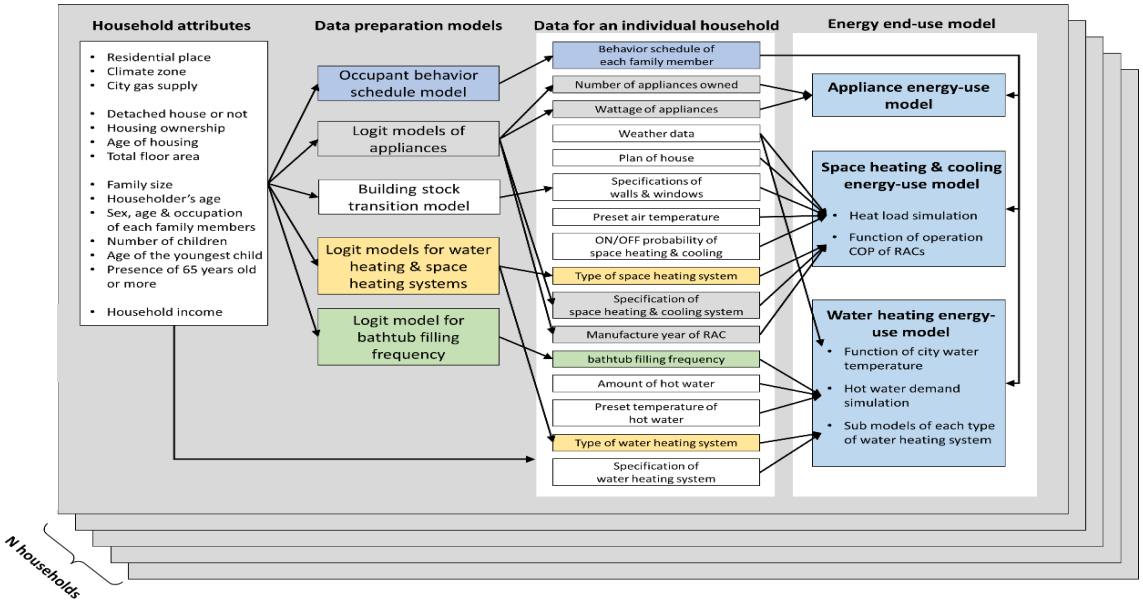

Figure 3: Overview of the TREES model

2. The Telecommuting scenario

Telecommuting becomes widespread. The Survey on Telecommuting Practices (MLIT, 2022) showed that occupation plays a major role in determining the feasibility of telecommuting. Figure 4 shows the number of telecommuters by occupation, estimated based on the percentage shown in Table 1. It is estimated that 39,589 workers, i.e., approximately 32.9% of all employees in Ibaraki City, are capable of telecommuting. Telecommuters work from home and the time previously spent commuting is now reassigned to resting at home.

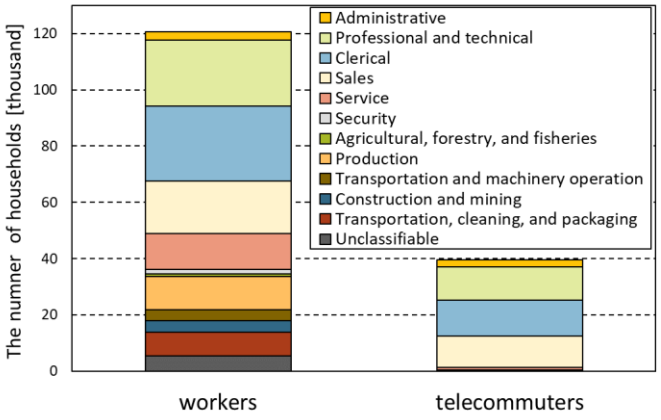

Figure 4: Number of workers and telecommuters by occupation in Ibaraki City

3. The Relocation scenario

Telecommuting triggers a shift from multi-family dwellings near stations, to detached houses farther away from stations. Firstly, as shown in Figure 5, small areas at the level of town and block in Ibaraki City are classified into three zones: close to stations, intermediate distance from stations, and far from stations. Secondly, the likelihood of whether each household will relocate is estimated as shown in the flowchart of Figure 6. The results showed that 7.4% of all households would likely relocate due to telecommuting.

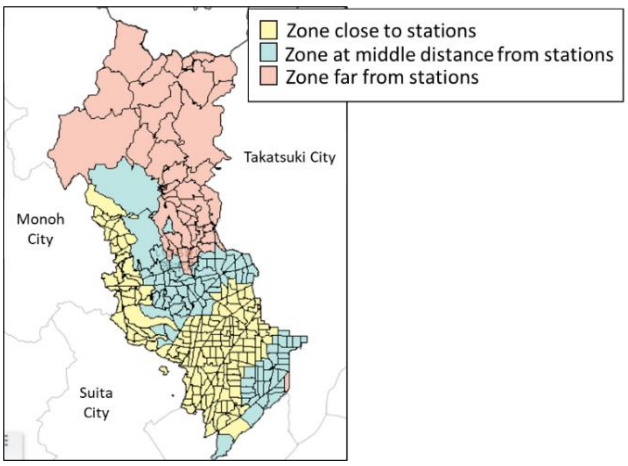

Figure 5: Classification of small areas in Ibaraki City

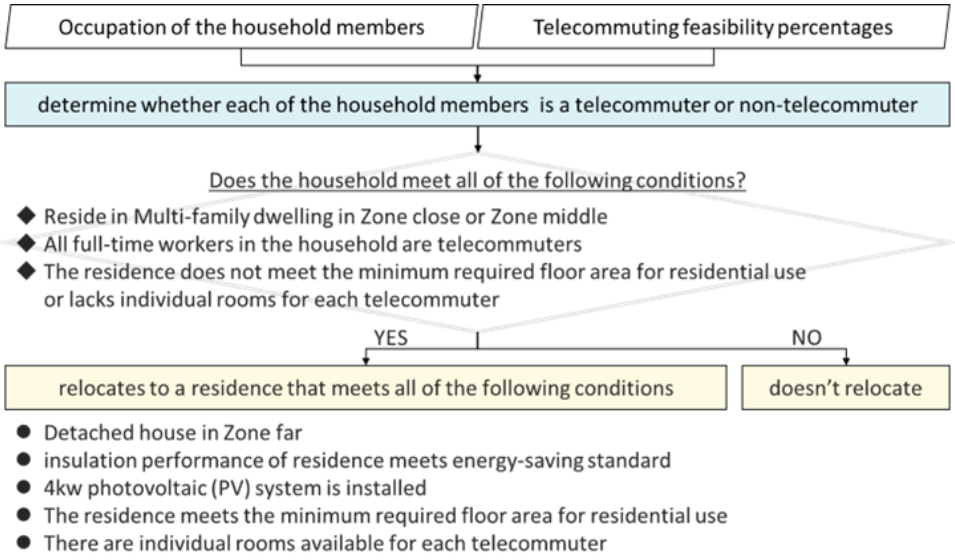

Figure 6: Flowchart of the household relocation decision

Commercial Sector: Simulation Model

To estimate the energy demand in office buildings, the Building Stock Energy Model (BSEM) developed by Yamaguchi et al. (2022) was used. The model considers building stock segments made by building size and systems. A physics-based energy simulation using EnergyPlus 8.6 was performed with reference building models each representing a building stock segment. The model uses an occupant behaviour model that stochastically simulates the occupancy condition (Kim et al. 2024), allowing for consideration of changes in occupancy conditions due to telecommuting and quantification of resultant changes in energy demand.

Commercial Sector: Calculation

The annual energy reduction due to telecommuting in office buildings is estimated using Equation (1):

$$\Delta E_{off} = pop_{tele} \times \frac{FloorArea_{off}}{pop_{off}} \times \frac{E_{off}}{FloorArea_{off}} \quad (1)$$

where pop_{tele} represents the number of telecommuters, set to 39,589 as estimated in the residential sector; $FloorArea_{off}/pop_{off}$ is the office floor area per person, set to 12.1 m²/person (XYMAX Real Estate Institute Corporation, 2023); and $E_{off}/FloorArea_{off}$ is the energy demand per unit area of office buildings in the Kinki region, set to 681 MJ/m² for electricity and 177 MJ/m² for fuel.

Since it is not possible to identify which office buildings the occupants of Ibaraki City commute to, the energy demand per unit area of office buildings in the Kinki region estimated by BSEMs is used.

Transportation Sector: Calculation

In the transportation sector, changes in energy consumption are estimated using a travel survey that records the origin, destination, purpose, and mode of transportation of trips that occurred in Ibaraki City (Keihanshin Metropolitan Area Transportation Planning Council (Keihanshin MATPC), 2012).

1. Telecommuting

The annual energy reduction due to the decrease in commuting by car is estimated using Equation (2):

$$\Delta E_{car_tele} = \frac{pop_{car\&tele} \times \overline{mileage} \times 2 \times days}{MPG} \quad (2)$$

where $pop_{car\&tele}$ represents the number of telecommuters who commute by car in Ibaraki City; $\overline{mileage}$ is the average distance per car commute in Ibaraki City; $days$ is the number of annual working days, set to 250; and MPG is the efficiency of electric vehicles, set to 6 km/kWh (Ministry of Environment, 2020).

To estimate $pop_{tel\&car}$, the probability of car usage for commuting by occupation is calculated based on the results of the travel survey (Keihanshin MATPC, 2012). $\overline{mileage}$ is estimated by aggregating the number of car

commuting trips occurring in Ibaraki City by destination and investigating the car travel distances between the main office at each destination and Ibaraki City Hall.

2. Ride-sharing

The annual reduction in energy consumption due to a 10% improvement in car occupancy rates is estimated using Equation (3):

$$\Delta E_{car_share} = \frac{\left(\sum_i^{c,s,f} mileage_i \times 2 \times days_i\right) \times 0.1}{MPG} \quad (3)$$

where $mileage_i$ represents the daily distance travelled for different purposes (c is commuting, s is school commuting, and f is free); $days_i$ is the number of days dedicated to each of these purposes annually (c, s: 250 and f: 365).

$mileage_i$ is calculated by multiplying the number of trips to each destination by the travel distance between each destination's main office and Ibaraki City Hall and summing the results (Keihanshin MATPC, 2012).

RESULTS AND DISCUSSION

Residential Sector

As a result of telecommuting, there is change in the energy consumption patterns of appliances, such as lighting, desktop computers, and room air conditioners (RAC). Figures 7 and 8 show the energy consumption of the same household on a certain summer weekday under the Telecommuting scenario and the BAU scenario. In the Telecommuting scenario, the operation of each appliance during the daytime and the total daily electricity consumption is higher than that in the BAU scenario. Figure 9 shows the change in primary energy usage under the Telecommuting scenario and the Relocation scenario compared to the BAU scenario. In the Telecommuting scenario, the increase in the operation of appliances, especially those associated with heating and cooling, contributes to the observed increase in energy consumption. In the Relocation scenario, the energy consumption associated with all usage increases due to changes in house specifications. However, the reduction in energy consumption attributable to power generation by PV cells is significant. When all of the generated electricity is self-consumed, it offsets the increase in energy consumption.

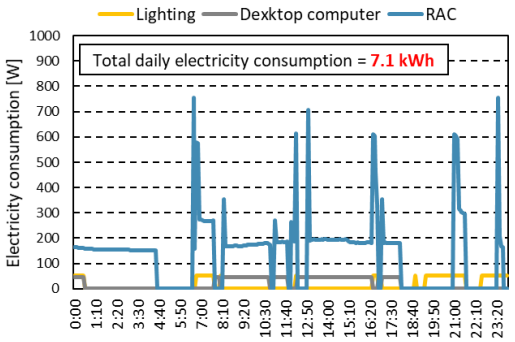

Figure 7: Electricity consumption on a certain summer weekday in the Telecommuting scenario

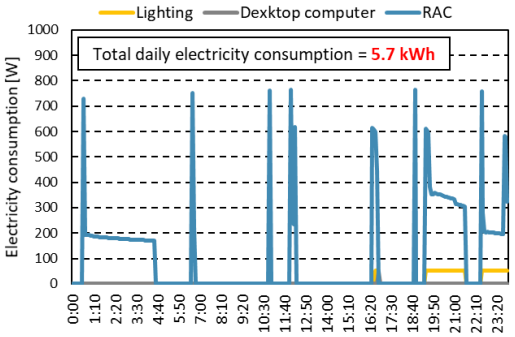

Figure 8: Electricity consumption on a certain summer weekday in the BAU scenario

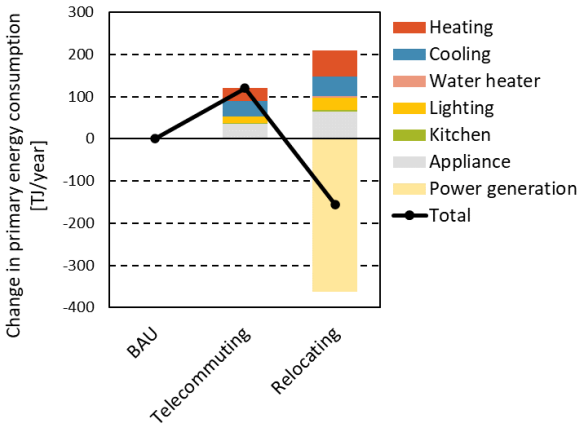

Figure 9: Changes in primary energy consumption from the BAU scenario

Residential, Commercial, and Transportation Sectors

Figure 10 shows the estimated annual primary energy change in the residential, commercial, and transportation sectors. Focusing on telecommuting, the reduction in energy consumption in the commercial sector (due to reduction in office floor space) and in the transportation sector (due to a reduction in commuting by car) is greater than the increase in energy consumption in the residential sector (due to an increase in household appliance usage). It is also suggested that, even if the spread of telecommuting promotes relocation, installing PV systems on rooftops and consuming the generated electricity have the effect of reducing overall energy consumption. In addition, ride-sharing (improvement in car occupancy rates) also significantly reduces energy consumption.

To verify changes in energy consumption across all sectors, two scenarios shown in Table 3 were established. Figure 11 shows the results estimated for each scenario. The results suggested that a reduction in annual primary energy consumption of 1.38 PJ could be achieved; this amount corresponds to 18% of the energy consumption in the Baseline scenario.

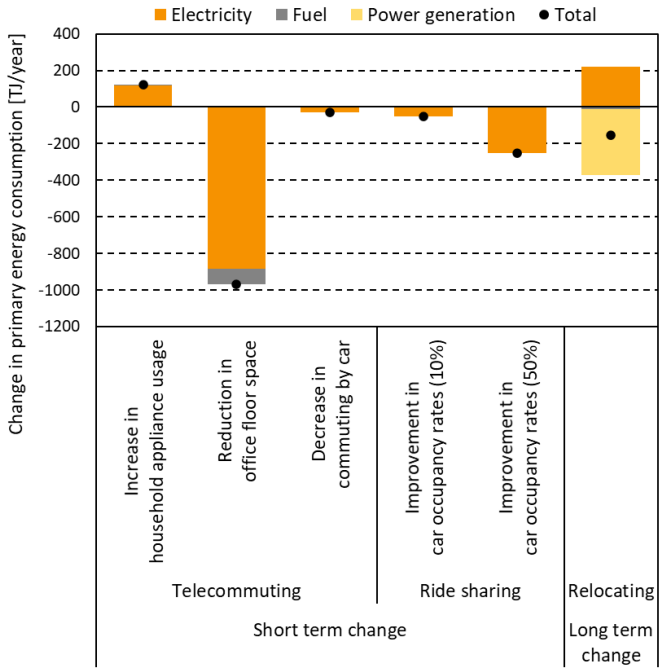

Figure 10: Changes in primary energy consumption across all sectors

Table 3: Scenario configuration parameters

	Baseline scenario	**Social Change scenario**
Residential	BAU scenario	Relocating scenario
Commercial	Office floor area per number of office workers	Reduction in office floor area per number of telecommuters
Transportation	Original car occupancy rates	Improvement in car occupancy rates (50%)

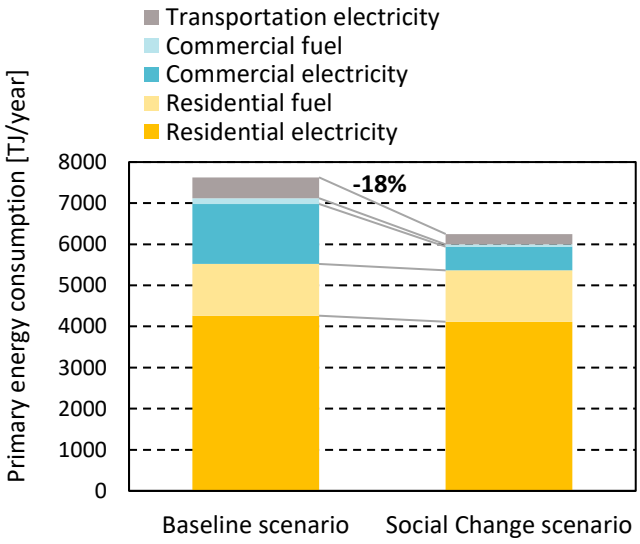

Figure 11: Primary energy consumption in Ibaraki City under the Baseline scenario and the Social Change scenario

CONCLUSIONS

In this study, the impact of digitalization, including telecommuting and ride-sharing, on urban energy consumption is estimated for Ibaraki City. The reduction in office floor area offers significant potential for lowering energy consumption. Therefore, promoting hot-desking and reducing office building space could lead to substantial energy savings.

Moreover, even in the scenario where relocation is considered, energy consumption can be mitigated through the installation of PV systems. This result highlights the potential for relocation to reduce energy

consumption, despite social changes that might oppose recent urban planning initiatives, such as transitioning from private cars to public transportation and promoting urban densification. This study reveals the importance of capturing the diverse impacts of digitalization on people's values and lifestyles and swiftly incorporating them into urban planning policies. However, as this study focuses on Ibaraki City, it is necessary to consider the characteristics of the residents when generalising the results. For example, Ibaraki City may have fewer car owners and more office workers due to its easy access to the center of Osaka.

FUTURE WORK

In this study, all workers identified as capable of telecommuting are assumed to work remotely for the entirety of their working hours. However, for a more realistic scenario, the frequency of telecommuting and ride-sharing should be assessed. Additionally, the rebound effects of telecommuting and ride-sharing must also be considered. For example, increased leisure time due to telecommuting could promote travel, and other household members may use the car more frequently instead of the owner who telecommutes. Furthermore, the recent trend towards digitalization has increased electricity consumption by data centres, which consume significant amounts of electricity.

ACKNOWLEDGEMENTS

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