The Impact of Demographic Changes on CO₂ Emission Profiles: Cases of East Asian Countries

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Abstract: The demographic changes of East Asian countries have accelerated in recent years. With consideration of the linkage between human behavior and carbon emissions, it is necessary to consider demographic characteristics for the CO₂ emission projections of these countries. This study examines how changes in the demographic structure affect the emission projections of three East Asian countries (South Korea, China, and Japan) by comparing two different vintages of population projections. The study constructed a dynamic computable general equilibrium (CGE) model and applied the most up-to-date dataset of population prospects, GTAP 10, and the labor force participation rate. By comparing UN2010 and UN2019 projections, the study examined the impact of demographic changes on CO₂ emission profiles of the three East Asian countries. The simulation result showed that GDP, which represents economic activity along with the population, is the direct channel of CO₂ emission projections. Moreover, the scenario analysis suggested the population factor as one of the main drivers of the CO₂ emission projection and a clear positive relationship between GDP and CO₂ emissions, though CO₂ emissions are generally inelastic in response to a GDP decrease in the three East Asian countries. The finding indirectly implies that not only the size of the population but also demographic composition should be considered to project CO₂ emissions, as the labor participation rate is an important factor to determine the production function.

Keywords: Global CGE Model; aging society; UN population projections; CO₂ projections

1. Introduction

Demographic changes, including the size of the population, age structure, and household characteristics, have become an important issue to many countries. The demographic transitions of East Asian countries have accelerated recently due to the low fertility rates and longer life expectancies. As human behavior affects energy consumption and carbon emissions via various channels, an understanding of the impacts of demographic changes on carbon emissions is necessary to forecast the future CO₂ emission profiles of these countries.

As life expectancy increases and the demographic structure changes, an increasing number of studies have examined the relationship and channels between demographics and carbon emissions. A number of studies have found that the changes in demographic characteristics affect the changes in CO₂ emissions via various channels. The studies, in general, suggest that demographic characteristics, which are related to social and economic activities, have significant effects on carbon emissions, but the direction of the effects of each characteristic is mixed. O’Neil et al. (2012) [1] examined existing literature of statistical analysis, including decomposition analysis and scenario analysis, to find how demographic factors affect CO₂ emissions from the use of fossil fuels. The study identified demographic factors, such as population size, urbanization, and the composition of households, and derived implications from the literature that an aging population and urbanization have statistically significant effects, though less than proportional, on carbon emissions. The age...
structure affects household size and energy use patterns, and the decrease of household size led to an increase in carbon emissions, while it found a negative elasticity for the aged population. Okada (2012) [2] analyzed the relationship between the aged population and carbon emissions from road transportation of 25 OECD/IEA countries and Japan over 1978–2008. The study found the existence of a quadratic relationship between carbon emissions per capita and the share of the aged population, and that the carbon emissions per capita from the road transportation sector decreases when the share of the aged population goes beyond a turning point.

Moreover, a number of existing literature has examined the relationship between demographic characteristics and the carbon emissions of a country through decomposition analysis, and many studies generally suggest that an increase in population is associated with an increase of carbon emissions, while the size of households has a negative relationship with carbon emissions. Balezentis (2020) [3] found the effects of factors of population, household size, dwelling area, energy intensity, and carbon factor by applying an index decomposition analysis. It found that declines in population and energy intensity were important factors leading to a decrease of CO\textsubscript{2} emissions, and that the effects of a decreasing household size and an increasing number of dwellings per capita and average dwelling area, which are related to the behavior of the population, increased the energy consumption and pushed Lithuanian households’ CO\textsubscript{2} emissions upward. Yu et al. (2018) [4] examined how the aging population and the industrial structure affect the carbon emissions of China over 1990–2014 by applying an extended STIRPAT model. In addition to wealth and industrial structure, it found that the aging population affects carbon emissions positively and significantly in China. From the demographic aspect, the study suggested that the aging of the population, increasing supporting problems, and an imperfect social security system contributed to the increase in CO\textsubscript{2} emissions. Wang et al. (2019) [5] used the STIRPAT model and SYS-GMM estimation and found that both the aging structure and migration are associated with an increase in CO\textsubscript{2} emissions per capita. Furthermore, the study found a non-linear impact of structural transition on CO\textsubscript{2} emissions per capita in China. Kim et al. (2020) [6] examined whether the aging population and low fertility rate affected the carbon emissions of South Korea over 1988–2016 through IPAT augmented environmental Kuznets curve analysis. Based on the economic and demographic information of 16 provinces in South Korea, the study found empirical evidence that the aging population leads to the reduction of carbon emissions, and as the aged population are less active, tend to live in smaller houses and have a significant preference of air quality; this may lead to the decrease of carbon emissions. The existing studies based on decomposition and econometric analysis showed that the aging population generally leads to a decrease in CO\textsubscript{2} emissions, while the trends of decreasing sizes of households lead to an increase in CO\textsubscript{2} emissions of countries through various channels.

In addition, some studies used economic and engineering modeling to demystify the relationship between demographic characteristics and carbon emissions. Yu et al. (2018) [7] applied the framework of the extended snapshot tool, which is a bottom-up engineering tool, to examine the effects of demographic structural change on the future energy consumption and carbon emissions of Chinese households. Based on the scenarios of future lifestyle and demographic structure of households in Sichuan province, China, the study found that the lifestyle and structural changes towards small household size and aging populations lead to an increase in energy consumption and carbon emissions of the less-developed Sichuan province, mainly caused by increasing demands for heating, cooking, transport, and consumption of goods and services. Carvalho et al. (2020) [8] used an input–output framework for the Brazilian economy to evaluate the changes in consumption patterns induced by demographic changes. By age group, the composition of household consumption differs, and the change of age structure is expected to lead towards consumption activities with fewer emissions. While the study found that the aged population groups of 60 to 69 years and over 70 years showed more emissions-intensive consumption, this attributed to the growth of those age groups.
Only a few studies constructed CGE models to find the effects of demographic components on carbon emissions [9–11]. Wei et al. (2018) [9] established a computable general equilibrium (CGE) model and examined the effects of labor force participation rates by gender and age on economies and emissions based on the policy scenarios of IEA World Energy Outlook and UN World Population Prospects 2015. The study found that aging populations lead to a decline in labor supply and economic growth, and eventually, lead to reductions in carbon emissions globally. Though there were trivial effects of gender-specific labor force participation rates, it found that the GDP of the aging regions, such as the US, EU, and Japan, would be further overestimated compared to other regions. Wei et al. (2018) [10] focused on China’s aging trends and applied the Chinese population’s expected age structure in 2050 to its economy in 2011 to understand the impact of changes in the aging structure on carbon emissions. This assumption led to the expected GDP loss of China, and found that aging trends would lead to reducing emissions by reducing consumption, labor supply, and investments. Niamir et al. (2020) [11] applied bottom-up agent-based models and top-down CGE models to incorporate behavior aspects of households, and the study found the importance of the regional dimension in a low-carbon economy transition, and demographic characteristics, including the individual’s age and type and size of dwellings, are the important factors amplifying the difference in transitions.

In summary, many empirical results and modeling research provide a general understanding that demographic characteristics, such as an aging population, lead to the decline in CO₂ emissions of countries by channels, such as changes in consumption patterns and reductions in labor forces, while the growth of populations and the trend of decreasing household size lead to the increase in CO₂ emissions in general. While many existing literatures found how the demographic structure, including the aging population, affects the carbon emissions of countries, many of the studies derived implications based on decomposition and econometric analysis.

The key research question of this study is to examine how the changes of demographic characteristics affect the future emission projections of three East Asian countries (South Korea, China, and Japan) by comparing the emission projections with two different vintages of UN population prospects. The study adopts population projections of the East Asian countries from UN Population Prospects 2010 and 2019 to the constructed CGE model. It compares the future carbon emissions from two different population projections; hence, the comparison illustrates the accelerated changes in the demographic structure of the East Asian countries, and describes the impact of accelerated aging trends of these East Asian countries on the future carbon emission projections. The study focuses on the impact of an aging population on labor supply and production. To examine the research question, this study constructs a dynamic CGE model and applies the most up-to-date dataset, such as UN Population Prospects 2019 [12], GTAP 10, and labor force participation rates from ILO [13], to systemically examine the future impact of demographic characteristics on the economy and carbon emissions of the three East Asian countries. The remainder of the paper is organized as follows: Section 2 describes the methodology used in the study, which is a global multi-regional recursive dynamic CGE model. Section 3 provides the simulation results of population structure, GDP, and CO₂ emissions of East Asian countries. Lastly, Section 4 discusses the implications of the study.

2. Materials and Methods

Global CGE Model Structure

A dynamic computable general equilibrium (CGE) model was constructed to examine the effects of aging populations on carbon emissions of East Asian countries. In general, a CGE model consists of a system of equations, describes the interactions among parts of an economy systematically, and solves the equations to find the economy-wide equilibrium [14]. A strong feature of CGE model-based analysis is that it enables the induction of quantitative effects of shocks, such as policy changes, with real data, so the CGE model is widely used in various areas of energy and carbon emissions research [15–17].
The regional households were assumed to maximize the Cobb–Douglas utility functions subject to budget constraints, where the sum of the total consumption expenditure and the saving cannot exceed the total factor income. The real government consumption was assumed to be of the fixed portion, set at its base year level, of real GDP. The government collects a variety of taxes, such as income taxes, factor taxes, consumption taxes, and tariffs. The government budget surplus/deficit was set at its base year level, and the income tax rates were accordingly adjusted endogenously. The current account surplus/deficit of each region was also assumed to be constant at its base year level. The firms were modeled to produce outputs using the nested CES technologies described in Figure 1. Each branch in the figure indicates the CES functional relationship between a single output (parent node) and multiple inputs (children nodes), and the constant elasticity of substitution for the branch is denoted by $\sigma$.

![Nesting structure of production technology.](image)

The dynamic structure of this model was recursive in nature, meaning that it determined its future one period at a time as it moved along the time path, unlike the full dynamic model that makes the one-shot decision for the entire planning horizon. The interval between periods was set to be five years in the modeling exercise for this study. In this recursive dynamic model, the household acted as if it was in an atemporal model, making only instantaneous decisions, but the model itself retained a dynamic structure as physical capital accumulated and entered into the future production process. As in many of the CGE models, the Armington specification was applied to the international trade block: the imported goods and domestically produced goods were treated as imperfect substitutes, and regions were allowed to simultaneously import and export the same commodity category. A two-level nested CES structure was applied for the imported goods: at the top nest, domestic agents choose the optimal combination of the domestically produced goods and aggregate import goods, and at the subsequent nest, agents allocate demand for the aggregate import across the trading partner regions.

The equilibrium of the multi-regional global economy is characterized by the set of equilibrium conditions for all of the commodities and regions: (i) market equilibrium conditions (for commodities and factors); (ii) consumption demand functions (for household, government, and investment); (iii) current account balance conditions, budget constraints (for household and government), and capital stock dynamic equations; (iv) zero-profit conditions; and (v) factor supply functions. The values of the key parameters in this model are listed in Table 1.
Table 1. Key parameters of the nested CES production functions.

| Parameter                                           | Notation | Value                                                                 |
|-----------------------------------------------------|----------|----------------------------------------------------------------------|
| Substitution between labor and capital–energy bundle | $\sigma_v$ | 0.2 for coal, oil, and gas; 1.26 for p_c and gdt; 0.24 for agr; 1.26 for ely, ren, and hom; 1.2 for mfr; 1.4 for cnt; 1.37 for ser; 1.68 for trn; GTAP data (esubva) is used |
| Substitution between capital–land bundle and energy  | $\sigma_r$ | 0.5                                                                   |
| Substitution between capital, land, and natural resources | $\sigma_k$ | 0                                                                     |
| Substitution between electricity and fossil fuel      | $\sigma^e$ | 0.5                                                                   |
| Substitution between renewable and non-renewable electricity | $\sigma^l$ | 1                                                                     |
| Substitution between fossil energies                  | $\sigma^f$ | 1                                                                     |
| Armington elasticity: domestic versus import          | $\sigma^m$ | GTAP data (esubdm) is used: 3.8–16.0, depending on sectors          |
| Armington elasticity: import sources                  | $\sigma^w$ | GTAP data (esubm) is used: 3.8–34.4, depending on sectors          |

The model was calibrated on exogenous growth rates of GDP and an autonomous energy efficiency improvement (AEEI). The social accounting matrix was constructed based on version 10 of the Global Trade Analysis Project (GTAP) database [18].

One hundred and forty-one regions of the GTAP 10 database were aggregated into nine regions, composed of five SSP regions [19] and four Asian countries, China, India, Japan, and South Korea. The four countries were separated from the corresponding SSP regions to examine more closely the policy implications for some major individual countries.

For computational tractability and the convenience of understanding, 76 sectors of the GTAP power database were also aggregated into 13 sectors, where most of the industries were grouped in broader categories while keeping the major energy sectors as detailed as the original GTAP classification. Twelve power sectors of the GTAP power database were aggregated into two, the renewable and non-renewable power generation, so that rapid technological development of renewable technologies could be accommodated in the simulation into the distant future. The National Renewable Energy Laboratory’s (NREL) Annual Technology Baseline 2020 predicts that offshore wind’s most likely mid-range LCOE will be $91.5/MWh in 2018 and $37.4/MWh in 2050, implying a compound annual reduction rate of 2.76%. Similarly, NREL forecasts that utility scale solar’s most likely mid-range LCOE will be $37.7/MWh in 2018 and $13.9/MWh in 2050, implying an annual reduction rate of 3.07%. Based on these future cost reduction forecasts, the total factor productivity of renewable power generation is assumed to be improving by 2.91%/y, the average of the cost reduction rate of the two renewable power technologies. A more detailed description and codes of the model sector and regional breakdown are provided in Appendix A Tables A1 and A2.

3. Population Structure and Scenarios

Six scenarios were constructed to evaluate the emission impacts of the change in demographic trends in the years up to 2100. We considered two UN projections, one from 2010 and the other from 2019, and three scenarios for each of the two projections: high, medium, and low growth scenarios. The year 2010 was chosen to base our study on the shared socio-economic pathways (SSP) scenarios, which is based on UN 2010 population projections. The year 2019 is the latest year with UN population projection data. We can evaluate the GHG emission impacts from the change of demographic forecasts in the recent
nine years and understand the policy implications of the recent trend of the population in terms of climate mitigation and adaptation.

The baseline scenario (named 2010MID) was constructed based on the UN 2010 medium projection of population. Total factor productivities of individual regions were calibrated to reproduce the real GDP forecast by OECD for the SSP2 scenario [20,21]. Labor force participation rates by age groups by the International Labor Organization (ILO) were applied to quantify the magnitude of labor supply in the CGE model. The labor supplies from individual age groups were assumed to be the product of population size and labor participation rates. The alternative scenario was constructed with the recent 2019 UN projection of population (named 2019MID). We can investigate the impact of the change of the demographic projection on labor supply and GHG emissions thereafter. High and low growth projection scenarios were also considered for evaluating the implications of population variability, and four more scenarios were established: 2010LOW, 2010HIGH, 2019LOW, and 2019HIGH.

As shown in Figure 2, the population distribution by age in South Korea differs significantly when comparing the United Nations’ medium projection in 2010 and that in 2019. In particular, the UN’s 2019 population projection shows that the rate of aging in South Korea is very high in 2050 and 2100. In 2010, the rate of the population aged 65 or older was 10–11%, but in 2050, it exceeded 30%. According to the UN population projection published in 2019, the rate of aging is the highest among East Asian countries, exceeding 38% in 2100.

![Figure 2. Demographic structure by scenario and country.](image)

In 2010, the rate of the population aged over 65 in China was about 8%, but by 2100 it will exceed 30%, which is a remarkable change. In particular, the rapid aging trend in the world’s first or second most populated nation has a very large socio-economic impact on economic activities, which leads to a significant impact on CO₂ emissions. In the case of Japan, the rate of the population aged 65 and over has already exceeded 20% in 2010. For Japan, it is also predicted that the rate of the population aged over 65 will be over 37% by 2100. On the other hand, it is predicted that the rate of the population aged over 65 will be around 20% for the rest of the world, except for the three East Asian countries.
In other words, the three East Asian countries will be countries with more than 30% of the population aged over 65 in 2050 and 2100, according to the UN population projections. This demographic change will bring about a change in the rate of the labor force by age group in the three East Asian countries. If there are changes in the working-age group population, the input factor, labor of production, will result in a change in the rate of labor participation for economic activities, which is a critical factor for change in the CO2 emissions in the future.

On the other hand, the share of the population under the age of 15 in South Korea will decrease from 16% in 2010 to 11% in 2100. Since the total population itself is to decline in South Korea, it is expected that there will be difficulties in supplying labor in the future, as the proportion of the population under the age of 15 continues to decline regardless of the timing of the population forecast. Although there are some differences in absolute values, this trend of a low share of age groups less than 15 is also occurring in China and Japan.

Figure 3 compares the labor participation rates in 2010 and 2030. Based on the ILO’s outlook, South Korea, China, Japan, and the rest of the world are compared. In the case of South Korea, along with aging, by 2030, the participation of people aged 45 and over in economic activities will increase significantly. Compared to 2010, the group aged 55–60 increases by 8% or more. Overall, in South Korea, the rate of labor participation in 2030 will increase significantly for each age group. On the other hand, in the case of China, the rate of labor participation decreases by 10% for those aged 15 to 25 years during the same period. This shows that the effect of the low fertility rate in China is becoming more pronounced.

![Graphs showing labor force participation rates in 2010 and 2030 for South Korea, Japan, China, and the rest of the world.](image)

**Figure 3.** Labor force participation rate (2010 and 2030).

In the case of Japan, the rate of labor participation increases significantly in all age groups in 2030 compared to 2010. Among the age groups for economic activity, between the ages of 25 and 60, the rate of labor participation exceeds 80% in both 2010 and 2030. It can be seen that among the three East Asian countries, Japan has the highest rate of labor participation. The rest of world shows no significant differences in labor participation rates between 2010 and 2030. In addition, the labor participation rate of each age group is less...
than 80%. In summary, the rates of labor participation in the three East Asian countries are very high, over 80%. In this study, it is assumed that the rate of labor participation for each country and region in 2030 is to have fixed values until 2100 for CGE model calculation, because there are no further forecasting values after 2030 by the ILO.

4. Analysis and Discussion

The study applied the scenarios of UN population prospects from 2010 and 2019 and labor force participation rates for CGE model calculation on future GDP and emission projections.

Figure 4 shows the results for South Korea. In the case of South Korea, under the UN2019 MID scenario, the population projection consistently decreases, compared with that of the UN2010 MID scenario. In 2099, the population projection is drastically decreasing by even more than 22%, making South Korea one of the countries in East Asia showing a trend of declining population size. However, during the same period, the labor participation rates among the economic activity population age groups over the age of 20 increases, which leads to a decrease in GDP from 2044. Accordingly, CO$_2$ emission starts to decrease after 2049, compared to the CO$_2$ emissions under the UN2010 MID scenario. CO$_2$ emissions in 2099 are set to decrease by only 7% compared to that of the reference scenario. Despite the fastest trend of low fertility and aging among East Asian countries, the decrease in GDP is relatively moderate due to the increase in the labor participation rate of the elderly.

Figure 5 shows the results for China. China’s population projection under the UN2019 MID scenario is consistently increasing, compared with that under the reference scenario. It increases by more than 10% after the 2080s. Nevertheless, labor participation rates decline relatively among the age groups under the age of 25, which derives the decrease of GDP slightly until 2040 under the UN2019 MID scenario. Accordingly, the CO$_2$ emission projection tends to also slightly decrease until 2040. However, after 2040, GDP increases relatively by more than 4% in 2099, which leads to an increase in CO$_2$ emissions.
Figure 5. Percentage change of key results for the UN2019 MID scenario (China) compared to the baseline UN 2010 MID scenario.

Figure 6 shows the results for Japan. In the case of Japan, the population projection under the UN2019 MID scenario is predicted to increase slightly until 2020, then decrease relatively, and decrease by about 18% by 2099. However, in the case of Japan, the labor participation rates relatively increase in almost all age groups, so the decrease in GDP is by 10% in 2099, which is less than the decrease of the population. Obviously, the decrease of CO₂ emissions is smaller than that of GDP, which is by 7.7% in 2099, compared to that of the reference scenario. The overall trends between Japan and Korea show similarities.

Figure 6. Percentage change of key results for the UN2019 MID scenario (Japan) compared to the baseline UN 2010 MID scenario.

Figure 7 shows the aggregated trend of the rest of the world except for the three East Asian countries. Basically, the trend is similar to that of China. Before 2040, the population...
projection under the UN2019 MID scenario is lower than that of the UN2010 MID scenario, while it is higher after 2040. However, unlike in the case of China, the increase in CO\textsubscript{2} emissions is relatively higher than the increase in GDP. However, it is difficult to derive meaningful interpretations from the aggregated results of many different countries.

From the results of this study, two findings in terms of population projection and demographic change are clear when the UN2019 MID scenario is compared with the UN2010 MID scenario, which is the reference case. First of all, if the population projection of UN2019 MID is higher than that of UN2010 MID, CO\textsubscript{2} emissions will increase. However, as shown in the case of South Korea and Japan, even if the population projection of UN2019 MID decreases by the middle of the twenty-first century compared to that of UN2010 MID, CO\textsubscript{2} emission projections tend to increase in the case of the increase in GDP. It implies that the GDP, which represents economic activity along with the population, directly affects the projection of CO\textsubscript{2} emissions. Second, the change of the labor participation rate is less than the change of the population projection, which means that the change of GDP is less elastic than the change of population or the change of demographics. It is worth noting that in this CGE model, the labor participation rate is one of the key parameters to determine the level of GDP. The two findings from this study tell us that not only the change of the population projection, but also the change of the labor participation rate, are very important to determine CO\textsubscript{2} emission projections.

Figure 8 shows the CO\textsubscript{2} emission projections for selected years in South Korea, China, and Japan under the six scenarios set in this study. First, it is clearly found that the CO\textsubscript{2} emission projections for all countries are positively related to the population projections. In other words, it is worth noting that the population factor is one of the main drivers of the CO\textsubscript{2} emission projection. In the case of South Korea and Japan, there is a trend of declining population, and these countries show that the declining population itself can have a significant impact on CO\textsubscript{2} emissions reduction. On the other hand, it shows that, in the case of China, where the population is increasing until the middle of the twenty-first century, the CO\textsubscript{2} emissions projection may increase depending on the population scenarios. However, under the scenario of declining population growth in China, it can
also be seen that CO$_2$ emissions decrease. The results of CO$_2$ emissions for the three East Asian countries tell us that population and CO$_2$ emissions have a positive relationship.

![Figure 8. CO$_2$ emissions by scenarios for selected years (South Korea, China, and Japan).](image)

Second, it is also clear that there is a positive relationship between GDP and CO$_2$ emissions. However, the growth rates of CO$_2$ emissions in the three East Asian countries are consistently lower than those of GDP. When the GDP decreases, the rate of CO$_2$ decrease is less than that of the GDP decrease. In other words, CO$_2$ emissions are generally inelastic in response to GDP decreases in the three East Asian countries. This finding indirectly implies that the demographic change indicating the change of the share of each age group should be considered in addition to the population projection itself to project CO$_2$ emissions, since the labor participation rate is an important factor to determine the production level in CGE modeling. In the case of South Korea and Japan, despite the low fertility rate and aging population, if the labor participation rate increases, the GDP decrease may be less than the population decrease, and thus the CO$_2$ decrease is relatively less.

5. Conclusions

This study applies a CGE model and provides projections of changes in GDP and CO$_2$ emissions of three East Asian countries (South Korea, China, and Japan) and the rest of the world by comparing five population scenarios with the UN MID scenario. As Figure 9 shows, the study found that the range of changes of CO$_2$ emission compared to the base scenario is smaller than that of GDP in all three East Asian countries and the rest of the world. Among the three East Asian countries, a huge decrease of GDP, in South Korea in particular, is expected due to the decrease in population and the increase in the proportion of the aged population in the UN 2019 population projections compared to the base scenario. However, the changes in CO$_2$ emissions are smaller than the change in GDP. Japan also shows a similar trend to South Korea. In China and the rest of the world, some population projections are higher than the base scenario, so these scenarios lead to an increase in GDP, and, accordingly, to an increase in CO$_2$ emissions compared to the base scenario. The implication of the results from South Korea and Japan is that the decreases in GDP and CO$_2$ emissions can happen even faster in China and the rest of the world if the population size declines, the aging trend is accelerated, and the proportion of the aged population becomes higher.
The demographic changes of the three East Asian countries can have some implications for the future demographic changes in the rest of the countries projecting their CO2 emissions. However, a limitation of this study is that the GDP projection after 2030 was not properly reflected, because each country’s labor participation rate was fixed after 2030; the parameter was projected by the ILO until 2030. Therefore, the projections of GDP after 2030 are not properly reflecting the change of the labor participation rate. The appropriate labor participation rate should be reflected in future research.

The impact of an aging labor force on GDP in the future is uncertain, which means that the impact of aging populations on CO2 emissions from the production side of the economy is also uncertain. However, in this study, the different population projections by the UN with age groups are incorporated into the CGE model, which needs further elaboration in CGE model development. Nevertheless, the fact that demographic changes, such as aging and low fertility, are very important factors in predicting CO2 emissions, along with population change, was sufficiently demonstrated through empirical analysis of the three East Asian countries.

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**Conflicts of Interest:** The authors declare no conflict of interest.
### Appendix A

**Table A1. Model Sectors.**

| Label | Description             | GTAP Sectors Code |
|-------|-------------------------|-------------------|
| Coa   | Coal                    | Coa               |
| Oil   | Oil                     | Oil               |
| Gas   | Natural gas             | Gas               |
| P_c   | Petroleum and coal product | P_c              |
| Gdt   | Gas distribution        | Gdt               |
| Agr   | Agriculture             | PDR, WHT, GRO, V_E, OSD, C_B, PFB, OCR, CTL, OAP, RMK, WOL, FRS, FSH |
| Ely   | Electricity (non-renewable) | NuclearBL, CoalBL, GasBL, OilBL, OtherBL, GasP, OilP, TnD |
| Ren   | Electricity (renewable)  | WindBL, HydroBL, HydroP, SolarP |
| Mfr   | Manufacturing           | OXT, CMT, OMT, VOL, MIL, PCR, SGR, OFD, B_T, TEX, WAP, LEA, LUM, PPP, CHM, BPH, RPP, NMM, I_S, NFM, FMP, ELE, MVH, OTN, EEQ, OME, OMF |
| Cnt   | Construction            | Cnt               |
| Ser   | Service                 | OSG, EDU, HHT, WTR, AFS, TRD, WHS, CMN, OFI, INS, RSA, OBS, ROS |
| Trn   | Transportation          | Otp, wtp, atp     |
| Hom   | Dwellings               | Dwe               |

**Table A2. Model Regions.**

| Label | Description                                           | GTAP Regions Code |
|-------|-------------------------------------------------------|-------------------|
| OECD  | OECD (except Japan and South Korea)                   | ALB, AUS, AUT, BEL, BGR, XER, CAN, CHE, CYP, CZE, DEU, DNK, ESP, EST, FIN, FRA, GBR, GRC, HRV, HUN, IRL, XEF, ITA, LTU, LUX, LVA, MLT, NLD, NOR, NZL, POL, PRI, PRI, ROU, SVK, SVN, SWE, TUR, USA |
| ASIA  | Asia (except China and India)                         | XSA, BGD, BRN, XOC, IDN, KHM, LAO, LKA, XEA, XSE, MNG, NPI, PDK, PHL, SGP, THA, TWN, VNM |
| LAM   | Latin America and Caribbean                           | XCB, ARG, XCA, BOL, BRA, CHL, COL, CRI, DOM, ECU, GTM, XSM, HND, JAM, MEX, NIC, PAN, PER, PRT, SLV, TTO, URY, VEN, XNA |
| MAF   | Middle East and Africa                                | XAC, ARE, XEC, BEN, BFA, BHR, BWA, XCE, CIV, CMR, XWF, XNF, EGY, ETH, GHA, GIN, IRN, XWS, ISR, JOR, KEN, KWT, XSC, MAR, MDG, MOZ, MUS, MWI, NAM, NGA, OMN, QAT, RSA, SAU, SEN, TGO, TUN, TZA, UGA, ZMB, ZWE, ZAF, XTW |
| REF   | Eastern Europe and the Former Soviet Union            | ARM, AZE, BLR, GEO, KAZ, KGZ, XEE, RUS, TJK, XSU, UKR |
| CHN   | China                                                 | CHN               |
| IND   | India                                                 | IND               |
| JPN   | Japan                                                 | JPN               |
| KOR   | South Korea                                           | KOR               |
References

1. O’Neill, B.C.; Liddle, B.; Jiang, L.; Smith, K.R.; Pachauri, S.; Dalton, M.; Fuchs, R. Demographic change and carbon dioxide emissions. *Lancet* 2012, 380, 157–164. [CrossRef]

2. Okada, A. Is an increased elderly population related to decreased CO₂ emissions from road transportation? *Energy Policy* 2012, 45, 286–292. [CrossRef]

3. Balezentis, T. Shrinking ageing population and other drivers of energy consumption and CO₂ emission in the residential sector: A case from Eastern Europe. *Energy Policy* 2020, 140, 111433. [CrossRef]

4. Yu, Y.; Deng, Y.; Chen, F. Impact of population aging and industrial structure on CO₂ emissions and emissions trend prediction in China. *Atmos. Pollut. Res.* 2018, 9, 446–454. [CrossRef]

5. Wang, J.; Wu, Y.; Zhao, Y.; He, S.; Dong, Z.; Bo, W. The population structural transition effect on rising per capita CO₂ emissions: Evidence from China. *Clim. Policy* 2019, 19, 1250–1269. [CrossRef]

6. Kim, J.; Lim, H.; Jo, H.-H. Do Aging and Low Fertility Reduce Carbon Emissions in Korea? Evidence from IPAT Augmented EKC Analysis. *Int. J. Environ. Res. Public Health* 2020, 17, 2972. [CrossRef] [PubMed]

7. Yu, B.; Wei, Y.-M.; Kei, G.; Matsuoka, Y. Future scenarios for energy consumption and carbon emissions due to demographic transitions in Chinese households. *Nat. Energy* 2018, 3, 109–118. [CrossRef]

8. Carvalho, T.S.; Santiago, F.S.; Perobelli, F.S. Demographic change in Brazil and its impacts on CO₂ emissions. *Econ. Syst. Res.* 2020, 1–17. [CrossRef]

9. Wei, T.; Zhu, Q.; Glomsrød, S. How Will Demographic Characteristics of the Labor Force Matter for the Global Economy and Carbon Dioxide Emissions? *Ecol. Econ.* 2018, 147, 197–207. [CrossRef]

10. Wei, T.; Zhu, Q.; Glomsrød, S. Ageing impact on the economy and emissions in China: A global computable general equilibrium analysis. *Energies* 2018, 11, 817. [CrossRef]

11. Niamir, L.; Ivanova, O.; Filatova, T. Economy-wide impacts of behavioral climate change mitigation: Linking agent-based and computable general equilibrium models. *Environ. Model. Softw.* 2020, 134, 104839. [CrossRef]

12. United Nations Department of Economic and Social Affairs. *World Population Prospect 2019: Population by Age Groups—Both Sexes* 2019; United Nations: New York, NY, USA, 2019.

13. International Labour Organization Labour. *Force Participation Rate by Sex and Age—ILO Modelled Estimates (%)*; International Labour Organization: Geneva, Switzerland, 2019.

14. Burfisher, M.E. *Introduction to Computable General Equilibrium Models*; Cambridge University Press: Cambridge, UK, 2017; ISBN 1316889378.

15. Matsumoto, K.; Fujimori, S. CGE models in energy economics. In *Routledge Handbook of Energy Economics*; Routledge: London, UK, 2019; p. 433.

16. Yun, T.; Cho, G.L.; Kim, J.-Y. Analyzing economic effects with energy mix changes: A hybrid CGE model approach. *Sustainability* 2016, 8, 1048. [CrossRef]

17. Dai, H.; Masui, T.; Matsuoka, Y.; Fujimori, S. The impacts of China’s household consumption expenditure patterns on energy demand and carbon emissions towards 2050. *Energy Policy* 2012, 50, 736–750. [CrossRef]

18. Aguiar, A.; Chepeliev, M.; Corong, E.L.; McDougall, R.; van der Mensbrugge, D. The GTAP data base: Version 10. *J. Glob. Econ. Anal.* 2019, 4, 1–27. [CrossRef]

19. IIASA Regional Definitions. Available online: https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10#regiondefs (accessed on 20 February 2020).

20. Dellink, R.; Chateau, J.; Lanzi, E.; Magné, B. Long-term economic growth projections in the Shared Socioeconomic Pathways. *Glob. Environ. Chang.* 2017, 42, 200–214. [CrossRef]

21. Riahi, K.; van Vuuren, D.P.; Kriegler, E.; Edmonds, J.; O’Neill, B.C.; Fujimori, S.; Bauer, N.; Calvin, K.; Dellink, R.; Fricko, O.; et al. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Glob. Environ. Chang.* 2017, 42, 153–168. [CrossRef]