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An Analysis of the Impact of Household Aging and Downsizing on Consumption and Carbon Neutrality Policies

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Abstract

This study investigates the economic implications of demographic changes—specifically population aging and household downsizing—on carbon neutrality policies in South Korea. While existing climate policies focus heavily on production-side transformations, this research highlights the necessity of considering consumption-side behavioral changes driven by demographic shifts. By categorizing households into 19 types based on the age of the household head and family size using the 2019 Household Expenditure Survey, we derive specific consumption share parameters for each group. These parameters are integrated into the UNICON-CGE (UNIfied Climate Options Nexus CGE) model, modified using the MIRAGE-HH methodology to reflect heterogeneous household consumption behaviors. Three scenarios are constructed: a Business-as-Usual (BAU) scenario, a Net Zero (NZ) scenario imposing carbon costs aligned with Korea's 2030 NDC and 2050 Carbon Neutrality pathways, and an NZ_dc_cpat scenario that additionally incorporates household-specific consumption patterns and demographic projections. The results reveal that demographic structural changes significantly alter the composition and magnitude of consumption-side emissions. Household aging and downsizing increase residential energy demand (electricity and heating) while reducing expenditures on education and transportation. When demographic change is incorporated (NZ_dc_cpat), the household sector achieves a smaller

emission reduction (-30.8%) relative to the standard NZ pathway (-36.3%), as elderly households' structurally higher energy demand partially offsets the carbon pricing effect. Meanwhile, production sectors achieve deeper reductions, and the required carbon price falls by 55.7% due to reduced economic activity. These findings underscore the importance of demographic-sensitive climate policy design and provide a basis for equitable carbon neutrality strategies.

Keywords: Computable General Equilibrium model; Household heterogeneity; Population aging; Household downsizing; Carbon neutrality; Consumption behavior; South Korea

1. Introduction

The climate crisis has become a tangible reality, with South Korea recording its highest average temperatures in 2024 since meteorological observations began in 1973. In response, the Korean government enacted the "Carbon Neutrality and Green Growth Act" and established a comprehensive roadmap for achieving carbon neutrality by 2050. However, attaining net-zero emissions requires a comprehensive transformation of the socio-economic system, extending beyond industrial restructuring to encompass fundamental changes in consumer behavior and household consumption patterns.

Concurrently, South Korea is experiencing rapid and pronounced demographic transitions. The population structure has shifted from a traditional pyramid shape to a bell shape, driven by persistently low birth rates and accelerating population aging. The average household size contracted to approximately 2.4 persons as of 2018, and projections indicate that by 2035, nearly 40% of all households will consist of one- or two-person elderly households with heads aged 60 or older (Statistics Korea, 2022). This dramatic restructuring of household composition carries significant implications for aggregate consumption patterns and, consequently, for the trajectory of greenhouse gas (GHG) emissions.

Prior research has established that demographic factors are significant determinants of consumption propensity and energy demand. Elderly households tend to allocate higher budget shares to electricity, heating, food products, and medical services, while younger and smaller households exhibit different spending patterns characterized by higher shares for dining out, housing (rental), and transportation (Fan et al., 2021; Bardazzi and Pazienza, 2017; Estiri and

Zagheni, 2019). The implications of these consumption shifts for climate policy, however, remain largely unexplored in the context of economy-wide modeling frameworks.

The existing literature on carbon neutrality impact assessment predominantly relies on representative agent models that treat all households as a single, homogeneous entity. This approach obscures the heterogeneous consumption behaviors across different household types and fails to capture the structural shifts in aggregate demand driven by demographic change. Several studies have attempted to address this limitation. Rausch and Rutherford (2010) proposed a Sequential Recalibration algorithm for incorporating multiple heterogeneous households into CGE models. Bouet et al. (2013) developed the MIRAGE-HH model that integrates household survey data with global CGE analysis. However, applications of these methodologies to the specific context of demographic aging and carbon neutrality policy remain scarce, particularly for East Asian economies experiencing rapid demographic transitions.

This study addresses this critical research gap by explicitly incorporating micro-level household consumption heterogeneity into a macro-level CGE framework. Using the 2019 Household Expenditure Survey by Statistics Korea, we classify households into 19 distinct types based on the age of the household head (5 groups) and household size (4 groups). The derived consumption share parameters are integrated into the UNICON-CGE model, which is modified to accommodate multiple household types following the MIRAGE-HH methodology. We then simulate three scenarios to analyze the economic impacts of carbon neutrality pathways under demographic shifts.

The contributions of this study are threefold. First, we provide a systematic empirical analysis of consumption pattern heterogeneity across household types in South Korea, with particular attention to energy-intensive goods and services. Second, we develop a methodological framework for integrating micro-level household survey data into a national CGE model, addressing practical challenges such as data harmonization between the Household Expenditure Survey and Input-Output tables. Third, we generate policy-relevant insights on how demographic structural changes interact with carbon neutrality pathways, offering implications for the design of equitable and effective climate policies.

The remainder of this paper is organized as follows. Section 2 reviews the related literature.

Section 3 describes the data sources and household classification methodology. Section 4 presents the consumption behavior analysis. Section 5 details the CGE model structure. Section 6 outlines the scenario design. Section 7 reports the simulation results. Section 8 discusses the policy implications, and Section 9 concludes.

2. Literature Review

2.1. Demographic change and energy consumption

A growing body of literature examines the nexus between population aging and energy consumption. Estiri and Zagheni (2019) demonstrated that residential energy use in the United States rises with the age of the household head, with elderly households (70+) exhibiting particularly high electricity consumption driven by heating and cooling needs. Garau et al. (2013) found similar patterns in Italy, where an aging population structurally increased residential energy demand. A recent study in Nature Humanities and Social Sciences Communications quantified that population aging contributed approximately 2.2% to the rise in total U.S. residential energy use between 1990 and 2020, with per capita energy consumption increasing by 11.3% due to aging effects alone.

In the East Asian context, studies on Japan provide particularly relevant insights. Research examining Japanese households' micro-level energy consumption data from 1989 to 2014 identified three distinct channels: the pure aging effect (elderly preference for thermal comfort), the cohort effect (generational differences in energy use intensity), and the family structure effect (declining household sizes reducing economies of scale). Fan et al. (2021) examined the impact of population aging on household carbon emissions in both urban and rural areas of China, finding that urban population aging increases household carbon emissions through altered consumption patterns.

2.2. Household heterogeneity in CGE models

The incorporation of household heterogeneity into CGE models has been a methodological frontier in applied general equilibrium analysis. Van der Mensbrugghe (2015) provided a comprehensive review of methods for including income distribution in global CGE models,

distinguishing among three approaches: explicit modeling of multiple household types, micro-simulation modeling, and direct modeling of income distribution.

Rausch and Rutherford (2010) proposed a Sequential Recalibration (SR) algorithm that uses a representative agent model as a proxy, iteratively re-calibrating preferences to match household-level demand responses. Rausch et al. (2011) subsequently demonstrated the feasibility of incorporating up to 15,588 household types.

Bouet et al. (2013) developed the MIRAGE-HH model using CES-LES utility functions with household-specific budget shares derived from national household survey data, matched to the GTAP database. In the Korean context, Kang et al. (2013) segmented the representative household into three income groups but did not consider demographic dimensions such as age structure or household size.

2.3. Climate policy and consumption-side analysis

The majority of CGE-based climate policy analyses focus on production-side transformations. Zhang et al. (2024) used a dynamic recursive CGE model to analyze the heterogeneous welfare impacts of carbon tax policies on urban and rural residents in China. Kim et al. (2024) analyzed the Korean road transport system using the UNICON-CGE model incorporating vehicle dynamics. This study builds on the same model infrastructure but shifts the focus to consumption-side demographic dynamics.

3. Data and Household Classification

3.1. Data sources

This study primarily utilizes two data sources: the 2019 Household Expenditure Survey conducted by Statistics Korea and the 2019 Input-Output tables compiled by the Bank of Korea. The Household Expenditure Survey is a monthly survey covering approximately 7,200 households across 900 survey areas, selected using balanced sampling via the Cube Method. The survey employs a “6-6-6 rotation sample system” whereby households participate for 6 consecutive months, rest for 6 months, and participate for another 6 months.

3.2. Comparison with Input-Output tables

Since the CGE model's Social Accounting Matrix (SAM) is constructed from the Input-Output tables, we compare the two data sources. The Household Expenditure Survey captures only about one-third of total expenditure reported in the Input-Output tables, consistent with international patterns documented by De Agostini et al. (2017). Despite this scale difference, the expenditure composition shows reasonable alignment, with most categories differing by less than 2 percentage points (Table 1).

Table 1 Comparison of expenditure shares: Input-Output tables vs. Household Expenditure Survey (2019)

Commodity	I-O Share (%)	HES Share (%)	Diff. (%p)
Coal & petroleum products	2.08	3.75	-1.67
Electricity	0.89	1.40	-0.51
Gas, steam & hot water	1.00	1.39	-0.39
Waste management	0.31	0.07	0.24
Water supply	0.22	0.56	-0.35
Agricultural & fishery products	2.05	3.87	-1.82
Food products	10.49	9.64	0.85
Medical & health services	4.44	5.02	-0.58
Chemical products	2.01	3.69	-1.68
Automobiles	3.98	3.61	0.37
Land transport	2.22	1.18	1.04
Air transport	0.44	0.48	-0.04
Textile & leather	6.82	5.55	1.27
Housing-related	14.10	8.41	5.69
Education	6.33	8.71	-2.39
Restaurants & accommodation	11.08	13.15	-2.07
Telecommunications	3.29	3.38	-0.09
Finance & insurance	7.92	5.83	2.09
Other services	4.68	7.37	-2.69

Note: 2019 extended I-O table based on 2015 benchmark. Wholesale margin allocated using 2015 margin ratios.

Source: Bank of Korea Input-Output Tables; Statistics Korea Household Expenditure Survey. Author's calculations.

3.3. Household type classification

Households are classified by the age of the household head (5 groups: ≤29, 30–39, 40–49, 50–59, ≥60) and household size (4 groups: 1, 2, 3, 4+ persons), yielding 19 types (the youngest group is limited to 3 size categories due to small samples).

Table 2 Sample distribution by household type (2019 Household Expenditure Survey, quarterly)

Age of HH head	1 person	2 persons	3 persons	4+ persons	Total
≤29	831	171	111*	—	1,113
30–39	620	464	644	746	2,474
40–49	610	643	921	1,658	3,832
50–59	1,071	1,705	1,296	819	4,891
≥60	3,048	4,337	937	252	8,574
Total	6,180	7,320	3,909	3,475	20,884

Note: * For HH head aged ≤29, sizes 3 and 4+ are combined into '3+' due to small sample sizes.

4. Consumption Behavior Analysis

4.1. Energy consumption patterns

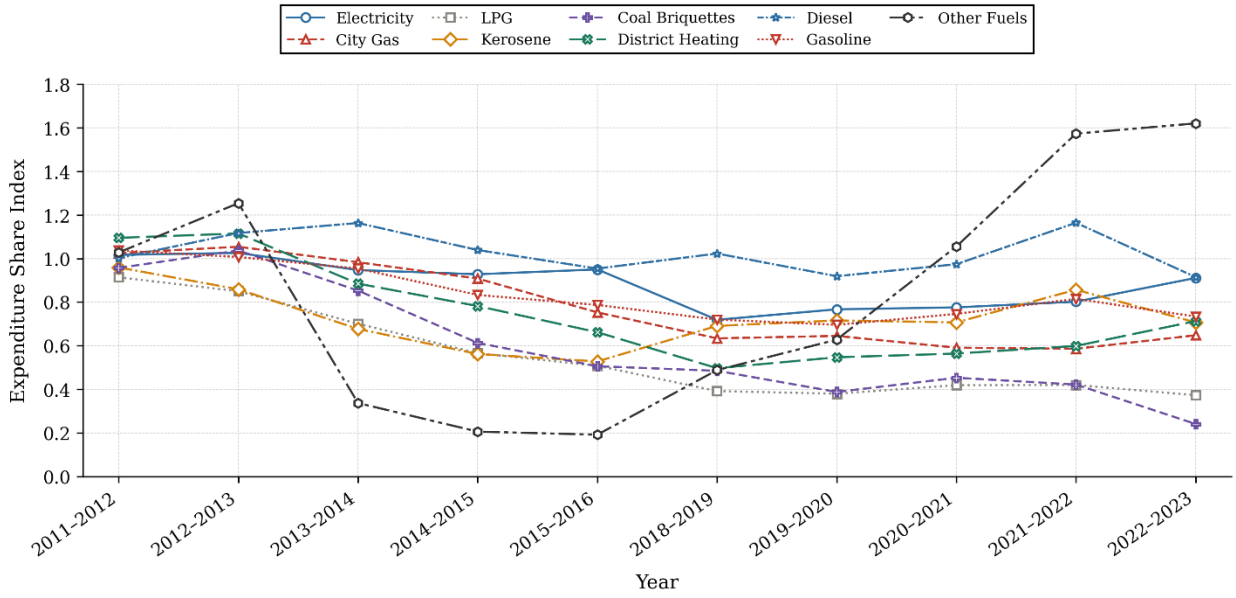
The analysis reveals distinct and systematic consumption heterogeneities across household types. For petroleum and coal products, households headed by those aged 40–59 show high expenditure shares for 1–2 person households, declining with size. Among the youngest (≤29), petroleum expenditure rises for 3+ person households, reflecting vehicle acquisition with family formation. For those aged 60+, petroleum expenditure increases with household size due to mobility needs of additional members.

Electricity expenditure shows a clear positive correlation with the household head's age. Monthly data confirms that elderly households (60+) consume substantially more electricity in winter, attributable to electric heating appliances. Single-person 60+ households allocate 2.31% to electricity versus 0.81% for single-person ≤29 households. District heating expenditure is similarly elevated among the 60+ group.

Examination of 11 years (2011–2016, 2019–2023) reveals declining briquette/LPG shares, recent declines in gasoline/diesel (post-2021) coinciding with EV adoption, and increasing accommodation expenditure reflecting evolving leisure preferences. These trends suggest that

2019 baseline shares may evolve over the projection horizon.

Fig. 1. Changes in expenditure share ratios of energy commodity (2011–2023, indexed to 2011=1)



Note: Index values are calculated relative to the base period expenditure share. A value greater than 1.000 indicates an increased share compared to base; a value less than 1.000 indicates a decreased share. Survey data are unavailable for 2016–2018 and 2017–2018 periods.
Source: Statistics Korea, Household Expenditure Survey(10.23333/RN.50150276.V2.2)

4.2. Non-energy consumption patterns

Food products account for 18.89% of spending for single-person 60+ households versus 6.87% for single-person ≤29 households. Conversely, restaurants and catering reach 17.17% for single-person ≤29 households versus 7.63% for single-person 60+ households. This generational shift from home cooking to dining out has implications for the food processing and food service sectors under demographic change.

Education services display a pronounced concentration in 3–4 person households headed by those aged 30–49, reaching 27.95% for 4-person households with heads aged 40–49. Medical and health services expenditure increases monotonically with age, reaching 8.61% for single-person 60+ households.

Table 3 Per-capita consumption expenditure shares by household head age and household size (selected categories, unit: %)

Category	1p/≤29	1p/60+	2p/30-39	4p+/40-49	2p/60+
Food products	6.87	18.89	10.46	9.60	17.73
Petroleum & coal	1.36	2.96	3.43	2.72	3.91
Electricity	0.81	2.31	0.93	0.93	2.23
Heating	1.33	2.11	1.61	1.30	1.90
Restaurants & catering	17.17	7.63	16.29	9.66	8.10
Housing services	14.81	11.64	7.24	2.67	7.20
Education	8.00	0.66	4.11	27.95	0.78
Medical & health	1.95	8.61	2.94	2.68	8.49
Transport services	10.11	3.59	4.76	3.47	4.47
Chemical products	2.61	5.27	3.11	2.12	4.90

Note: Full 19-type × 20-category table available in Appendix. 1p = 1-person HH; 4p+ = 4-or-more-person HH.

Source: Statistics Korea Household Expenditure Survey 2019. Author's calculations.

5. CGE Model Structure

5.1. Overview of the UNICON-CGE model

The UNICON-CGE (UNIfied Climate Options Nexus CGE) model is a single-country, recursive dynamic CGE model for South Korea, developed as part of the UNICON (UNIfied Climate Options Nexus) integrated assessment model (IAM) framework. The UNICON project, a collaborative initiative between Yonsei University and the Korea Environment Institute (KEI), aims to comprehensively assess the impact of global temperature changes and the effects of both domestic and international shifts in policy and technology on climate mitigation pathways (Jung et al., 2021; Moon et al., 2024). The UNICON framework links sectoral bottom-up models (covering buildings, power generation, industry, and transport sectors) with a top-down global CGE model (UNICON-G-CGE) that is fully integrated with a climate module and a damage assessment module (Jung and Park, 2023). The UNICON-G-CGE model has been utilized in several recent studies analyzing Korea's carbon neutrality pathways and has participated in the multi-model comparison of Korea's power sector decarbonization strategies (Moon et al., 2025). The model has also been applied to analyze the economic impacts of implementing net-zero policies through combined top-down and bottom-up approaches (Jung and Park, 2023)

The domestic variant used in this study, UNICON-K-CGE, is a single-country version tailored

for detailed analysis of the Korean economy. The model is calibrated to the 2019 Social Accounting Matrix (SAM) constructed from the Bank of Korea's Input-Output tables. Domestic output production is modeled as a Leontief function of the value-added composite and intermediate inputs. The value-added composite combines labor and capital through a CES (Constant Elasticity of Substitution) function. Energy inputs are nested separately from non-energy intermediates, allowing for substitution between different energy sources in response to relative price changes. The model is solved for a set of equilibrium conditions encompassing market equilibrium, consumption demand functions, current account balance conditions, budget constraints, capital stock dynamics, zero-profit conditions, and factor market clearing (Jung et al., 2021).

5.2. Modification of the model

For the purpose of this study, the model's commodity classification has been expanded to 60 sectors to capture the detailed consumption patterns identified in the household survey analysis. In particular, the food products sector (originally aggregated as a single sector) is disaggregated into 9 sub-sectors (including meat and dairy, grain milling, beverages and tobacco, etc.), and the services sector is expanded to 21 sub-sectors (including education, medical and health, housing services, restaurants, culture and tourism, etc.) to better reflect the differential consumption patterns of elderly versus younger households.

Table 4 CGE model commodity classification (60 sectors)

Code	Sector Name	Code	Sector Name
A_CRP	Crops	D_HYP	Hydropower
A_LSP	Livestock	D_THP	Thermal power
A_FRP	Forestry products	D_NUC	Nuclear power
A_FHP	Fishery products	D_REN	Renewables
B_CL	Coal	D_GST	Gas, steam & hot water
B_CONG	Crude oil & natural gas	E_WWM	Water, waste & recycling
C01_MDY	Meat & dairy	G_WRS	Wholesale & retail
C01_GML	Grain milling	H_LTS	Land transport
C01_BVT	Beverages & tobacco	I_RES	Restaurants
C02_TLP	Textile & leather	J_ICS	Info. & comm.
C04_ORP	Refined petroleum	K_FNS	Finance & insurance

Code	Sector Name	Code	Sector Name
C05_CHP	Chemical products	L_HGS	Housing services
C09_COM	Computers & electronics	P_EDU	Education
C10_EEQ	Electrical equipment	Q_MED	Medical & health
C12_TRE	Transport equipment	R_CUL	Culture & tourism
...	(30 additional sectors)	ST_OSS	Other services

Note: Full 60-sector list provided in Appendix. Sectors grouped into Agriculture (5), Mining (3), Manufacturing (24), Energy (6), Construction (1), Services (21).

Furthermore, this study disaggregates the single representative household into 19 distinct types, differentiated by the age of the household head and household size, as detailed in Table 5.

Table 5 Household type classification in the CGE model

HH Size	HH Head Age	Type Code	HH Size	HH Head Age	Type Code
1 person	≤29	1h	3 persons	≤29	11h
1 person	30–39	2h	3 persons	30–39	12h
1 person	40–49	3h	3 persons	40–49	13h
1 person	50–59	4h	3 persons	50–59	14h
1 person	≥60	5h	3 persons	≥60	15h
2 persons	≤29	6h	4+ persons	30–39	16h
2 persons	30–39	7h	4+ persons	40–49	17h
2 persons	40–49	8h	4+ persons	50–59	18h
2 persons	50–59	9h	4+ persons	≥60	19h
2 persons	≥60	10h			

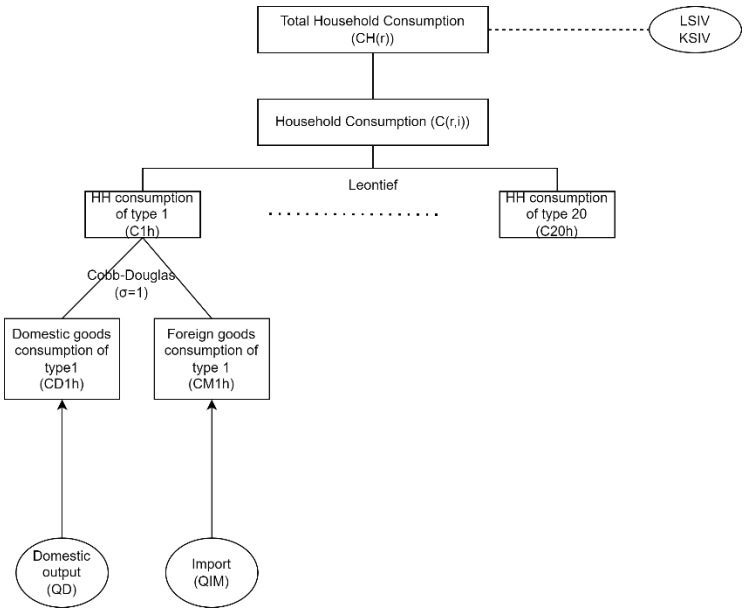
Following the MIRAGE-HH approach (Bouet et al., 2013), the household consumption structure is reformulated as follows. Total household consumption (CH) is a CES composite of commodity-specific bundles. Each commodity-specific bundle is a CES composite of 19 household types with an elasticity of substitution of 2. For household type h, consumption of commodity i is:

$$QC(h,r,i) = PopH(h,r) \times MemH(h,r) \times QCPC(h,r,i) \quad (1)$$

where PopH is the number of households, MemH is average household members, and QCPC

is per-capita consumption. Each type's consumption is further decomposed into domestic and imported goods through Cobb-Douglas aggregation (σ=1).

Fig. 2. Structure of household consumption in the modified UNICON-CGE model



6. Scenario Design

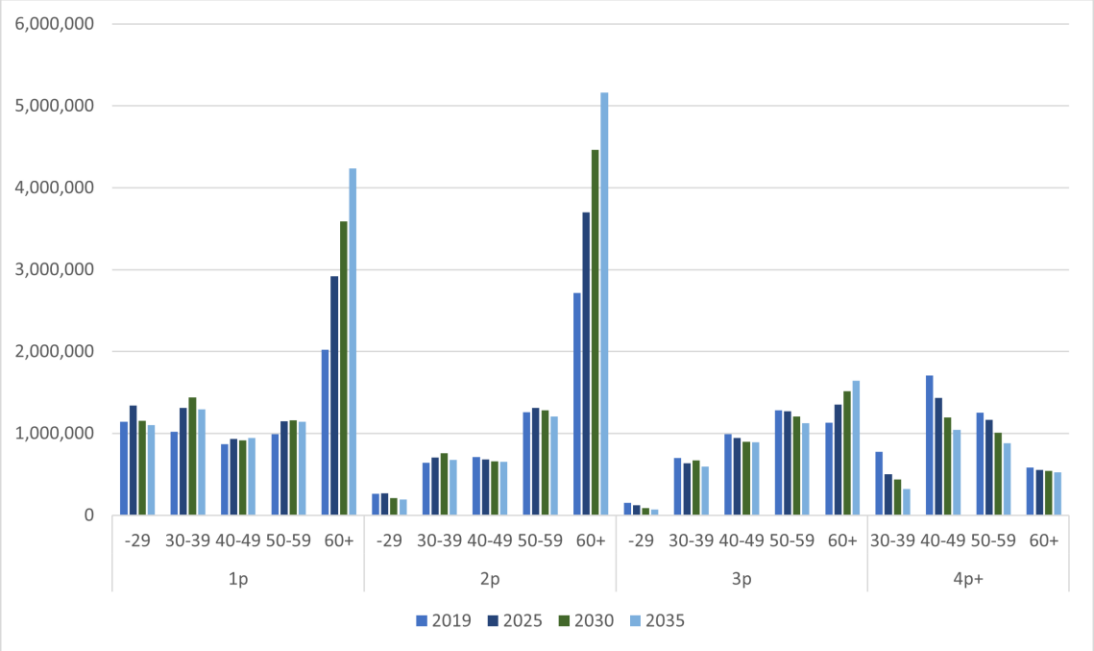
Table 7 Scenario design and analytical objectives

Scenario	Description
BAU	Business as Usual; no carbon constraints
NZ	Carbon cost imposed for 2035 NDC
NZ_dc_cpat	NZ + demographic change + HH consumption patterns

The emission constraint in the NZ scenario follows Korea's official climate targets: a 40% reduction from 2018 emissions by 2035 (approximately 37.9% below the 2019 base year used in this model).

Scenario ‘NZ_dc_cpat’ includes demographic changes in Korea. Demographic evolution follows Statistics Korea’s Long-term Household Projections. Total households increase from 20.22 million (2019) to 23.70 million (2035). The share of single-person 60+ households rises from 10% to 17.9%, while 4+ person households decline from 21.6% to 11.8%. By 2035, approximately 40% of all households will be 1–2 person households with heads aged 60+.

Fig. 3. Household number projections by type (2019–2035)



To incorporate heterogeneous household consumption patterns, the NZ_dc_cpat scenario adopts the type-specific expenditure shares derived from the consumption behavior analysis in Section 4. Specifically, elderly households (60+) allocate significantly higher budget shares to electricity (2.31% vs. 0.81% for single-person households) and heating (2.11% vs. 1.33%), while spending substantially less on education (0.66% vs. 8.00%) and restaurants (7.63% vs. 17.17%). By assigning these differentiated consumption shares to each of the 19 household types and combining them with the projected demographic shifts from Statistics Korea, the NZ_dc_cpat scenario captures how the changing composition of the household sector alters aggregate consumption patterns and, consequently, the sectoral distribution of emissions under the carbon neutrality pathway.

7. Results

This section presents the simulation results in two stages. First, we compare the BAU and NZ scenarios to quantify the economic costs of carbon neutrality policy (Section 7.1). Second, we compare the NZ and NZ_dc_cpat scenarios to isolate how demographic structural change alters the sectoral incidence of the carbon neutrality pathway (Section 7.2). Since both scenarios are measured relative to the common BAU baseline, differences between NZ and NZ_dc_cpat reveal the pure effect of demographic change on the distribution of emission reductions and economic impacts. The key macroeconomic and sectoral results are summarized in Table 8 and Table 9.

7.1. Carbon neutrality pathway impacts (BAU vs. NZ)

7.1.1. Carbon costs

Under the NZ scenario, the endogenous carbon price rises from 100,000 KRW/tCO2eq in 2030 to 366,000 KRW/tCO2eq by 2035 (Table 8), reflecting escalating marginal abatement costs as the economy approaches the 2050 net-zero target. This trajectory is consistent with the broader CGE literature on Korean climate policy (Jung and Park, 2023).

7.1.2. GDP impacts

Under the NZ scenario, the annual GDP growth rate declines from 1.42% (BAU) to 1.08% in 2030 and from 1.31% to 0.69% in 2035, representing 0.34 to 0.62 percentage points of foregone growth that widens over time (Table 8). Despite these reductions, the economy maintains positive growth, suggesting that the carbon neutrality pathway is achievable without triggering an economic contraction (Bohringer and Rutherford, 2012).

Table 8 Key macroeconomic indicators by scenario

	BAU	NZ	NZ_dc_cpat
Carbon cost (KRW/tCO2eq)	-	2030: 100,000 KRW 2035: 366,000 KRW	2030: 55,000 KRW 2035: 162,000 KRW
Annual GDP growth rate	2030: 1.42% 2035: 1.31%	2030: 1.08% 2035: 0.69%	2030: 0.11% 2035: 0.06%

7.1.3. Sectoral emission reductions

The emission reductions vary substantially across sectors (Table 9). The household sector achieves the deepest reduction among the sectors examined (-36.3% relative to BAU by 2035), reflecting significant carbon cost pass-through into residential energy prices. Agriculture shows a 15.1% reduction, followed by the high-emitting manufacturing sectors at 12.3%, the service sector at 11.0%, and other manufacturing at 8.3%.

The relatively lower reduction rates in manufacturing and services can be attributed to their already established efficiency levels, while agriculture's moderate reduction (15.1%) reflects the inherent difficulty of abating process emissions such as methane from rice paddies and livestock.

7.1.4. Sectoral output impacts

The sectoral output impacts largely mirror emission reductions but with attenuated magnitudes (Table 9). High-emitting manufacturing sees a 6.3% output decline, while other manufacturing declines by 3.9%. The service sector, which is less emission-intensive, experiences a comparatively modest output reduction of 2.8%, indicating that the structural shift toward a service-oriented economy partially buffers the aggregate economic impact of carbon pricing. Agriculture shows a 2.6% output reduction, reflecting both direct energy cost increases and indirect effects through higher input prices.

7.2. Impact of demographic structural change (NZ vs. NZ_dc_cpat)

7.2.1. Carbon cost effects

The carbon price under NZ_dc_cpat is substantially lower: 55,000 KRW/tCO2eq in 2030 (vs. 100,000 under NZ) and 162,000 KRW/tCO2eq in 2035 (vs. 366,000), representing reductions of 45% and 55.7%, respectively (Table 8). This reflects the fact that demographic aging and household downsizing contract aggregate economic activity, reducing baseline energy demand and total emissions. With lower baseline emissions, the same absolute emission target can be met at a lower carbon price. However, this apparent easing of the policy burden comes at a significant cost: GDP growth declines to 0.06% by 2035 under NZ_dc_cpat, indicating that the demographic transition partially "solves" the emission challenge through reduced economic vitality rather than technological progress or efficiency gains.

7.2.2. Emission reallocation across sectors

The most distinctive finding concerns how demographic change reshapes the sectoral distribution of emission reductions (Table 9). When both scenarios are compared against the common BAU baseline, production-side sectors achieve substantially deeper emission reductions under NZ_dc_cpat than under NZ. Agriculture falls from -15.1% (NZ) to -20.6% (NZ_dc_cpat), high-emitting manufacturing from -12.3% to -19.2%, other manufacturing from -8.3% to -15.4%, and services from -11.0% to -19.0%. These deepened reductions reflect the contraction in aggregate economic activity resulting from demographic aging, including reduced labor supply, lower aggregate demand, and the compositional shift in consumption patterns.

In contrast, the household and power generation sectors show attenuated emission reductions under demographic change, constituting the central finding of this study. Household emissions fall by 30.8% under NZ_dc_cpat, compared to 36.3% under NZ—a 5.5 percentage point attenuation. Similarly, the power generation sector's reduction narrows from 84.2% to 70.7%, a 13.5 percentage point gap. As documented in Section 4, elderly households (60+) allocate significantly higher budget shares to electricity (2.31% vs. 0.81% for single-person households) and heating (2.11% vs. 1.33%). As the household composition shifts toward elderly one- and two-person households, aggregate residential energy demand increases structurally relative to the non-aging scenario, partially offsetting the emission reduction achieved through carbon pricing. The power generation sector's attenuated reduction follows directly, as increased residential electricity demand sustains higher fossil-fuel generation than would otherwise occur.

This finding parallels the international literature: Estiri and Zagheni (2019) documented an 11.3% increase in U.S. per capita residential energy consumption due to aging effects alone. Our CGE simulation extends such micro-level findings to a general equilibrium context, demonstrating that under a fixed carbon budget, demographic aging shifts the relative emission burden away from production sectors and toward the residential energy system.

7.2.3. GDP and sectoral output effects

Demographic change exerts a significant additional drag on growth. Under NZ_dc_cpat, GDP

growth declines to 0.11% in 2030 and 0.06% in 2035, compared to 1.08% and 0.69% under NZ (Table 8). The additional 0.6–1.0 percentage point reduction is primarily attributable to labor supply contraction from population aging, underscoring that demographic challenges are quantitatively larger than those posed by carbon pricing alone.

The sectoral output effects are uniformly deeper under NZ_dc_cpat than under NZ. Services decline by 15.9% (vs. 2.8% under NZ), agriculture by 15.2% (vs. 2.6%), and high-emitting manufacturing by 17.9% (vs. 6.3%). The power generation sector shows a more moderate deepening, from 23.7% to 27.4%, consistent with elderly households' higher electricity demand partially sustaining power sector output. The disproportionate service sector decline reflects the sharp contraction in education demand as household composition shifts from child-rearing families (education = 27.95% of spending for 4-person/40-49 households) toward elderly singles (0.66%).

Table 9 Sectoral emission and output changes by scenario (2035)

		NZ (relative to BAU scenario)	**NZ_dc_cpat (relative to BAU scenario)**
Sectoral Emission (2035)	Agriculture	-15.1%	-20.6%
	Manufacturing (high-emitting)	-12.3%	-19.2%
	Manufacturing (others)	-8.3%	-15.4%
	Power generation	-84.2%	-70.7%
	Service	-11.0%	-19.0%
	Household	-36.3%	-30.8%
Sectoral Output	Agriculture	-2.6%	-15.2%
	Manufacturing (high-emitting)	-6.3%	-17.9%
	Manufacturing (others)	-3.9%	-16.0%
	Power generation	-23.7%	-27.4%
	Service	-2.8%	-15.9%

Taken together, the results demonstrate that demographic structural change interacts with carbon neutrality policy in complex ways. While the carbon price falls by up to 55.7% due to reduced economic activity, the sectoral composition of emission reductions shifts markedly: production sectors achieve deeper cuts (5–8 percentage points beyond NZ), while the household

and power generation sectors achieve shallower reductions (5.5 and 13.5 percentage points less than NZ, respectively). This asymmetric redistribution of the emission reduction burden—away from production and toward the residential energy system—is a compositional effect that conventional representative agent models would entirely miss, highlighting the importance of incorporating demographic heterogeneity into climate policy modeling.

8. Discussion

The results yield several important policy implications. First, the attenuated household emission reduction under demographic change (30.8% vs. 36.3% under NZ) challenges the assumption that an aging, shrinking economy will naturally facilitate climate targets. While aggregate emissions decline, elderly households' structurally higher residential energy demand means that the household sector contributes relatively less to the overall emission reduction effort. This implies that demand-side energy efficiency policies targeting elderly households—including building envelope retrofits, smart heating systems, and age-appropriate energy management technologies—are essential complements to supply-side decarbonization strategies.

Second, the 55.7% reduction in the required carbon price under demographic aging, while superficially positive, masks a structurally weakened economy approaching near-zero growth (0.06% by 2035). Policymakers should not interpret the lower carbon price as evidence that climate targets become easier; rather, it reflects the severe economic contraction accompanying rapid demographic aging. The power generation sector's attenuated emission reduction (70.7% vs. 84.2%) further implies that power sector decarbonization targets must account for the demographic-driven increase in residential electricity demand.

Third, the decline in education expenditure under demographic change implies structural shifts in human capital investment with long-term productivity consequences. Fourth, the disproportionate energy cost burden on elderly, low-income households raises equity concerns for carbon pricing. Revenue recycling mechanisms such as energy vouchers should target vulnerable demographic groups.

Limitations include: (i) the 2019 baseline consumption shares may evolve due to technological change; (ii) the projection horizon extends only to 2035; (iii) the housing services harmonization

remains imperfect; and (iv) welfare distributional analysis is reserved for future work.

9. Conclusion

This study has investigated the economic implications of population aging and household downsizing for carbon neutrality policies in South Korea. We classify households into 19 types, derive consumption parameters from the 2019 Household Expenditure Survey, integrate them into the UNICON-CGE model using the MIRAGE-HH methodology, and simulate three policy scenarios.

The key finding is that demographic change redistributes the emission reduction burden across sectors: the household sector achieves a 5.5 percentage point shallower reduction (-30.8% vs. -36.3%) and the power sector a 13.5 percentage point shallower reduction (-70.7% vs. -84.2%) relative to the standard NZ pathway, while production sectors achieve 5–8 percentage point deeper reductions. These compositional shifts, combined with a 55.7% lower carbon price driven by economic contraction, underscore the need for demographic-sensitive climate policy design. Demand-side energy efficiency policies targeting elderly households must complement supply-side decarbonization strategies. Future research will extend the horizon to 2050, refine data harmonization, and conduct welfare distributional analysis.

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Appendix

Appendix A: Full 60-sector classification table

Appendix B: Complete 19-type × 20-category consumption expenditure share matrix

Appendix C: Harmonization mapping between Household Expenditure Survey categories and Input-Output table sectors