Capturing Capital Transition: A Multi-Vintage CGE Analysis of Carbon Intensity and Carbon Taxation

1. Introduction

Climate change mitigation and greenhouse gas reduction have become central policy challenges in modern economies, and countries worldwide have adopted various mitigation policies. Among these, carbon tax is a representative market-based instrument that internalizes the external costs of greenhouse gas emissions by assigning a price to carbon (Chang et al., 2023). The implementation of a carbon tax not only reduces fossil fuel consumption and promotes energy transition, but also incentivizes technological innovation by firms. In addition, due to its flexibility in policy coverage and cost-effectiveness, carbon tax has been widely recognized as a key mitigation instrument and is extensively discussed as a central climate policy tool (Wen et al., 2026).

Given its importance, a large body of literature has examined the impacts of carbon tax on economic growth, industrial structure, energy consumption, and greenhouse gas emissions. Many studies emphasize that carbon tax may impose short-term economic costs (Timilsina et al., 2021; Li et al., 2020; Ojha et al., 2020). In addition, studies on policy design highlight that tax rates, coverage, and revenue recycling are critical determinants of policy effectiveness (Rajabi, 2023; Sun et al., 2021; Presley and Lin, 2019; Duan et al., 2014). More recently, increasing attention has been paid to the interaction between carbon tax and technological progress, showing that carbon pricing can stimulate improvements in energy efficiency and productivity (Chai et al., 2025). Since the effects of carbon tax are determined not within a single market but through the interdependent structure of the entire economy, computable general equilibrium (CGE) models have been widely employed as a primary analytical tool to capture these economy-wide interactions.

This study builds upon the global recursive dynamic CGE model, LINKAGE, developed by van der Mensbrugghe (2005). In conventional CGE models, capital is typically treated as a homogeneous aggregate stock without distinguishing its installation period or vintage. As a result, new investment is simply added to the existing capital stock, making it difficult to explicitly capture the gradual transition process associated with capital turnover. To address this limitation, the LINKAGE model distinguishes between old and new capital. In this framework, old capital embodies past technology choices and exhibits limited substitution possibilities once installed, whereas new capital can flexibly respond to changes in relative prices. This structure allows for heterogeneity in capital adjustment across vintages, albeit only at a two-vintage level.

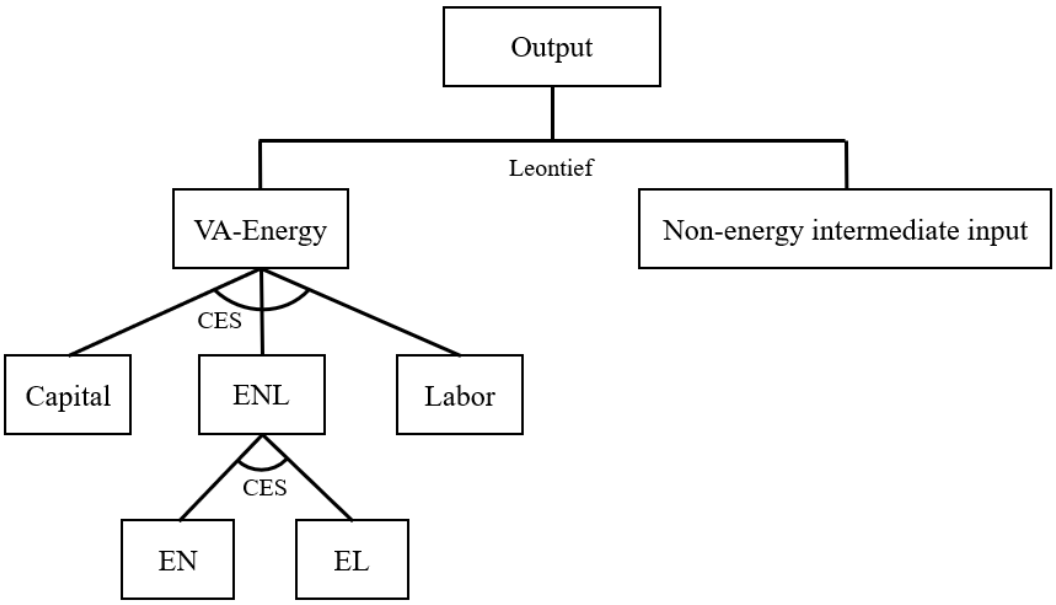
This study extends the LINKAGE framework by disaggregating capital into multiple vintages (beyond the two-vintage structure) in order to more precisely capture capital transition associated with new investment. Since depreciation and sectoral investment decisions vary across capital vintages and are determined on an annual basis, changes in the composition of the capital stock occur gradually over time. By introducing a more detailed vintage capital structure, the model is able to capture heterogeneity in capital adjustment rates, thereby providing a more realistic representation of the dynamic adjustment path of the economy. Building on this enhanced framework, this study analyzes how carbon intensity and the associated carbon tax evolve over time, and evaluates how accounting for capital vintage dynamics affects the estimation of economic costs and policy outcomes of carbon pricing.

2. Methodology

2.1. Dynamic CGE model

This study employs a dynamic recursive CGE model to analyze how the vintage structure of capital affects changes in industrial carbon intensity and macroeconomic outcomes. The model is based on the LINKAGE Model, where capital is represented using a putty–semi-putty specification that distinguishes between new and old capital. Newly installed capital is fully flexible and allows substitution among production factors in response to relative price changes, whereas existing capital reflects technological rigidities embodied in past investment decisions and thus permits only limited substitution. However, the standard LINKAGE framework represents capital using only two categories, new and old capital, which may not adequately capture heterogeneity in production technologies, energy efficiency, and carbon intensity across capital stocks. To address this limitation, this study extends the model by disaggregating capital into multiple vintages according to the time of installation, allowing each vintage to exhibit distinct production characteristics and carbon intensity. This extension enables a more realistic representation of capital turnover and technological transition, thereby improving the analysis of dynamic adjustment paths under carbon pricing policies.

Production block in each sector is represented by a nested structure that combines value-added, energy, and intermediate inputs. At the top level, output is produced using a value-added–energy composite and non-energy intermediate inputs under a Leontief specification. Within the value-added–energy composite, capital, labor, and energy are combined through a constant elasticity of substitution (CES) function. The energy composite is further disaggregated into electricity and non-electric energy inputs through an additional CES nest. Non-electric energy inputs include coal, crude oil, petroleum products, natural gas, and gas distribution fuels, while electricity inputs consist of conventional electricity and renewable electricity. This classification allows the model to distinguish between fossil-based energy and electricity, and to capture substitution possibilities both across energy types and between electricity and other energy sources.



[Figure 1] Production structures of goods

The income-expenditure block describes the generation and allocation of income among economic agents. Household income is derived from factor payments generated in production, including returns to labor and capital. After direct taxation, household income is allocated between private consumption and savings. Firms generate revenue from the sale of goods and services to domestic and foreign markets. This revenue is distributed to factor payments, taxes, and savings, ensuring consistency between production activities and income generation. Government revenue is collected from direct taxes, indirect taxes on commodity transactions, tariffs on international trade, and carbon tax revenues. These revenues are allocated to public consumption and government savings, with government consumption linked to the level of real GDP.

The trade block describes the interactions between the domestic economy and the rest of the world through imports, exports, and interregional trade flows. Following the Armington assumption, goods are differentiated by their place of origin, and domestic and imported goods are treated as imperfect substitutes. Domestic demand is therefore allocated between domestically produced goods and imports based on relative prices. On the supply side, producers allocate output between domestic markets and exports according to relative price signals, allowing for imperfect transformation between domestic sales and exports. International trade is represented through bilateral flows across regions, capturing trade linkages between trading partners. Imports are subject to tariffs and trade-related costs, while exports are valued at world prices. In addition, trade and transport margins are incorporated to account for the costs associated with moving goods across regions.

The model adopts a standard neoclassical closure with three key macroeconomic balance conditions: government budget balance, external balance, and savings–investment balance. The government budget constraint requires that total government revenue equals government expenditures, including public consumption and savings. Government revenue is derived from direct taxes, indirect taxes, tariffs, and carbon tax revenues. The external balance condition is satisfied through the equality between foreign savings and the trade balance. Foreign savings are treated as exogenous, while trade flows adjust to maintain equilibrium in the external account. The model assumes a savings-driven investment closure in which total savings from households, firms, the government, and the rest of the world finance aggregate investment. As a result, investment is determined by available savings, ensuring consistency between savings and investment at the regional level. In the factor market, full employment is assumed, and factors of production—particularly labor—are perfectly mobile across industries, leading to equalization of factor returns. Commodity markets clear through the Armington composite structure, where total supply of each good equals total demand from households, government, investment, and intermediate use. These closure rules ensure that all markets clear in each period of the recursive dynamic framework.

To incorporate environmental policies into the CGE framework, monetary energy inputs are linked to physical energy use through energy balance. This linkage is established by introducing industry-specific emission coefficients, which convert energy expenditures into corresponding CO_2 emissions. These coefficients represent the amount of CO_2 emitted per unit of energy expenditure for each fuel type across industries. Total emissions are calculated by aggregating emissions across all industries and energy inputs. Carbon pricing is then implemented by applying a carbon tax rate to the emissions associated with taxed activities. In the model, this is operationalized by adjusting the effective prices of energy-related inputs through emission coefficients and the carbon tax rate, thereby internalizing the cost of emissions into production and consumption decisions. Under policy scenarios, the total carbon tax revenue is determined by the product of aggregate emissions and the carbon tax rate, and is incorporated into the government budget. In addition, emission targets can be imposed by exogenously specifying allowable emissions over time, enabling the analysis of endogenous carbon pricing paths consistent with emission reduction goals.

2.2. Capital Market Equilibrium in a Multiple Vintage Framework

The model adopts a vintage capital framework to capture the heterogeneity and gradual adjustment of capital over time. Instead of treating capital as a homogeneous and perfectly mobile factor, the total capital stock is decomposed into multiple vintages, each representing capital installed at different points in time. These vintages differ in terms of technological characteristics, productivity, and substitution possibilities with other production factors. Newly installed capital is assumed to exhibit relatively high flexibility in factor substitution (putty), whereas older vintages are more rigid and operate under previously fixed input structures (semi-putty). As a result, adjustments to economic shocks such as the introduction of a carbon tax do not occur instantaneously across the entire capital stock. Existing capital depreciates over time, and new capital is introduced through investment, leading to a gradual reallocation of the capital composition. Through this mechanism, the model captures the pathway of technological transition in a more realistic manner. It also enables a more accurate assessment of the impacts of economic shocks.

The capital output ratio ($\chi_{i,v}$) is defined by Equation (1), which specifies the capital requirement per unit out output for each vintage capital. This formulation provides a technological link between specific vintage capital stocks ($Kv_{i,v}$) and production ($QPv_{i,v}$), thereby translating capital availability into productive capacity. Variation in this ratio across vintages reflects technological heterogeneity associated with the timing of capital installation. Therefore, this equation provides the basis for determining the contribution of each capital vintage to aggregated output.

$$\chi_{i,v} = \frac{Kv_{i,v}}{QPv_{i,v}} \qquad (1)$$

The rate of return ($RR_{i,v}$) specifies the supply schedule of old vintage capital in Equation (2). The numerator represents the demand for capital, derived from the output of old capital using the capital output ratio, and covers vintages from one period newer than v to the oldest vintage $\bar{v}$. When this ratio is less than one, it implies that the demand for capital is smaller than the capital accumulated from vintage capital v onward, and capital in this sector is released.

$$\mathrm{RR}_{\mathrm{i,v}}^{\eta_{i,v}} = \min\left(\chi_{i,v} \times \frac{\sum_{\tilde{v}\geq v^{-}} QP_{i,\tilde{v}} \times (1+PTP_{i,\tilde{v}})}{\sum_{\tilde{v}\geq v} Kv_{i,\tilde{v}}}, 1\right) \tag{2}$$

Aggregate output in sector i, QP_i, composed of output produced by existing vintage capitals and output produced by new vintage capital. It is equated to the sector's production demand in Equation (3). Old output is determined based on the installed capital and is adjusted to be consistent with aggregate demand. When the output generated by existing vintage capitals is insufficient to meet aggregate demand, the difference between aggregate output and old output is satisfied by production from new vintage capital.

$$QP_i = \sum_v QPv_{i,v} \tag{3}$$

In a dynamic recursive CGE framework with disaggregated capital by vintage, each vintage capital declines gradually over time according to a turnover. In this study, the survival rate of each vintage capital is modeled using a Weibull distribution. The average life is set to 35 years, based on a weighted average of asset-specific lifetimes using their respective capital shares, and the shape parameter is assumed to be 2. The survived vintage capital is calculated as Equation (4). When the average lifetime exceeds the number of vintages, the oldest vintage capital ($Kv_{i,\bar{v}}$) represents the accumulation of the remaining capital. In this case, the oldest vintage capital is calculated as Equation (5). The sum of all vintage capital is required to be consistent with the total capital stock of the economy (KS), as specified in Equation (6).

$$Kv_{i,v} = Survival\,rate_{i,v-1} \times Kv_{i,v-1}, \quad v < \bar{v} \tag{4}$$

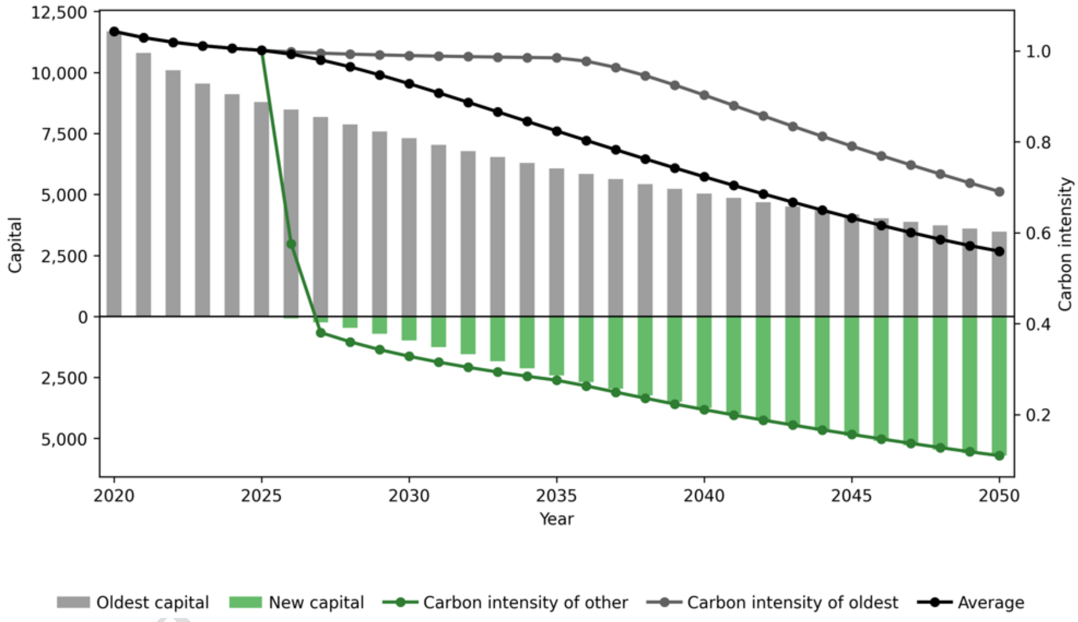
$$Kv_{i,\bar{v}} = Survival\,rate_{i,\bar{v}-1} \times Kv_{i,\bar{v}-1} + Survival\,rate_{i,\bar{v}} \times Kv_{i,\bar{v}} \tag{5}$$

$$KS = \sum_0^{\bar{v}} Kv_{i,v} \tag{6}$$

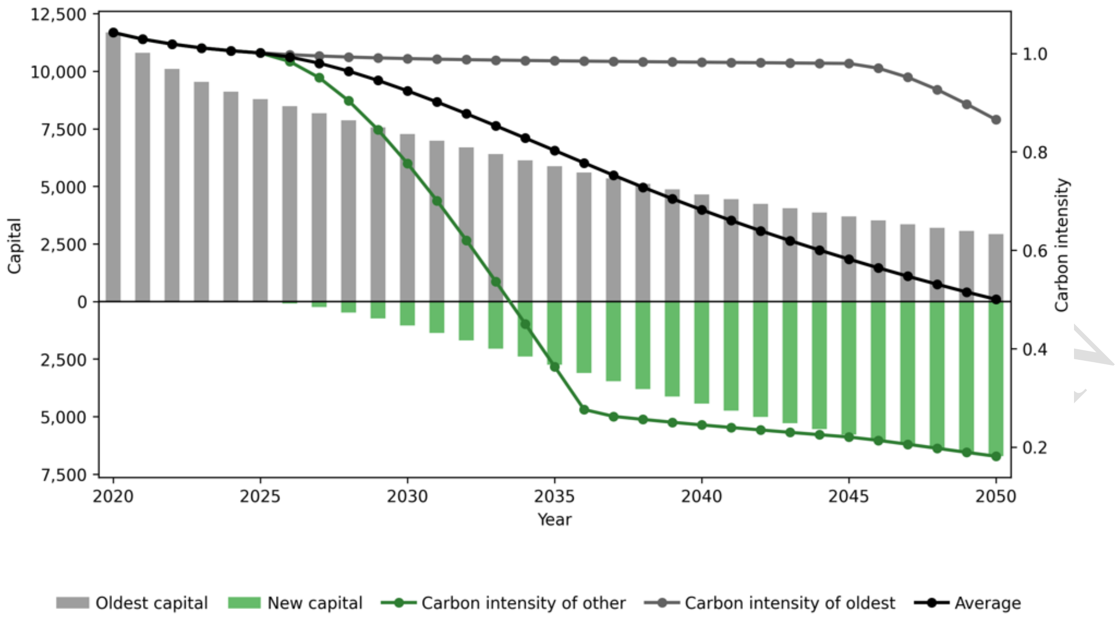
3. Results

3.1. Impacts on production sectors

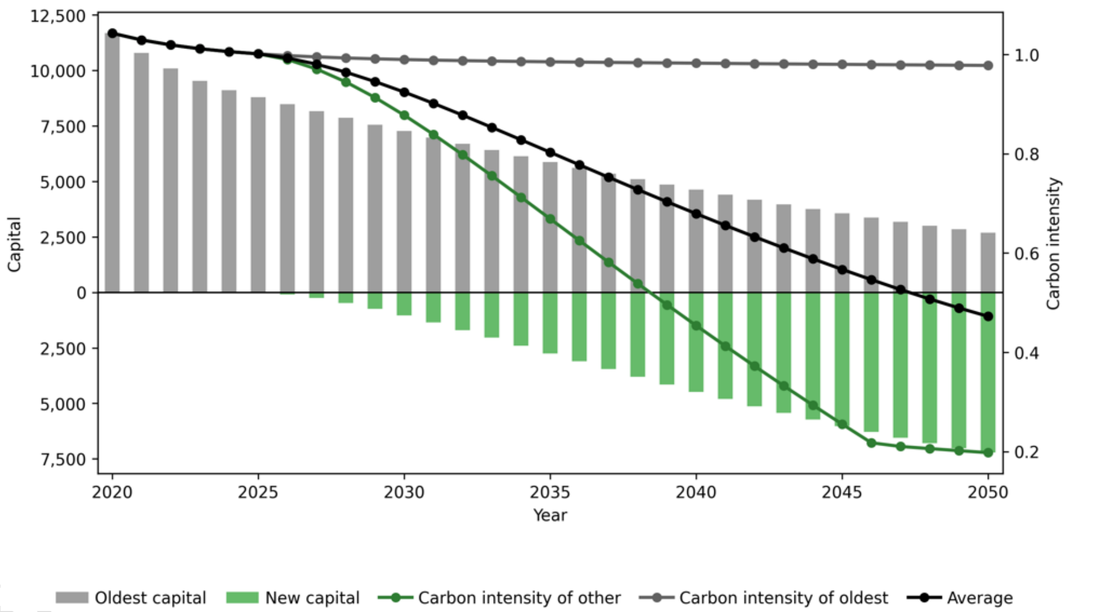
This study examines the transition of capital across vintages by disaggregating capital stocks and analyzing how such transitions influence carbon intensity over time. Figure 2-4 illustrate the transition of capital composition in the steel sector under carbon emission constraints for the different number of vintage disaggregation, with 10, 20, and 30 vintages, respectively. In each figure, the oldest capital refers to the capital stock installed in the base year, while new capital represents investment undertaken subsequent periods. The bar charts depict the changing composition of capital over time, reflecting the gradual replacement of the oldest vintages by newly installed capital.



[Figure 2] Composition of Capital Vintages and Carbon Intensity (10 Vintages)



[Figure 3] Composition of Capital Vintages and Carbon Intensity (20 Vintages)

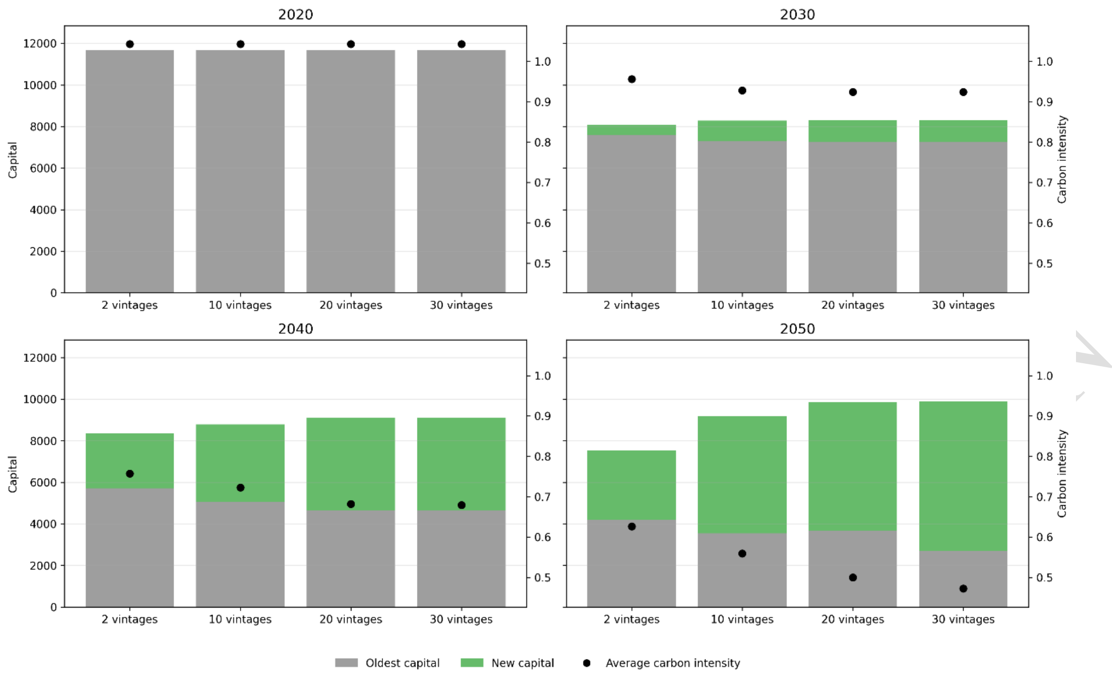


[Figure 4] Composition of Capital Vintages and Carbon Intensity (30 Vintages)

As the capital composition evolves, substitution between energy and other production factors leads to changes in carbon intensity. Carbon intensity is decomposed into two components: that associated with the oldest capital vintage and that associated with the remaining vintages. The line graphs illustrate the evolution of these carbon intensity measures over time. Comparing Figures 2-4 highlights how the degree of vintage disaggregation affects the pace and extent of capital transition and the resulting dynamics of carbon intensity.

In the initial period, the deployment of new capital is limited due to the presence of excess capital relative to the level required to meet production demand. As a result, existing capital stocks gradually depreciate, and surplus capital is released. During this period, carbon intensity declines gradually, primarily driven by substitution away from energy inputs toward other production factors. However, this adjustment occurs at a relatively slow pace due to the limited flexibility of older capital vintages. New capital investment begins as excess installed capital is released. At this stage, the carbon intensity associated with the remaining capital vintages decreases at a faster rate. This is because these vintages exhibit relatively higher substitution elasticity compared to older capital, allowing for more rapid adjustment in input use. After a period equal to the number of capital vintages considered in the model, capital installed in a given period becomes part of the oldest vintage capital. As a result, the rate at which the carbon intensity of the oldest capital group declines increases, as cleaner capital gradually replaces older, more carbon-intensive capital within this category. This reflects the cumulative effect of capital turnover, whereby the gradual integration of newer and more flexible capital vintages leads to a further reduction in carbon intensity.

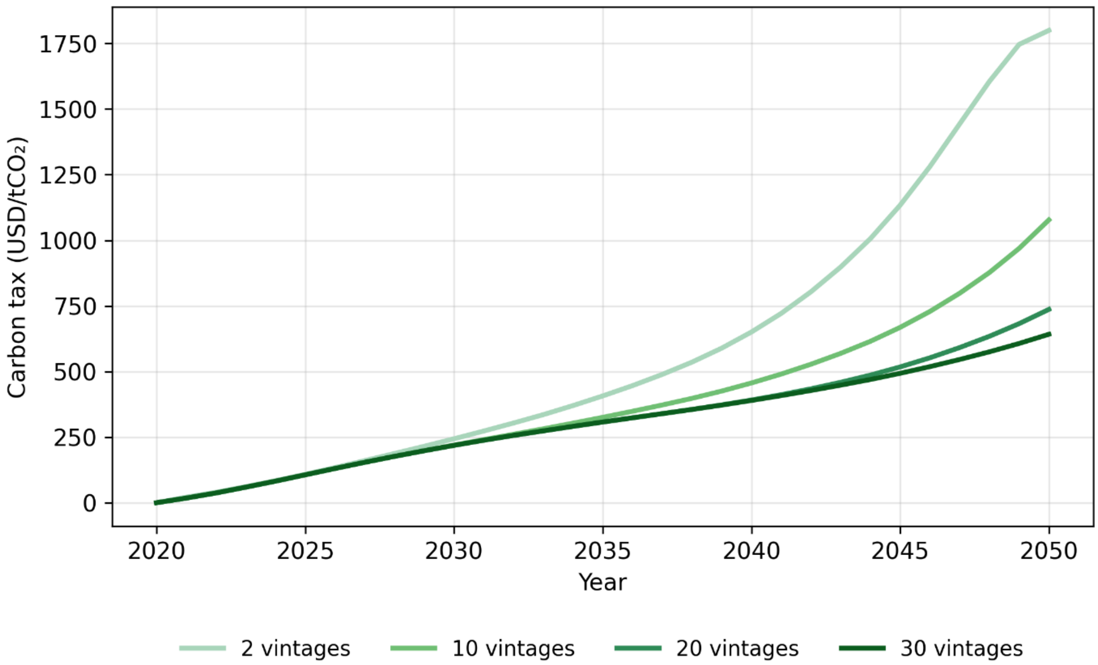
Figure 5 compares capital composition and carbon intensity across different time periods and levels of vintage disaggregation. The results indicate that the extent of capital turnover differs across vintage structures. As the number of vintages increases, capital turnover becomes more pronounced, allowing for a faster replacement of older capital with newly installed capital. This leads to a higher share of new capital in the overall capital composition when a larger number of vintages is considered. As a result, changes in capital composition are more substantial, which directly affects carbon intensity. In particular, a higher degree of vintage disaggregation is associated with a larger reduction in carbon intensity over time.



[Figure 5] Time-Series Comparison of Capital Composition and Carbon Intensity across Vintage structure

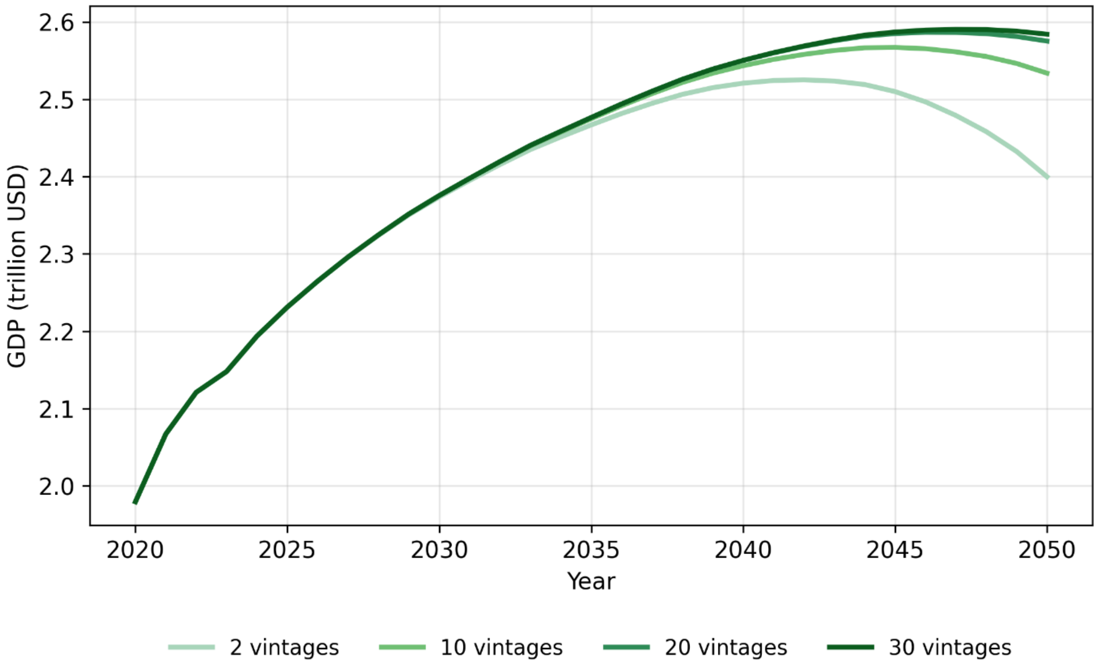
3.2. Impact of Vintage Disaggregation on Carbon Tax and GDP

The level of vintage capital disaggregation leads to differences in the scale of new capital investment and carbon intensity, which in turn implies variations in macroeconomic outcomes. Figure 6 illustrates the evolution of carbon tax trajectories over time under different vintage structures. When capital is represented by only two categories, old and new capital, the carbon tax increases sharply as emission constraints become more stringent. In contrast, as vintage capital is more finely disaggregated, the rate of increase in the carbon tax becomes more moderate. This suggests that a more detailed vintage structure facilitates smoother capital turnover, promoting the introduction of new capital and enabling a gradual transition toward cleaner technologies.



[Figure 6] Comparison of Carbon Tax Paths across Vintage Structures

Figure 7 presents the evolution of gross domestic product (GDP) over time across different levels of vintage disaggregation. The results show that GDP follows a broadly increasing trend in all cases, but the trajectory differs depending on the number of capital vintages. Models with a finer vintage structure consistently exhibit higher GDP levels compared to those with fewer vintages. After the mid-2040s, GDP in models with limited vintage representation begins to stagnate or decline, whereas models with a larger number of vintages maintain higher GDP levels. This pattern is driven by differences in carbon tax trajectories: less disaggregated models require higher carbon prices to meet emission constraints, imposing a greater adjustment burden on the economy. In contrast, a more detailed vintage structure facilitates smoother capital turnover and enables a gradual transition toward cleaner technologies, thereby mitigating the negative impact on GDP. Overall, these results highlight that a more detailed representation of capital vintages reduces the economic cost of emission mitigation and underscores the importance of accounting for capital heterogeneity in macroeconomic assessments of climate policy.



[Figure 7] Comparison of GDP across Vintage Structures