energies

MDPI

Article

Primary Energy Demand in Korea: Substitution and Structural Change

Ji-Whan Kim [1] and Yoon-Kyung Kim [2,*]

[1] Resource Economics Research Department, Korea Institute of Geoscience and Mineral Resources (KIGAM), Daejeon 34132, Republic of Korea; kjiwhan@kigam.re.kr
[2] Department of Economics, Ewha Womans University, Seoul 03760, Republic of Korea
* Correspondence: yoonkkim@ewha.ac.kr

Abstract

International energy price changes can lead energy-importing economies to adjust their input factor choices, and Korea provides a useful case given its very high dependence on imported primary energies. This study estimates a primary energy input-demand system for Korea using quarterly data from 2000 to 2021, covering coal; crude oil; natural gas; labor; and others, including non-primary energy inputs. Our analysis uses LA-AIDS specifications. Breakpoint unit-root and cointegration tests support structural change around the global financial crisis, and this shift is incorporated through period-specific parameters within a unified demand system. The compensated elasticities indicate that crude oil becomes more price sensitive after the break, while coal and natural gas become less responsive to their own prices. Cross-price relationships also change, with weaker substitution among the primary energies and greater substitution between crude oil and others. These findings suggest that the ability to adjust inputs and the economic effects of international price changes can vary over time, which should be taken into account in energy policy evaluation.

Keywords: primary energy demand; Almost Ideal Demand System (AIDS); structural change; price elasticity

1. Introduction

Primary energy price swings shape macroeconomic outcomes by altering production costs, inflation, and the current account balance. The scale and persistence of these effects depend on how quickly producers can reallocate cost shares across primary energy sources and other inputs when relative prices change. When the ability to adjust input use is limited, a given price shock translates into larger cost pressures and stronger spillovers to economic activity [1,2].

This channel is particularly salient for Korea, where primary energy supply relies almost entirely on imports. In 2022, Korea ranked fifth globally in energy imports, and coal, crude oil, and natural gas accounted for 25.4% of total imports, with 99.8% of domestic primary energy supply sourced from abroad [3]. Because imported primary energies are subsequently refined or converted into secondary products, international price changes influence domestic production cost conditions and propagate through the trade balance and the exchange rate [4]. High import dependence also heightens sensitivity to external disruptions, including shipping bottlenecks and changes in geopolitical conditions, making it especially important to quantify substitution at the primary energy stage. Demand

Check for updates

Academic Editor: Benjamin McLellan

Received: 12 March 2026
Revised: 12 April 2026
Accepted: 14 April 2026
Published: 20 April 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

analysis at the primary energy stage therefore provides a direct basis for assessing sensitivity to external price changes and the effectiveness of price-based instruments [5].

Despite the policy implications, empirical research often evaluates price-based measures using elasticities that are implicitly treated as stable over time. Yet evidence from recent studies indicates substantial heterogeneity—and, in many cases, change over time—in estimated energy-demand elasticities, cautioning against relying on a single long-sample response for evaluation [6,7]. In Korea, industrial structure, technologies, and import channels have evolved over time, suggesting that substitution possibilities—and thus the effects of price changes—may also have changed. Related Korea-focused analyses emphasize oil-price shocks and macroeconomic responses, but they do not identify compensated cross-substitution within a theory-consistent demand system [8], and demand-system applications commonly maintain parameter stability over the full sample [9]. More broadly, energy price responsiveness can differ widely across countries and periods [10], so applying a single set of elasticities to policy evaluation may be misleading. Time-varying or rolling methods are appealing, but they are difficult to implement with quarterly data when the system must satisfy adding-up, homogeneity, and symmetry; a two-period division around the break offers a practical alternative.

Recent studies have used various alternative approaches to capture changes in energy-demand elasticities. In addition to time-varying models, alternative demand-system specifications such as QUAIDS allow greater flexibility in expenditure responses. For example, ref. [7] reviews the broader evidence on time-varying elasticities, while [11] estimates Korean sectoral electricity demand with a time-varying cointegrating vector using monthly data, covering 1995:01–2012:12 for the residential sector and 1985:01–2012:12 for the commercial and industrial sectors. Reference [12] estimates Turkey's crude-oil import demand with a TVP model using annual data for 1966–2012, and related work on Turkey's electricity demand also applies a time-varying approach to annual data for 1960–2008 [13]. Recent comparative evidence suggests that time variation is not uniformly strong across countries, and that some elasticities may remain effectively stable over time [14]. However, the present study is concerned less with tracing continuous coefficient drift in a single-equation setting than with estimating own- and cross-price substitution patterns within a theory-consistent multi-input demand system. In this context, maintaining adding-up, homogeneity, and symmetry is important because the elasticities are jointly determined within the system. Although QUAIDS offers additional flexibility, that flexibility is mainly intended to capture nonlinear expenditure responses, whereas the present analysis focuses on compensated substitution among multiple inputs under fixed output. Given the quarterly sample structure, the evidence of structural change, and the need to preserve these system-wide restrictions, LA-AIDS-type demand-system models provide a more parsimonious and interpretable framework for the present analysis.

Given the evidence of structural change around the 2008 global financial crisis, estimates are obtained for two subperiods using quarterly data from 2000 to 2021. The demand system includes coal, crude oil, and natural gas, together with labor and a composite non-primary energy component (hereafter, "others"), defined as the remaining cost component after accounting for the three primary energies and labor. The empirical model employs the Linear Approximate Almost Ideal Demand System (LA-AIDS), providing a flexible yet theory-consistent representation of cost shares across multiple inputs [15]. Static, dynamic, and error-corrected specifications are considered. Breakpoint unit-root and cointegration evidence points to a structural break around the global financial crisis, with some estimated break dates in 2008Q4–2009Q3. The preferred specification is the dynamic LA-AIDS model, selected by minimizing an information-inaccuracy measure based on the discrepancy between observed and fitted cost shares.

This paper makes three contributions. First, it estimates a theory-consistent primary energy input demand system for Korea and provides compensated own- and cross-price elasticities for coal, crude oil, natural gas, labor, and a composite non-primary energy component. Second, by explicitly allowing for structural change around the global financial crisis, it shows that elasticity-based policy inferences are not invariant over time: both own-price responsiveness and cross-component substitution differ materially between the two periods. Third, it translates the estimated elasticities into implied demand adjustments under common price-change scenarios, thereby clarifying the economic magnitude of substitution in an import-dependent economy.

Reliable inference on substitution requires a system approach because own- and cross-price responses are jointly determined and must satisfy the adding-up, homogeneity, and symmetry restrictions implied by economic theory. Share-based demand systems are widely used for this purpose because they deliver internally consistent elasticities and allow substitution to be traced across components within a unified system. Among these, the Almost Ideal Demand System (AIDS) offers a flexible yet tractable representation of share equations, and its linear approximation (LA-AIDS) facilitates estimation with standard data requirements [15]. Although originally proposed for consumer expenditure, the same share-equation structure has been applied in the factor-demand literature to model cost allocation across production inputs while maintaining standard theoretical restrictions [16–18]. Many studies adopt an energy–labor–others structure [19,20]. This study disaggregates energy into coal, crude oil, and natural gas to examine substitution among individual primary energy sources.

The remainder of the paper is organized as follows. Section 2 presents the model specification. Section 3 describes the data and reports the breakpoint unit-root and cointegration tests. Section 4 presents the estimation results, model selection, and elasticity estimates. Section 5 discusses the economic interpretation and policy implications of the findings. Section 6 concludes this paper.

2. Model Specification

Empirical studies of demand systems often begin with static models, under which adjustment to a new equilibrium following changes in prices is assumed to be instantaneous. In factor-demand applications, this implies that producers reallocate inputs immediately after relative prices change. However, this assumption is too strong when short-run adjustment costs, limited substitution possibilities, or persistence in input use constrain immediate responses [21]. For more realistic estimates, short-run elasticities are often considered more appropriate [22].

Dynamic models complement static ones by accounting for intertemporal behavior and short-run adjustments [23]. When time-series variables exhibit unit roots or cointegrating relationship, static models can be biased, while dynamic approaches such as the dynamic and error-corrected LA-AIDS are more likely to provide consistent estimates [21,24–26].

Within the AIDS framework, the demand system for primary energies, labor, and others is estimated using static, dynamic, and error-corrected LA-AIDS specifications. Structural change is incorporated through a dummy variable equal to one after the identified breakpoint. Theoretical regularity conditions of adding-up, homogeneity, and symmetry are imposed across the full sample, even when structural shifts are present [27].

More specifically, the structural break is handled through regime-dependent parameter shifts within a unified demand system rather than by estimating two fully separate systems. Let D_t denote a dummy variable that equals zero before the breakpoint and one thereafter. Then, each regime-dependent coefficient can be written as a baseline parameter plus a dummy-shift parameter, so that Period 1 is characterized by the baseline coefficients, and

Period 2 by the sum of the baseline and shift coefficients. This specification is preferred because it preserves a single constrained SUR (Seemingly Unrelated Regression) framework while allowing period-specific responses to be identified. It is also more efficient than fully separate estimation, given that the quarterly sample contains only 36 observations in the first regime and 52 in the second. To maintain theoretical consistency in both regimes, the adding-up, homogeneity, and symmetry restrictions are imposed on both the baseline and shift parameters, so that the standard AIDS restrictions hold regime by regime within the full-sample estimation.

2.1. Static LA-AIDS

The AIDS model is derived from the PIGLOG (Price-Independent Generalized Logarithmic) function and provides a theoretically consistent and tractable framework. The corresponding share equation is expressed as follows.

$$\omega_i = \alpha_i + \sum_{j=1}^{n} \gamma_{ij} log(p_j) + \beta_i \log\left(\frac{M}{P}\right) \qquad i = 1, 2, 3, \ldots, n \tag{1}$$

where w_i denotes the budget share of the ith commodity, p_j is the price of the j-th commodity, and M = $\sum_{i=1}^{n} p_i q_i$ represents total expenditure. The P is an aggregate price index, defined as follows:

$$\log(P) = \sum_{k=1}^{n} a_k \log(p_k) + \frac{1}{2} \sum_{k=1}^{n} \sum_{j=1}^{n} \gamma_{kj} \log(p_k) \log(p_j) \tag{2}$$

Because the price index is nonlinear in parameters, estimation using aggregate time-series data can be computationally complex. To address this issue, an externally specified price index—the Stone's price index, a share-weighted geometric mean of prices—has been proposed [21]. This Stone's price index is employed in the empirical estimation:

$$\text{Stone's price index}: \ \log(P) = \sum_{k=1}^{n} w_k \log(p_k) \tag{3}$$

The share equations, as derived above, must satisfy standard theoretical regularity conditions to ensure consistency with economic theory. These include the adding-up, homogeneity, and symmetry conditions originally proposed by [15]. These constraints could not be ignored and are imposed in the estimation of the share equations [18,28,29].

- Adding-up: $\sum_{i=1}^{n} \alpha_i = 1$, $\sum_{i=1}^{n} \beta_i = 0$, $\sum_{i=1}^{n} \gamma_{ij} = 0$.
- Homogeneity: $\sum_{j=1}^{n} \gamma_{ij} = 0$.
- Symmetry: $\gamma_{ij} = \gamma_{ji}$ for $i, j = 1, 2, \ldots, n$ and $i \neq j$.

The AIDS framework is well-suited to analyzing demand systems and can be extended to input demand. In the context of factor demand, the share equations represent factor shares, and total expenditure is replaced by output Y. This study estimates a factor demand system composed of three primary energies, labor, and others.

Based on the estimated parameters of the share equations, compensated (Hicksian) price elasticities can be derived under the assumption of constant output. These elasticities measure substitution effects along the isoquant [18].

$$\begin{aligned} \varepsilon_{ii} &= w_i + \frac{\gamma_{ii}}{w_i} - 1, \\ \varepsilon_{ij} &= w_j + \frac{\gamma_{ij}}{w_i}, \qquad i, j = 1, 2, \ldots, \ n \text{ and } i \neq j \end{aligned} \tag{4}$$

2.2. Dynamic LA-AIDS

As noted above, concerns regarding the immediate adjustment of demand to price changes, as well as the time-series properties of the data, provide sufficient justification for the use of dynamic models. Studies such as Kesavan et al. [30], and Alessie and Kapteyn [31] proposed a dynamic LA-AIDS specification by incorporating lagged share

terms. This represents a basic extension of the static model into a dynamic framework and is specified as follows.

$$\omega_{it} = \alpha_i + \sum_{j=1}^{n} \theta_{ij}\omega_{jt-1} + \sum_{j=1}^{n} \gamma_{ij} log(p_j) + \beta_i \log\left(\frac{M}{P}\right), \quad i = 1, 2, \ldots, n \tag{5}$$

2.3. Error-Corrected LA-AIDS

Similar to the rationale for employing a Dynamic LA-AIDS, the presence of time-series properties in the data necessitates careful treatment to ensure reliable estimation and inference. Specifically, it is essential to examine whether the variables are non-stationary, in which case unit root and cointegration tests must be conducted prior to estimation. If the variables are integrated of order one, I(1), and found to be cointegrated, the error-corrected LA-AIDS can be appropriately applied. The model is given as follows.

$$\Delta\omega_{it} = \alpha_i + \rho_i \Delta\omega_{it-1} + \sum_{j=1}^{n} \gamma_{ij} \Delta log(p_j) + \beta_i \Delta \log\left(\frac{M_t}{P_t}\right) + \lambda_i \mu_{it-1} + \varepsilon_{it}, \; i = 1, 2, 3, \ldots, n \tag{6}$$

where Δ is the first-difference operator, and μ_{it-1} is the error correction term measuring deviations from long-run equilibrium, estimated using the residuals from the static AIDS model specified in Equation (1). Since time-series data are used in estimating the demand system, verifying the stationarity properties of the variables is a necessary first step. This ensures that long-run demand relationships are not spurious but economically meaningful [21,32–34]. The inclusion of lagged dependent variables reflects the persistence of previous demand behavior in current budget allocation decisions, which may arise due to technological inertia or input rigidity in production. Such persistence can be linked to short-run adjustment costs and limited substitution possibilities, as well as to broader forms of technological lock-in and delayed factor substitution documented in the literature [35–38].

3. Empirical Analysis

3.1. Data

The Korean economy experienced structural adjustment following the Asian Financial Crisis. In November 1997, the Korean government requested financial assistance from the International Monetary Fund (IMF) and implemented fiscal austerity and structural reform measures. Domestic policy measures and global economic conditions supported Korea's economic recovery between late 1998 and early 1999. By 2000, following a significant recovery of the Korean economy, the government had repaid its IMF loan. Thus, the sample period is set from 2000, marking the start of economic recovery, to 2021, when economic disruptions intensified with the COVID-19 pandemic. The end year is also influenced by data availability, as the wage index from the IFS database is available only up to 2021 at the time of analysis. The empirical analysis therefore uses a sample ending in 2021.

Shocks and policy changes such as the 2008 global financial crisis, large swings in international oil prices, and changes in Korean energy policy are consistent with a structural break around 2008–2009, a period that has also been identified in the literature as involving broader structural shifts in the Korean economy [9,39–41]. To compare demand systems before and after this break and to model dynamic adjustment, a sufficient number of observations are required. Hence, quarterly data are used, yielding 88 observations. The series are not seasonally adjusted, as detecting structural change may be affected by seasonal filtering. In addition, the labor share is constructed by converting annual compensation of employee data into quarterly values through equal allocation, which makes consistent seasonal adjustment difficult. This choice of using unadjusted quarterly data should not be interpreted as implying that seasonal specifications were disregarded. In the specification-selection stage, we also considered a version using seasonally adjusted variables and

another including seasonal dummy variables. These alternatives were not retained, because the baseline specification remained more coherent with the overall empirical framework of the paper, taking into account fit, coefficient stability, and the break-based time-series evidence used for periodization.

The model comprises five inputs, coal, crude oil, natural gas, labor, and others. The share of the category "others" is computed residually as total expenditure on inputs minus the shares of the three primary energies and labor. Expenditures on the three primary energies are measured using import values for each energy. Labor expenditure is taken from the Bank of Korea's annual employee compensation series and converted to quarterly shares by allocating the annual totals evenly across the four quarters. Additional robustness checks based on alternative quarterly labor-compensation constructions are reported in Appendix C.

The coal–oil–gas–labor–others structure is adopted to keep the analysis focused on Korea's primary energy demand system. In this framework, the term "others" denotes the residual non-primary energy cost margin after accounting for coal, crude oil, natural gas, and labor, rather than a separately identified input. It may encompass non-energy intermediate goods and services, electricity-using equipment and processes, and some substitution channels through imported intermediate or petrochemical products. Further disaggregation is not pursued here, because it would require not only sufficiently consistent quarterly expenditure and price data, but also a clear and economically meaningful basis for defining additional inputs within the demand system. The present specification therefore retains a parsimonious structure suited to the paper's objective of identifying substitution among primary energies and between primary energies and the remaining non-primary energy cost margin.

The demand system is derived from a PIGLOG expenditure function and is therefore specified in terms of price indices. Coal, crude oil, and natural gas prices are represented by Korea's import price indices, reflecting the country's import dependence. The labor price index (i.e., a wage index) is constructed from weekly earnings data in the International Monetary Fund (IMF), and the Producer Price Index (PPI) for others reflects prices of domestically produced goods and services rather than the prices of imported energy and labor. Summary statistics of the share variables are presented in Table 1.

Table 1. Summary (descriptive) statistics of input shares.

Period	**2000Q1–2008Q4**				**2009Q1–2021Q4**			
(No. of Quarters)	**(36)**				**(52)**			
Variables	**Mean**	**Std.**	**Min**	**Max**	**Mean**	**Std.**	**Min**	**Max**
Coal	0.0072	0.0033	0.0045	0.0215	0.0115	0.0034	0.0058	0.0194
Oil	0.0490	0.0168	0.0258	0.1047	0.0565	0.0210	0.0200	0.0991
Gas	0.0128	0.0060	0.0052	0.0348	0.0198	0.0080	0.0076	0.0401
Labor	0.4737	0.0092	0.4598	0.4863	0.4933	0.0179	0.4675	0.5279
Others	0.4574	0.0312	0.3741	0.5018	0.4188	0.0226	0.3678	0.4597

In quantitative terms, the mean share of "others" remains substantial in both periods, amounting to 0.4574 in Period 1 and 0.4188 in Period 2, as reported in Table 1.

For completeness, Appendix A reports a comparison of the baseline specification with two alternative seasonal specifications, one using seasonal dummy variables and the other using seasonally adjusted variables.

3.2. Testing for Time-Series Properties and Structural Change

Since both static and dynamic specifications are estimated, the time-series properties of the data are examined prior to the empirical analysis. The share variables are first tested for unit roots. If all series are found to be integrated of order one, I(1), cointegration tests are then conducted. Given the assumed structural change after the fourth quarter of 2008, both the unit root and cointegration tests are implemented in models that allow for a single break. The unit root tests follow Vogelsang and Perron [42], and the following specification with one breakpoint is applied to each series.

$$y_t = \mu + \theta DU_t(T_b) + \omega D_t(T_b) + \alpha y_{t-1} + \sum_{i=1}^{k} c_i \Delta y_{t-i} + u_t \quad (7)$$

The variable $DU_t(T_b)$ is an intercept break dummy that takes the value of 0 prior to the break date, T_b, and 1 thereafter. The variable $D_t(T_b)$ is a one-time break dummy that equals 1 at the break date and 0 otherwise. This specification follows the framework proposed by Perron and Vogelsang [43,44], and Vogelsang and Perron [42]. Based on this setup, we implement the Dickey–Fuller test.

Cointegration with a single structural break is tested following Gregory–Hansen [45]. ADF-, Zα-, and Zt-type statistics are calculated to test the null of no cointegration against cointegration with a possible regime shift. The test allows for a single break of unknown timing in the intercept and slope coefficients and is more powerful than the conventional ADF test for detecting cointegration in the presence of a break. It extends the standard no-break model by considering three types of structural change: (1) level shift (C), (2) level shift with trend (C/T), and (3) regime shift (C/S).

Model 1. Level shift (C):

$$y_{1t} = \mu_1 + \mu_2 \varphi_{t\tau} + \alpha^T y_{2t} + e_t, \quad t = 1, \cdots, n, \quad (8)$$

Model 2. Level shift with trend (C/T):

$$y_{1t} = \mu_1 + \mu_2 \varphi_{t\tau} + \beta t + \alpha^T y_{2t} + e_t, \quad t = 1, \cdots, n, \quad (9)$$

Model 3. Regime shift (C/S):

$$y_{1t} = \mu_1 + \mu_2 \varphi_{t\tau} + \alpha_1^T y_{2t} + \alpha_2^T y_{2t} \varphi_{t\tau} + e_t, \quad t = 1, \cdots, n, \quad (10)$$

Here, $\varphi_{t\tau}$ is a dummy variable for structural change, taking the value of 0 for $t \leq [n\tau]$ and 1 otherwise. The unknown parameter, $\tau \in (0,1)$, denotes the relative timing of the change point, and [ ] indicates the integer part. μ and t denote the intercept and time trend, respectively. Gregory and Hansen [45] provide approximate asymptotic critical values for each model at different significance levels based on Monte Carlo experiments.

Using the methods described above, unit root and cointegration tests allowing for a single breakpoint were conducted. The results are reported in Tables 2 and 3.

The results of the breakpoint unit root tests suggest that all variables used in this study are non-stationary and integrated of order one, I(1). The share variables for primary energies are found to have a breakpoint between the fourth quarter of 2008 and the third quarter of 2009.

The Gregory–Hansen cointegration tests yield mixed results across types and models. In all types, the level-shift model indicates a cointegrating relationship among the primary energies, with estimated breakpoints between the second quarter of 2008 and the third quarter of 2009. Several other models also reject the null of no cointegration, but the estimated breakpoints are not consistent. Given the results of the breakpoint unit root tests, the cointegration analysis therefore relies on the level-shift specification, and the energy demand system is estimated using dynamic and error-corrected LA-AIDS models, distinguishing between the periods before and after the fourth quarter of 2008.

Table 2. Breakpoint unit root test results for input shares and prices.

Series	Level Series			First Differences		
	Test Statistics	***p*-Value**	**Breakpoint**	**Test Statistics**	***p*-Value**	**Breakpoint**
Shares of…						
Coal	−3.9674	0.1668	2009Q3	−10.4073	0.0000	2008Q4
Oil	−2.8599	0.7577	2014Q3	−9.2081	0.0076	2009Q1
Gas	−3.2499	0.5355	2010Q2	−5.8044	0.0086	2009Q3
Labor	−2.4186	0.9223	2017Q4	−10.9358	0.0102	2019Q1
Others	−3.1653	0.5875	2004Q3	−10.0355	0.0098	2009Q2
Log prices of…						
Coal	−4.0133	0.1524		−6.9629	0.0128	
Oil	−3.0518	0.6556		−9.7729	0.0022	
Gas	−3.6164	0.3224		−8.3919	0.0080	
Labor	−4.9104	0.0120		−7.1016	0.0092	
Others	−2.1215	0.9722		−9.2403	0.0102	
$\log\left(\frac{M}{P}\right)$	−4.6048	0.0325		−7.4274	0.0096	

Table 3. Gregory–Hansen cointegration test results.

ADF Type	Model 2: Level Shift (C)			Model 3: Level Shift with Trend (C/T)			Model 4: Regime Shift (C/S)		
Dependent	**Test Stat.**		**Break Date**	**Test Stat.**		**Break Date**	**Test Stat.**		**Break Date**
Share of…									
Coal	−5.83	**	2008Q2	−5.49		2012Q2	−13.02	***	2008Q4
Oil	−5.84	**	2008Q4	−4.55		2006Q2	−4.94		2008Q4
Gas	−1.79		2009Q2	−3.74		2016Q4	−5.91		2009Q1
Labor	−3.98		2012Q1	−3.98		2018Q1	−6.75	**	2018Q3
Others	−4.48		2018Q3	−4.43		2018Q3	−6.19	*	2016Q4
Z_α Type									
Share of…									
Coal	−61.00	**	2008Q4	−60.42	*	2009Q2	−73.06	*	2008Q4
Oil	−63.13	**	2009Q1	−55.33		2009Q1	−75.33	*	2008Q4
Gas	−55.24	*	2008Q4	−60.13	*	2008Q4	−79.60	**	2016Q4
Labor	−39.24		2006Q1	−51.33		2012Q1	−73.66	*	2014Q1
Others	−44.37		2006Q2	−41.24		2016Q2	−43.24		2016Q2
Z_t Type									
Share of…									
Coal	−5.53	*	2008Q2	−5.63	*	2014Q2	−6.64	**	2018Q2
Oil	−5.88	**	2009Q2	−5.71	*	2006Q2	−6.42	**	2006Q2
Gas	−4.52		2009Q3	−5.71	*	2008Q3	−3.66		2017Q2
Labor	−5.11		2008Q1	−3.33		2014Q1	−6.33	*	2018Q3
Others	−4.63		2012Q4	−4.63		2012Q4	−5.10	*	2017Q1

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

4. Estimation Results

The rationale for compensated elasticities is to hold output constant along the isoquant. Homogeneity, symmetry, and adding-up restrictions are imposed on both translog and AIDS models. Linear homogeneity or constant returns to scale requires $\sum_j \gamma_{ij} = 0$. Symmetry, due to Young's theorem, implies $\gamma_{ij} = \gamma_{ji}$. Input share equations sum to total cost, requiring the adding-up restriction, $\sum_i \beta_i = 1$ [18].

Most empirical applications of the AIDS adopt Zellner's [46] Seemingly Unrelated Regression (SUR) approach [32]. SUR is appropriate when equations have distinct dependent variables but contemporaneously correlated error terms. While each share equation may be estimated separately, joint estimation generally yields more efficient coefficient

estimates. As noted above, the homogeneity and symmetry restrictions are imposed during the SUR estimation. Because AIDS-type share systems satisfy adding-up by construction, the disturbance covariance matrix is typically singular, and the standard practice is to estimate the system after omitting one share equation and to recover the omitted equation using the adding-up restrictions [15,29,46]. This treatment is also consistent with applied LA-AIDS studies such as the one by Rathnayaka et al. [21] that estimate the system by SUR and explicitly note that singularity arises because the expenditure shares sum to unity. More generally, the use of constrained share-system estimation in factor-demand analysis is consistent with both the theoretical design literature on energy substitution in production [20] and empirical applications such as that of Thompson [18]. In addition, Wald tests indicate that the adding-up restriction could not be rejected. Detailed Wald test results for the Period-2 adding-up and homogeneity restrictions are reported in Appendix B Table A2.

4.1. Share Equation Estimates

Table 4 presents the estimation results. The share equations estimated under the LA-AIDS and Dynamic LA-AIDS produce more statistically significant coefficients compared to those from the error-corrected LA-AIDS. The period dummy variables were significant in many cases. The estimates from the static and the dynamic LA-AIDS model generally have the same sign, even with some differences in significance levels.

λ_i in the error-corrected LA-AIDS model is the error correction coefficient, which measures the adjustment of past disequilibrium in budget allocation toward long-run equilibrium.

The error-correction coefficient should be negative in models based on cointegration. The estimates show that the coefficient was negative for oil and labor in the earlier period, and only for labor in the later period. In all other cases, the coefficients were positive and did not yield meaningful estimates.

4.2. Information Inaccuracy

The preferred demand system is selected by applying information inaccuracy, a measure of goodness of fit, to each equation and to the overall model [21]. This metric quantifies the divergence between observed and predicted budget shares for each good and for the model as a whole.

$$I_{it} = \omega_{it} ln\left(\frac{\omega_{it}}{\widehat{\omega_{it}}}\right) + (1-\omega_{it}) ln\left(\frac{1-\omega_{it}}{1-\widehat{\omega_{it}}}\right) \tag{11}$$

$$I_t = \sum_{i=1}^{n} \omega_{it} ln\left(\frac{\omega_{it}}{\widehat{\omega_{it}}}\right) \tag{12}$$

Let $\omega_{1t}, \ldots, \omega_{nt}$ denote the observed budget shares at time t for n goods, and let $\widehat{\omega_{1t}}, \ldots, \widehat{\omega_{nt}}$ represent the corresponding predicted shares. The information inaccuracy for good i at time t, denoted I_{it}, and the overall model inaccuracy, I_t, are defined accordingly.

The information inaccuracy index measures the extent to which the predicted budget share ($\widehat{\omega_{it}}$) deviates from its observed value (ω_{it}). Both I_{it} and I_t are accuracy measures, and larger values indicate larger errors [21,47].

Table 5 reports the average information inaccuracy for each good, with the final row for each model summarizing the overall model inaccuracy. At the level of each component, the best-fit column indicates that the dynamic LA-AIDS model performs better than both the static LA-AIDS and error-corrected LA-AIDS specifications. On the basis of this goodness-of-fit measure, the dynamic LA-AIDS model is the preferred specification.

Table 4. Estimation results of share equations.

Parameter	LA-AIDS					Dynamic LA-AIDS					Error Corrected LA-AIDS				
	Coal	**Oil**	**Gas**	**Labor**	**Others**	**Coal**	**Oil**	**Gas**	**Labor**	**Others**	**Coal**	**Oil**	**Gas**	**Labor**	**Others**
α_i	−0.094	0.574	0.039	−0.741	1.224	−0.087	0.508	−0.057	0.361	0.276	0.196	0.202	0.201	0.195	0.195
	(0.044)	(0.128)	(0.101)	(0.233)	(0.285)	(0.034)	(0.113)	(0.108)	(0.155)	(0.227)	(0.007)	(0.003)	(0.008)	(0.005)	(0.005)
$d_{\alpha,i}$	0.104	−0.415	−0.099	0.676	0.258	0.119	−0.524	−0.105	0.038	0.533	−0.196	−0.202	−0.202	−0.194	−0.194
	(0.059)	(0.162)	(0.125)	(0.375)	(0.416)	(0.046)	(0.125)	(0.114)	(0.215)	(0.286)	(0.021)	(0.020)	(0.023)	(0.020)	(0.020)
$\gamma_{i,\ coal}$	0.003	0.000	0.005	−0.011	0.004	0.001	−0.003	0.004	−0.010	0.009	−0.074	−0.106	−0.128	−0.071	0.379
	(0.001)	(0.001)	(0.002)	(0.003)	(0.005)	(0.001)	(0.001)	(0.002)	(0.002)	(0.003)	(0.088)	(0.051)	(0.071)	(0.073)	(0.177)
$d_{i,coal}$	0.006	0.001	−0.005	0.002	−0.006	0.005	0.002	−0.004	0.007	−0.010	0.072	0.102	0.138	0.063	−0.346
	(0.001)	(0.002)	(0.002)	(0.005)	(0.007)	(0.002)	(0.002)	(0.002)	(0.004)	(0.005)	(0.117)	(0.078)	(0.097)	(0.102)	(0.648)
$\gamma_{i,\ oil}$	0.000	0.052	0.001	−0.006	−0.037	−0.003	0.039	−0.009	−0.002	−0.027	−0.106	−0.078	−0.138	−0.098	0.420
	(0.001)	(0.004)	(0.004)	(0.006)	(0.008)	(0.001)	(0.004)	(0.004)	(0.004)	(0.006)	(0.051)	(0.049)	(0.058)	(0.057)	(0.175)
$d_{i,oil}$	0.001	−0.005	0.006	−0.002	−0.012	0.002	−0.007	0.008	−0.002	−0.005	0.102	0.111	0.125	0.085	−0.353
	(0.002)	(0.005)	(0.004)	(0.008)	(0.009)	(0.002)	(0.004)	(0.004)	(0.005)	(0.007)	(0.078)	(0.078)	(0.085)	(0.085)	(0.634)
$\gamma_{i,\ gas}$	0.005	0.001	0.009	0.000	−0.022	0.004	−0.009	0.010	−0.002	−0.013	−0.128	−0.138	−0.134	−0.157	0.557
	(0.002)	(0.004)	(0.004)	(0.006)	(0.008)	(0.002)	(0.004)	(0.006)	(0.006)	(0.008)	(0.071)	(0.058)	(0.101)	(0.083)	(0.185)
$d_{i,gas}$	−0.005	0.006	0.008	0.007	0.007	−0.004	0.008	0.006	0.000	0.000	0.138	0.125	0.156	0.168	−0.462
	(0.002)	(0.004)	(0.005)	(0.008)	(0.010)	(0.002)	(0.004)	(0.005)	(0.005)	(0.007)	(0.097)	(0.085)	(0.127)	(0.108)	(0.703)
$\gamma_{i,\ labor}$	−0.011	−0.006	0.000	−0.044	0.076	−0.010	−0.002	−0.002	0.022	0.017	−0.071	−0.098	−0.157	−0.060	0.387
	(0.003)	(0.006)	(0.006)	(0.019)	(0.021)	(0.002)	(0.004)	(0.006)	(0.012)	(0.013)	(0.073)	(0.057)	(0.083)	(0.192)	(0.228)
$d_{i,labor}$	0.002	−0.002	0.007	0.141	−0.163	0.007	−0.002	0.000	0.046	−0.060	0.063	0.085	0.168	0.104	−0.470
	(0.005)	(0.008)	(0.008)	(0.041)	(0.043)	(0.004)	(0.005)	(0.005)	(0.023)	(0.027)	(0.102)	(0.085)	(0.108)	(0.266)	(0.677)
$\gamma_{i,\ others}$	0.003	−0.040	−0.015	0.061	−0.047	0.008	−0.026	−0.012	−0.008	0.014	0.379	0.420	0.557	0.387	0.364
	(0.004)	(0.008)	(0.007)	(0.020)	(0.023)	(0.003)	(0.006)	(0.007)	(0.220)	(0.015)	(0.177)	(0.175)	(0.185)	(0.228)	(0.212)
$d_{i,others}$	0.006	0.053	0.039	−0.096	0.003	−0.003	0.058	0.062	−0.017	−0.105	−0.346	−0.353	−0.462	−0.470	−0.328
	(0.007)	(0.018)	(0.014)	(0.044)	(0.047)	(0.005)	(0.013)	(0.012)	(0.025)	(0.032)	(0.648)	(0.634)	(0.703)	(0.677)	(0.680)
β_i	0.009	−0.045	−0.002	0.105	−0.051	0.015	−0.025	0.012	0.000	−0.002	−0.053	−0.036	0.185	−0.054	−0.042
	(0.004)	(0.011)	(0.009)	(0.020)	(0.027)	(0.003)	(0.009)	(0.009)	(0.012)	(0.018)	(0.245)	(0.165)	(0.301)	(0.294)	(0.225)
$d_{\beta,i}$	−0.013	0.015	−0.021	−0.087	0.090	−0.016	0.022	−0.019	−0.016	0.026	0.072	0.057	−0.113	−0.051	0.258
	(0.005)	(0.013)	(0.010)	(0.031)	(0.036)	(0.004)	(0.010)	(0.009)	(0.018)	(0.023)	(0.976)	(0.947)	(1.067)	(0.976)	(0.999)

Table 4. *Cont.*

Parameter	LA-AIDS					Dynamic LA-AIDS					Error Corrected LA-AIDS				
$\theta_{i,coal}$						0.316	0.409	0.110	0.012	−1.046					
						(0.068)	(0.206)	(0.188)	(0.224)	(0.370)					
$\theta_{i,oil}$						−0.019	0.370	0.102	−0.230	−0.088					
						(0.029)	(0.083)	(0.081)	(0.086)	(0.150)					
$\theta_{i,gas}$						−0.128	−0.388	−0.059	−0.033	0.683					
						(0.039)	(0.104)	(0.093)	(0.106)	(0.177)					
$\theta_{i,labor}$						−0.103	−0.259	−0.097	0.518	−0.085					
						(0.019)	(0.066)	(0.059)	(0.068)	(0.116)					
$\theta_{i,others}$						−0.067	−0.132	−0.055	−0.267	0.536					
						(0.015)	(0.048)	(0.044)	(0.050)	(0.083)					
λ_i											1.903	−0.245	1.193	0.403	−1.363
											(7.371)	(0.742)	(3.408)	(1.412)	(0.762)
$d_{\lambda,i}$											−3.574	−0.143	−1.941	−0.388	0.703
											(9.452)	(0.907)	(4.154)	(1.561)	(0.854)
	Coal	**Oil**	**Gas**	**Labor**	**Others**	**Coal**	**Oil**	**Gas**	**Labor**	**Others**	**Coal**	**Oil**	**Gas**	**Labor**	**Others**
ρ_i											−4.414	−0.036	−0.533	−0.709	0.356
											(7.557)	(0.800)	(3.066)	(2.038)	(0.674)
$d_{\rho,i}$											5.183	0.800	0.990	0.911	−0.662
											(8.539)	(0.990)	(3.380)	(2.354)	(0.809)
Adjusted R^2	0.894	0.901	0.747	0.839	0.928	0.931	0.950	0.777	0.959	0.946	0.661	0.304	0.532	0.407	0.749
Log-Likelihood					2016.360					2183.884					1446.156

Note: Standard error is in parentheses.

Table 5. Information inaccuracies, I_{it} and I_t.

Input	Demand Model			Best Fit
	Static LA-AIDS	Dynamic LA-AIDS	Error Corrected LA-AIDS	
Coal	0.0067	0.0045	0.7852	Dynamic LA-AIDS
Oil	0.0408	0.0192	0.6186	Dynamic LA-AIDS
Gas	0.0449	0.0371	0.7788	Dynamic LA-AIDS
Labor	0.0087	0.0021	0.3587	Dynamic LA-AIDS
Others	0.0018	0.0088	0.3782	Static LA-AIDS
Total (I_t)	**0.0966**	**0.0604**	**1.8199**	**Dynamic LA-AIDS**

To provide a more rounded comparison of model fit, supplementary goodness-of-fit measures are also reported. Specifically, Table 4 additionally presents equation-level adjusted R^2 values and the system-level log-likelihood for the Static, Dynamic, and Error-Corrected LA-AIDS specifications. These additional statistics are broadly consistent with the information-inaccuracy ranking. The Dynamic LA-AIDS shows the highest system-level log-likelihood and the most favorable equation-level adjusted R^2 values across the five share equations, while the Error-Corrected LA-AIDS performs least well overall. Information inaccuracy remains the primary model-selection criterion in this study, because it directly evaluates the divergence between observed and fitted budget shares within the constrained demand system. The additional fit statistics are therefore interpreted as complementary evidence, and together they reinforce the choice of the Dynamic LA-AIDS as the preferred specification.

For completeness, Appendix A reports a comparison of the baseline specification with two alternative seasonal specifications, one including seasonal dummy variables and the other using seasonally adjusted variables. These comparisons do not overturn the selection of the baseline Dynamic LA-AIDS as the preferred specification.

4.3. Price Elasticities of Energy Demand

The estimation of input demand systems is conducted under a constant-output (isoquant) assumption, focusing on input responses to price changes [18]. This study therefore reports compensated (Hicksian) elasticities, which measure input-demand responses to input-price variation under cost minimization with fixed output. In this framework, the purpose is to identify substitution and input reallocation across components conditional on output, rather than to estimate total input-demand responses that combine substitution and output effects. Uncompensated elasticities are therefore not reported in the present analysis.

Elasticity estimates, summarized in Table 6, cover two periods: 2000Q1–2008Q4 (Period 1) and 2009Q1–2021Q4 (Period 2). Economic theory predicts negative own-price elasticities and cross-price elasticities that are positive for substitutes and negative for complements, and the results generally conform to these expectations. Own-price elasticity of crude oil becomes more elastic in Period 2, whereas coal and natural gas become more inelastic.

Labor and "others" also show higher elasticities in the later period. For cross-price elasticities, oil shows weaker complementarity with coal and natural gas after 2008, while its relationship with "others" shifts from complementarity to substitution, consistent with reduced reliance on oil. Labor exhibits the largest cross-price response to oil in Period 2.

Table 6. Elasticities of each model.

	Model Dependent	LA	D	EC	LA	D	EC	LA	D	EC	LA	D	EC	LA	D	EC
Price	**Period**	**Coal**	**Coal**	**Coal**	**Oil**	**Oil**	**Oil**	**Gas**	**Gas**	**Gas**	**Labor**	**Labor**	**Labor**	**Others**	**Others**	**Others**
coal	1	−1.130	−0.993	−0.950	0.088	−0.499	−1.289	0.740	0.582	−1.314	−1.300	−1.067	−0.937	0.920	0.795	4.490
		(0.006)	(0.001)	(0.037)	(0.002)	(0.018)	(0.056)	(0.031)	(0.026)	(0.057)	(0.078)	(0.068)	(0.043)	(0.024)	(0.050)	(0.193)
	2	−0.109	−0.389	−0.015	0.148	−0.157	−0.026	0.033	−0.026	0.056	−0.393	−0.794	−0.138	1.292	0.663	0.209
		(0.037)	(0.027)	(0.003)	(0.002)	(0.003)	(0.001)	(0.001)	(0.001)	(0.002)	(0.036)	(0.014)	(0.004)	(0.039)	(0.044)	(0.010)
oil	1	0.013	−0.072	−0.185	−0.951	−0.024	−0.210	0.034	−0.221	−0.229	0.333	−0.508	−0.137	−0.590	−1.035	0.760
		(0.000)	(0.003)	(0.009)	(0.003)	(0.040)	(0.006)	(0.001)	(0.009)	(0.011)	(0.007)	(0.001)	(0.009)	(0.044)	(0.031)	(0.033)
	2	0.031	−0.033	−0.006	0.012	−0.398	0.003	0.159	−0.054	−0.010	0.331	−0.561	−0.063	0.545	0.238	0.110
		(0.001)	(0.001)	(0.000)	(0.052)	(0.040)	(0.005)	(0.007)	(0.001)	(0.000)	(0.008)	(0.006)	(0.001)	(0.010)	(0.035)	(0.008)
gas	1	0.442	0.348	−0.785	0.137	−0.914	−0.952	−0.166	−0.350	−0.920	0.503	−0.651	−0.880	−0.916	−0.677	3.538
		(0.028)	(0.024)	(0.051)	(0.004)	(0.055)	(0.063)	(0.053)	(0.041)	(0.054)	(0.001)	(0.011)	(0.061)	(0.086)	(0.018)	(0.229)
	2	0.020	−0.015	0.035	0.461	−0.155	−0.030	0.009	−0.076	0.046	0.953	−0.634	−0.018	1.080	0.158	0.296
		(0.000)	(0.000)	(0.002)	(0.022)	(0.004)	(0.001)	(0.057)	(0.045)	(0.008)	(0.028)	(0.009)	(0.002)	(0.159)	(0.138)	(0.020)
labor	1	−0.017	−0.029	−0.013	0.036	−0.052	−0.012	0.013	−0.017	−0.020	−0.619	−0.442	−0.067	0.586	−0.475	0.112
		(0.001)	(0.000)	(0.000)	(0.003)	(0.003)	(0.000)	(0.001)	(0.001)	(0.000)	(0.002)	(0.001)	(0.000)	(0.005)	(0.005)	(0.001)
	2	−0.007	−0.018	−0.003	0.040	−0.063	−0.007	0.035	−0.025	−0.001	−0.308	−1.356	−0.048	0.388	−0.471	−0.054
		(0.000)	(0.000)	(0.000)	(0.003)	(0.003)	(0.000)	(0.001)	(0.001)	(0.000)	(0.001)	(0.003)	(0.000)	(0.003)	(0.003)	(0.000)
others	1	0.016	0.014	−0.010	−0.019	−0.110	−0.018	−0.080	−0.043	−0.033	0.641	−0.435	0.046	−0.646	−0.526	0.016
		(0.001)	(0.000)	(0.000)	(0.002)	(0.003)	(0.000)	(0.001)	(0.001)	(0.000)	(0.003)	(0.001)	(0.000)	(0.006)	(0.005)	(0.000)
	2	0.006	−0.011	−0.004	−0.046	−0.134	−0.017	−0.064	−0.054	−0.014	0.286	−0.596	−0.047	−0.687	−1.637	−0.039
		(0.000)	(0.000)	(0.000)	(0.002)	(0.003)	(0.000)	(0.001)	(0.001)	(0.000)	(0.003)	(0.002)	(0.000)	(0.004)	(0.001)	(0.000)

Note: Standard errors are in parentheses.

Coal and natural gas show a marked weakening of substitution over time, with only suggestive evidence of complementarity in Period 2. Their cross-price elasticity is positive in Period 1 but becomes negative in Period 2. Labor and the "others" component generally become more price elastic over time, except in their relationship with coal. Overall, oil demand becomes more price responsive over time. Substitution among the primary energies takes place less, while substitution toward the "others" component strengthens.

4.4. Robustness

To assess the stability of the main findings, additional robustness checks are conducted along two dimensions. First, the preferred dynamic LA-AIDS specification is re-estimated using alternative Stone-type price indices. Second, the sensitivity of the results to the choice of structural-break date is examined by comparing the baseline periodization with nearby alternative breakpoints. These checks are intended to assess whether the main elasticity patterns are preserved under reasonable modifications of the baseline specification and to clarify which interpretations can be made with greater or lesser confidence.

As a first robustness check, the preferred dynamic LA-AIDS specification was re-estimated using two alternative Stone-type price indices in addition to the baseline contemporaneous-share Stone index: a fixed-share Stone index based on average budget shares and a lagged-share Stone index based on one-period-lagged budget shares. These alternatives reduce the dependence of the aggregate price index on contemporaneous budget shares and provide a useful check on whether the main elasticity patterns are sensitive to the construction of the price index. Table 7 shows that the main oil-related findings remain broadly similar across the three price-index specifications. In particular, crude oil becomes more own-price elastic in Period 2 under all three constructions, and the oil–others relationship changes from complementarity in Period 1 to substitution in Period 2 in every case. By contrast, the coal–gas relationship appears less stable across specifications. Under the contemporaneous-share and fixed-share Stone indices, the Period 2 cross-price elasticity remains close to zero, whereas under the lagged-share Stone index, it becomes slightly negative. Taken together, these results suggest that the coal–gas relationship is more consistent with a weakening of substitution over time than with a clearly robust shift to complementarity. Overall, the robustness check suggests that the main oil-related results do not appear to depend materially on the specific choice of Stone-type price index, whereas the coal–gas result should be interpreted more cautiously.

Table 7. Robustness of key compensated elasticities to alternative Stone price indices.

Elasticity	Period	Baseline	Fixed-Share	Lagged-Share
Crude oil own-price	Period 1	−0.024	−0.025	−0.012
Crude oil own-price	Period 2	−0.398	−0.400	−0.381
Oil–others cross-price	Period 1	−1.035	−0.605	−3.535
Oil–others cross-price	Period 2	0.238	0.240	0.238
Coal–gas cross-price	Period 1	0.582	0.578	0.671
Coal–gas cross-price	Period 2	−0.026	−0.030	0.002

As a second robustness check, the preferred dynamic LA-AIDS specification was re-estimated using nearby alternative break dates, namely 2008Q4 and 2009Q2, in addition to the baseline periodization at 2009Q1. For comparability with the first robustness exercise, the corresponding compensated elasticities were evaluated at period-average shares. As reported in Table 8, the main oil-related findings again remain broadly similar across the alternative breakpoint choices. In particular, crude oil becomes substantially more own-price elastic in Period 2 under all three breakpoint specifications, and the oil–others relationship consistently changes from complementarity in Period 1 to substitution in

Period 2. By contrast, the coal–gas relationship is more sensitive to the exact breakpoint choice. The baseline estimates are consistent with a sign change, but the alternative specifications do not support that pattern uniformly. The more cautious interpretation is therefore that substitution between coal and natural gas weakens markedly over time, while the possibility of a shift toward complementarity in the later period should be regarded as suggestive rather than definitive. Taken together, the robustness checks indicate that the main conclusions concerning oil-price responsiveness and the expanding substitution role of the "others" component are relatively stable, whereas the coal–gas relationship should be interpreted with greater caution.

Table 8. Robustness of the main compensated elasticity results to nearby alternative breakpoint.

Elasticity	Period	Baseline	2008Q4	2009Q2
Crude oil own-price	Period 1	−0.024	−0.046	−0.012
Crude oil own-price	Period 2	−0.398	−0.402	−0.466
Oil–others cross-price	Period 1	−1.035	−2.148	−2.519
Oil–others cross-price	Period 2	0.238	0.235	0.264
Coal–gas cross-price	Period 1	0.582	−0.065	0.601
Coal–gas cross-price	Period 2	−0.026	−0.128	0.033

5. Discussion

This study estimates a primary energy input demand system for Korea using the LA-AIDS framework and examines how price responsiveness and substitution relationships differ before and after the global financial crisis. The findings underscore that elasticity-based policy inferences can change materially when structural change is explicitly taken into account.

The post-break increase in crude-oil price responsiveness suggests that the effective scope for adjustment widened in the later period, potentially reflecting changes in technology adoption, sourcing, and the cost structure faced by energy users. As a result, price-based instruments targeting oil use may induce larger demand-side adjustments in the later period than would be implied by pre-break elasticities.

In contrast, coal and natural gas exhibit weaker own-price responsiveness in the later period, and their relationship is more consistent with a marked weakening of substitution, with only suggestive evidence of complementarity. In the Korean context, this pattern is consistent with the fact that coal demand is concentrated mainly in power generation, with smaller but still policy-relevant uses in briquettes and metallurgical processes, while natural gas demand is tied not only to LNG-fired generation but also to city-gas use, industrial heat demand, and petrochemical feedstock use. Because these uses depend on fuel-specific boilers, turbines, furnaces, pipeline and LNG infrastructure, and medium- to long-term procurement arrangements, short-run substitution between coal and gas can remain limited even when relative prices change. This implies that price instruments may work better when complemented by non-price measures that relax these adjustment constraints, including stricter efficiency standards for coal- and gas-using equipment and buildings; accelerated retirement or retrofit of inefficient coal-using facilities; support for electrification or fuel conversion in residential and industrial applications where technically feasible; targeted replacement support for residual briquette use; and investment in LNG receiving, storage, and regasification facilities, as well as in gas pipeline networks, and grid and storage infrastructure, that widens the margin for substitution away from coal and oil. More broadly, recent evidence suggests that efficiency-improving investment, resource reallocation, and innovation can widen non-price adjustment channels alongside relative-price signals [48].

The results indicate that crude oil became more price-elastic in Period 2 (2009Q1–2021Q4), while the transmission of oil-price changes to other primary energies weakened. Oil's own-price elasticity increased in absolute value, indicating stronger responsiveness, whereas its cross-price elasticities with coal and natural gas moved toward zero, reflecting weaker complementarity. The "others" component shows the largest change, as its cross-price elasticity with respect to oil shifted from −1.035 in Period 1 to 0.238 in Period 2, implying a transition from complementarity to substitution.

In Korea, crude oil is mainly used, after refining, as fuel or feedstock. The share of oil-fired power generation in total electricity output declined from 9.2% in 1999 to 6.1% in 2009 and 0.9% in 2020 [3,49]. The "others" component may include electricity from renewable sources, battery-powered equipment and transport, electrically driven industrial machinery, and imported petrochemical products. Changes in production technologies in Asian economies and the expansion of regional trade may have widened the scope for replacing crude-oil-based domestic production with imports, suggesting that the "others" component has become a closer substitute for crude oil in the later period.

This interpretation does not imply that the average share of "others" increased in Period 2. Rather, although its mean share declined, the elasticity estimates and the scenario results in Tables 7 and 8 could be consistent with the possibility that the residual non-primary energy margin became a more relevant adjustment channel in the later period. This possibility appears most clearly in relation to crude oil, but it may also apply, to a lesser extent, to natural gas, whose own-price responsiveness weakens in the later period.

For coal and natural gas, own-price elasticities became less elastic in the second period, while their cross-price elasticity suggests a marked weakening of substitution over time, with only limited evidence of complementarity in the second period. These results are consistent with policy shifts: during the first period, coal and natural gas were treated as alternative fuels for power generation, but after the 2011 Fukushima accident, LNG gained preference due to lower environmental and safety risks, while coal faced stricter regulation for its emissions. Over this period, coal's role in base-load generation declined, and LNG expanded in peak-load operation. Their shares in power generation changed from 44.6% and 15.1% in 2009 to 32.5% and 27.5% in 2022, respectively. The share of refined petroleum products in power generation also fell from 3.2% in 2009 to 0.3% in 2022 [3,49,50]. These shifts indicate a reduced sensitivity of coal and natural gas demand to oil prices over time.

Elasticities describe marginal responses, but their economic magnitude can be hard to gauge. To give a tangible sense of size, Tables 9 and 10 report implied percentage changes in conditional input demands under a 10 percent increase in import prices, using the compensated elasticities from the preferred Dynamic LA-AIDS model in Table 6.

Table 9 focuses on a 10 percent increase in the crude-oil import price. The results show a clear change across periods. In Period 1, the implied response of others is strongly negative, whereas in Period 2, it becomes positive, consistent with greater scope to shift cost away from crude oil when crude oil becomes more expensive.

Because primary energy prices in the international market often move together, Table 10 reports the implied changes when the import prices of coal, crude oil, and natural gas rise simultaneously by 10 percent. This calculation incorporates cross-price effects across the three primary energies. The sign change for "others" remains visible, which motivates a closer discussion of what the category "others" captures in Korea and how substitution opportunities may have expanded over time.

Several limitations merit consideration. First, the analysis focuses on conditional input demands at the primary energy stage and does not directly model heterogeneity across end-use sectors. Second, the "others" category aggregates diverse components and should be interpreted as a composite adjustment margin rather than a single technology. Third,

the quarterly labor share is constructed from annual employee-compensation data because no observed quarterly compensation series covering the full sample was available. Since the true quarterly path is unobserved, the direction and magnitude of any effect on the estimated labor dynamics cannot be determined directly, and labor-related dynamics in the dynamic specification should therefore be interpreted with caution. Future work could disaggregate "others," examine sector-specific systems, and further assess the sensitivity of the results to alternative break dates and additional robustness checks.

Table 9. Implied % changes in input demands under a 10% increase in the crude-oil import price.

Period Input	Period 1 (2000Q1–2008Q4)	Period 2 (2009Q1–2021Q4)
Coal	−0.69	−0.31
Crude oil	−0.23	−3.79
Natural gas	−2.11	−0.51
Labor	−4.84	−5.35
Others	−9.86	2.27

Table 10. Implied % changes in input demands under a 10% increase in the import prices of three primary energies.

Period Input	Period 1 (2000Q1–2008Q4)	Period 2 (2009Q1–2021Q4)
Coal	−6.84	−4.17
Crude oil	−13.70	−6.77
Natural gas	0.10	−1.49
Labor	−30.75	−18.96
Others	−8.74	10.09

6. Conclusions

This study estimates a primary energy input-demand system for Korea using quarterly data from 2000 to 2021. The system covers coal, crude oil, and natural gas, together with labor and others, where "others" is defined as the residual cost component after accounting for the three primary energies and labor. Breakpoint unit-root and cointegration evidence supports structural change around the global financial crisis, and the Dynamic LA-AIDS specification is selected as the preferred model based on its fit to observed cost shares.

The results indicate meaningful differences across the two periods. Crude oil becomes more price responsive after the break, while its cross-price elasticities with coal and natural gas move closer to zero, indicating weaker complementarity. Coal and natural gas become less responsive to their own prices over time, and their relationship is more consistent with a weakening of substitution from Period 1 to Period 2, with only suggestive evidence of complementarity in the later period. The largest change is observed in the relationship between crude oil and others, as the cross-price elasticity with respect to crude oil turns from negative in Period 1 to positive in Period 2, suggesting expanded scope to reallocate costs away from crude oil in the later period.

Tables 9 and 10 make the magnitude of these changes easier to interpret by reporting implied percentage adjustments in conditional input demands under common price-change scenarios. Under a 10 percent increase in the crude-oil import price, crude-oil demand contracts much more in Period 2, and the response of others switches from a contraction to an expansion.

These findings have direct implications for an import-dependent economy exposed to international price movements. First, policy evaluation based on a single set of elasticities can be misleading when substitution possibilities change over time. Second, limited own-price responsiveness for coal and natural gas suggests that price instruments in Korea are

likely to work better when complemented by non-price measures tailored to their main end uses, including stricter efficiency standards for coal- and gas-using facilities; support for equipment conversion and electrification; targeted replacement of residual coal briquette use; and continued investment in LNG, pipeline, grid, and storage infrastructure. Third, the higher price responsiveness of crude oil in the later period implies that price-based measures can induce larger reallocations where substitution channels are available, including adjustments captured by others through electrification, imported intermediates, and changes in sourcing.

The analysis also points to priorities for future work. Because the category "others" aggregates diverse items, further disaggregation would help identify the most important channels behind the stronger substitution with crude oil in the later period. Extensions that allow more flexible parameter movement over time may also be informative, but the period comparison used here provides a disciplined and interpretable way to reflect structural change while maintaining the theoretical restrictions required by a demand system.

Author Contributions: Conceptualization, J.-W.K. and Y.-K.K.; methodology, J.-W.K.; formal analysis, J.-W.K.; data curation, J.-W.K.; writing—original draft preparation, J.-W.K.; writing—review and editing, Y.-K.K.; supervision, Y.-K.K.; project administration, Y.-K.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Basic Research Project of the Korea Institute of Geoscience and Mineral Resources (KIGAM; Project No. GP2025-002).

Data Availability Statement: The raw data used in this study are publicly available from the sources cited in the References, including KEEI/KESIS energy statistics, international energy databases, and macroeconomic statistics. The constructed quarterly dataset and the code used to estimate the LA-AIDS specifications and compute the reported elasticities are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Comparison of Baseline and Alternative Seasonal Specifications

As part of the specification-selection process, two alternative seasonal specifications were also considered: one including seasonal dummy variables and another using seasonally adjusted variables. These alternatives were compared with the baseline specification based on unadjusted quarterly data.

The comparison indicates that the alternative seasonal specifications improve some in-sample fit measures, but they do not provide a more suitable basis for the preferred specification when considered together with coefficient stability and the break-based time-series evidence reported in Section 3. In particular, the seasonal-dummy specification yields stronger equation-level fit, whereas the seasonally adjusted-variable specification produces more mixed breakpoint unit-root and Gregory–Hansen evidence. On balance, the baseline specification remains the most suitable specification for elasticity estimation in the present study.

Table A1. Comparison of baseline and alternative seasonal specifications.

Specification	Baseline	Alternative 1	Alternative 2
Seasonal Specification	**Unadjusted**	**Seasonal Dummies Included**	**Seasonally Adjusted Variables**
System log-likelihood	2183.8	2271.8	2174.4
Range of adjusted R^2	0.777–0.959	0.910–0.969	0.898–0.967
Significant common coefficients	35/71	30/71	33/71
Significant shift coefficients	12/29	8/29	9/29

Table A1. *Cont.*

Specification	Baseline	Alternative 1	Alternative 2
Seasonal Specification	**Unadjusted**	**Seasonal Dummies Included**	**Seasonally Adjusted Variables**
Breakpoint unit-root evidence	All variables treated as I(1); breakpoints concentrated around 2008Q4–2009Q3	Same underlying raw series as baseline	More mixed integration-order and breakpoint evidence
Gregory–Hansen evidence	Level-shift specification provides the most consistent evidence	Same underlying raw series as baseline	More mixed and less consistent than baseline

Note: The seasonal-dummy specification uses the same underlying unadjusted series as the baseline, so the breakpoint unit-root and Gregory–Hansen evidence is unchanged at the data level. The seasonally adjusted-variable specification was additionally examined using breakpoint unit-root and Gregory–Hansen tests, which yielded more mixed results than the baseline. The seasonally adjusted-variable specification contains one fewer observation because its effective estimation sample begins one quarter later.

Appendix B. Wald Tests for Period-2 Theoretical Restrictions

As noted in the main text, the dynamic LA-AIDS system is estimated under theoretical restrictions. For Period 1, the regularity conditions are imposed directly in the model specification, so separate Wald tests are not informative because the corresponding restrictions hold by construction. Likewise, symmetry is imposed for both periods in the estimation, and therefore a separate Wald test for symmetry is not meaningful in the present specification.

Table A2. Individual Wald test results for Period-2 adding-up and homogeneity restrictions.

Category	Restriction	χ^2 Statistic	*p*-Value	Inference
Adding-up (Period 2)	Intercept shift	0.2023	0.6528	Not rejected
	Coal price column	0.0289	0.8650	Not rejected
	Oil price column	0.7844	0.3758	Not rejected
	Gas price column	2.6254	0.1328	Not rejected
	Labor price column	0.3549	0.5513	Not rejected
	Others price column	0.0039	0.9501	Not rejected
	Output term	0.1240	0.7247	Not rejected
	Lagged coal share	2.4668	0.1163	Not rejected
	Lagged oil share	3.5517	0.0595	Not rejected
	Lagged gas share	0.4533	0.5008	Not rejected
	Lagged labor share	0.8651	0.3523	Not rejected
	Lagged others share	0.3117	0.5766	Not rejected
Homogeneity (Period 2)	Coal equation	0.8073	0.3689	Not rejected
	Oil equation	2.2180	0.1364	Not rejected
	Gas equation	3.5116	0.0609	Not rejected
	Labor equation	1.5746	0.2095	Not rejected
	Others equation	3.1650	0.0752	Not rejected

Note: This table reports individual Wald tests for the Period-2 adding-up and homogeneity restrictions in the estimated dynamic LA-AIDS system. Period-1 restrictions are imposed by construction and therefore are not separately tested. Symmetry is imposed in both periods and is likewise not reported as a separate Wald test. The null hypothesis in each reported test is that the corresponding restriction holds.

For this reason, the Wald tests reported here focus only on the Period-2 restrictions that remain empirically informative in the presence of the structural-shift specification. Specifically, individual Wald tests are conducted for the Period-2 adding-up and homogeneity restrictions. The null hypothesis in each case is that the corresponding restriction holds. As reported in Appendix B Table A2, none of the tested Period-2 restrictions is rejected at conventional significance levels. These results provide additional support for the internal consistency of the estimated demand system in the post-break regime.

Appendix C. Robustness to Alternative Quarterly Labor-Compensation Constructions

As an additional robustness check, the preferred Dynamic LA-AIDS specification was re-estimated using alternative quarterly labor-compensation series in place of the baseline equal-allocation construction. Two alternatives were constructed using Chow–Lin temporal disaggregation, which derives higher-frequency series from lower-frequency benchmarks using related indicators [51]. In CL_1, quarterly labor compensation is constructed using quarterly employment only. In CL_2, it is constructed using a quarterly payroll-like indicator given by employment multiplied by the labor wage index. In both cases, annual employee compensation is retained as the benchmark.

A further alternative, SPL_1, was constructed using a simple spline-based interpolation. Specifically, a shape-preserving cubic spline was applied to the cumulative annual employee-compensation series, and quarterly values were recovered by first differencing the interpolated cumulative path. This provides a benchmark-preserving mechanical alternative to the indicator-based Chow–Lin constructions [52,53].

Table A3 reports the fit comparison across the baseline and alternative specifications, and Table A4 reports the corresponding key compensated elasticities. The results show that CL_1 yields the weakest fit, mainly because the labor-share equation fit deteriorates substantially. By contrast, CL_2 and SPL_1 remain closer to the baseline in overall fit. The elasticity comparison indicates that the main post-break oil-related findings remain broadly stable across the alternative quarterly labor constructions; however, some pre-break cross-price relationships are more sensitive and should be interpreted with caution.

Table A3. Comparison of baseline and alternative quarterly labor-compensation constructions.

Specification	Baseline	CL_1	CL_2	SPL
Quarterly labor-compensation construction	Annual employee compensation allocated equally across four quarters	Chow–Lin disaggregation using quarterly employment only	Chow–Lin disaggregation using quarterly employment × labor wage index	Annual-sum-preserving cumulative spline interpolation
System log-likelihood	2183.8	1870.9	1973.1	2087.3
Range of adjusted R^2	0.777–0.959	0.178–0.953	0.809–0.955	0.808–0.960
Significant common coefficients	35/71	16/71	40/71	37/71
Significant shift coefficients	12/29	6/29	17/29	15/29

Table A4. Robustness of key compensated elasticities to alternative labor compensations.

Elasticity	Period	Baseline	CL_1	CL_2	SPL
Crude oil own-price	Period 1	−0.024	0.014	−0.046	0.005
Crude oil own-price	Period 2	−0.398	−0.287	−0.333	−0.337
Oil–others cross-price	Period 1	−1.035	0.021	−0.181	−0.436
Oil–others cross-price	Period 2	0.238	1.011	0.972	0.613
Coal–gas cross-price	Period 1	0.582	0.613	0.929	0.907
Coal–gas cross-price	Period 2	−0.026	0.086	0.176	0.053

Appendix D. Robustness to Exclusion of the COVID-19 Pandemic Period

As noted in the main text, the baseline specification of this study is defined over the full quarterly sample from 2000 to 2021 and is organized around a break-based two-period structure. Within that empirical framework, this appendix reports an additional sample-sensitivity check to examine whether the main elasticity patterns are disproportionately influenced by the COVID-19 pandemic period. For this purpose, results based on the

baseline specification are compared with those obtained from a sample ending in 2019Q4, while preserving the same break-based periodization and system restrictions.

Consistent with the baseline empirical framework described in the main text, Table A5 compares the overall fit of the baseline specification with that of the corresponding specification using data through 2019Q4.

Table A5. Comparison of baseline and COVID-excluded specifications.

Specification	Baseline	Excluding 2020Q1–2021Q4
Sample period for Period 2	2009Q1–2021Q4	2009Q1–2019Q4
System log-likelihood	2183.8	1999.9
Range of adjusted R^2	0.777–0.959	0.792–0.950

Note: The comparison is intended as a supplementary sample-sensitivity check within the baseline empirical framework. The same break-based periodization and system restrictions are maintained in both specifications.

Within the same comparison, Table A6 reports the corresponding key compensated elasticities in order to assess whether the main post-break elasticity patterns are materially altered when the COVID-19 pandemic period is excluded.

The comparison between the baseline and the 2000–2019 specification indicates that the main post-break oil-related findings remain broadly stable. In particular, crude oil continues to appear more own-price elastic in the later period, and the oil–others relationship in the later period remains consistent with substitution rather than complementarity. By contrast, the coal–gas relationship remains more sensitive to sample choice and should therefore continue to be interpreted with caution.

Table A6. Robustness of key compensated elasticities to exclusion of the COVID-19 pandemic period.

Elasticity	Period	Baseline	Excluding 2020Q1–2021Q4
Crude oil own-price	Period 1	−0.024	−0.035
Crude oil own-price	Period 2	−0.398	−0.357
Oil–others cross-price	Period 1	−1.035	−1.024
Oil–others cross-price	Period 2	0.238	0.208
Coal–gas cross-price	Period 1	0.582	0.473
Coal–gas cross-price	Period 2	−0.026	−0.030

Note: The baseline specification uses the full quarterly sample through 2021, whereas the comparison specification excludes the COVID-19 pandemic period (2020Q1–2021Q4). The table is reported to assess the sensitivity of the main post-break elasticity patterns to this exclusion.

References

1. Hamilton, J.D. Causes and consequences of the oil shock of 2007–08. *Brook. Pap. Econ. Act.* **2009**, *40*, 215–283. [CrossRef]
2. Kilian, L. Not all oil price shocks are alike: Disentangling demand and supply shocks in the crude oil market. *Am. Econ. Rev.* **2009**, *99*, 1053–1069. [CrossRef]
3. Korea Energy Economics Institute (KEEI). Yearbook of Energy Statistics. Available online: https://kesis.keei.re.kr/ (accessed on 3 March 2025).
4. U.S. Energy Information Administration (EIA). Country Analysis Brief: South Korea. Available online: https://www.eia.gov/international/content/analysis/countries_long/South_Korea/south_korea.pdf (accessed on 3 March 2025).
5. International Energy Agency (IEA). Korea: Energy Mix. Available online: https://www.iea.org/countries/korea/energy-mix (accessed on 29 November 2024).
6. Labandeira, X.; Labeaga, J.M.; López-Otero, X. A meta-analysis on the price elasticity of energy demand. *Energy Policy* **2017**, *102*, 549–568. [CrossRef]
7. Liddle, B.; Parker, S.; Hasanov, F. Is timing everything? Assessing the evidence on whether energy/electricity demand elasticities are time-varying. *Energy Econ.* **2023**, *124*, 106872. [CrossRef]
8. Lee, J.; Cho, H.C. Impact of structural oil price shock factors on the gasoline market and macroeconomy in South Korea. *Sustainability* **2021**, *13*, 2209. [CrossRef]

9. Kim, J.W.; Kim, Y.K. Estimation of primary energy demand in Korea using the demand system model. *Korea Energy Econ. Rev.* **2024**, *23*, 125–147. (In Korean)
10. Dahl, C.A. Measuring global gasoline and diesel price and income elasticities. *Energy Policy* **2012**, *41*, 2–13. [CrossRef]
11. Chang, Y.; Kim, C.S.; Miller, J.I.; Park, J.Y.; Park, S. Time-varying long-run income and output elasticities of electricity demand with an application to Korea. *Energy Econ.* **2014**, *46*, 334–347. [CrossRef]
12. Ozturk, I.; Arisoy, I. An estimation of crude oil import demand in Turkey: Evidence from time-varying parameters approach. *Energy Policy* **2016**, *99*, 174–179. [CrossRef]
13. Arisoy, I.; Ozturk, I. Estimating industrial and residential electricity demand in Turkey: A time varying parameter approach. *Energy* **2014**, *66*, 959–964. [CrossRef]
14. Liddle, B.; Hasanov, F. Are the income and price elasticities of economy-wide electricity demand in middle-income countries time-varying? Evidence from panels and individual countries. *Environ. Ecol. Stat.* **2023**, *30*, 827–849. [CrossRef]
15. Deaton, A.D.; Muellbauer, J. An almost ideal demand system. *Am. Econ. Rev.* **1980**, *70*, 312–326.
16. Weng, W.; Mount, T.D. *Demand Systems for Energy Forecasting: Practical Considerations for Estimating a Generalized Logit Model*; Working Paper 97-02; Department of Agricultural, Resource, and Managerial Economics, Cornell University: Ithaca, NY, USA, 1997; pp. 1–27.
17. Hilmer, C.E.; Holt, M.T. The almost ideal supply system and agricultural production in the United States. In Proceedings of the 1999 Annual Meeting, American Agricultural Economics Association, Nashville, TN, USA, 8–11 August 1999.
18. Thompson, A. An almost ideal supply system estimate of US energy substitution. *Energy Econ.* **2013**, *40*, 813–818. [CrossRef]
19. Dissou, Y.; Ghazal, R. *Energy Substitutability in Canadian Manufacturing: Econometric Estimation with Bootstrap Confidence Intervals*; Working Paper No. 0809E; University of Ottawa: Ottawa, ON, Canada, 2008.
20. Thompson, H. The applied theory of energy substitution in production. *Energy Econ.* **2006**, *28*, 410–425. [CrossRef]
21. Rathnayaka, S.D.; Selvanathan, E.A.; Kler, P. Modelling Sri Lankan consumption patterns using error corrected LA-AIDS. *Econ. Model.* **2019**, *80*, 185–191. [CrossRef]
22. Eakins, J.M.; Gallagher, L.A. Dynamic almost ideal demand systems: An empirical analysis of alcohol expenditure in Ireland. *Appl. Econ.* **2003**, *35*, 1025–1036. [CrossRef]
23. Selvanathan, S.; Jayasinghe, M.; Selvanathan, E.A.; Rathnayaka, S.D. Dynamic modelling of consumption patterns using LA-AIDS: A comparative study of developed versus developing countries. *Empir. Econ.* **2024**, *66*, 75–135. [CrossRef]
24. Karagiannis, G.; Velentzas, K. Explaining food consumption patterns in Greece. *J. Agric. Econ.* **1997**, *48*, 83–92. [CrossRef]
25. Anderson, G.; Blundell, R. Testing restrictions in a flexible dynamic demand system: An application to consumers' expenditure in Canada. *Rev. Econ. Stud.* **1983**, *50*, 397–410. [CrossRef]
26. Blanciforti, L.; Green, R. An almost ideal demand system incorporating habits: An analysis of expenditures on food and aggregate commodity groups. *Rev. Econ. Stat.* **1983**, *65*, 511–515. [CrossRef]
27. Holt, M.T.; Goodwin, B.K. *The Almost Ideal and Translog Demand Systems*; MPRA Paper No. 15092; University Library of Munich: Munich, Germany, 2009. Available online: https://mpra.ub.uni-muenchen.de/15092/ (accessed on 3 March 2026).
28. Lecocq, S.; Robin, J.-M. Estimating almost-ideal demand systems with endogenous regressors. *Stata J.* **2015**, *15*, 554–573. [CrossRef]
29. Poi, B.P. Easy demand-system estimation with QUAIDS. *Stata J.* **2012**, *12*, 433–446. [CrossRef]
30. Kesavan, T.; Hassan, Z.A.; Jensen, H.H.; Johnson, S.R. Dynamics and long-run structure in US meat demand. *Can. J. Agric. Econ.* **1993**, *41*, 139–153. [CrossRef]
31. Alessie, R.; Kapteyn, A. Habit formation, interdependent preferences and demographic effects in the almost ideal demand system. *Econ. J.* **1991**, *101*, 404–419. [CrossRef]
32. Forgenie, D.; Khoiriyah, N.; Mahase-Forgenie, M.; Adeleye, B.N. An error-corrected linear approximate almost ideal demand system model for imported meats and seafood in Indonesia. *Heliyon* **2023**, *9*, e21390. [CrossRef]
33. Nzuma, J.M.; Sarker, R. An error corrected almost ideal demand system for major cereals in Kenya. *Agric. Econ.* **2010**, *41*, 43–50. [CrossRef]
34. Karagiannis, G.; Katranidis, S.; Velentzas, K. An error correction almost ideal demand system for meat in Greece. *Agric. Econ.* **2000**, *22*, 29–35. [CrossRef]
35. Mokyr, J. Technological inertia in economic history. *J. Econ. Hist.* **1992**, *52*, 325–338. [CrossRef]
36. Unruh, G.C. Understanding carbon lock-in. *Energy Policy* **2000**, *28*, 817–830. [CrossRef]
37. Pellet, T.; Tahbaz-Salehi, A. Rigid production networks. *J. Monet. Econ.* **2023**, *137*, 86–102. [CrossRef]
38. Attinasi, M.-G.; Boeckelmann, L.; Meunier, B. The Economic Costs of Supply Chain Decoupling. ECB Working Paper No. 2839. 2023. Available online: https://ssrn.com/abstract=4532103 (accessed on 3 March 2026).
39. Jin, I. Analysis of Structural Changes in the Korean Economy and Sustainable Growth. *J. Budget Policy* **2020**, *9*, 93–130. (In Korean) [CrossRef]

40. Lee, J. *The Republic of Korea's Economic Growth and Catch-Up: Implications for the People's Republic of China*; ADBI Working Paper No. 571; Asian Development Bank Institute: Tokyo, Japan, 2016. Available online: http://www.adb.org/publications/republic-korea-economic-growth-catch-up-implications-prc/ (accessed on 3 March 2026).
41. Pirie, I. A comparative analysis of the impact of the 1997 Asian crisis and the contemporary global economic crisis on the Korean political economy. *Contemp. Polit.* **2012**, *18*, 416–433. [CrossRef]
42. Vogelsang, T.J.; Perron, P. Additional tests for a unit root allowing for a break in the trend function at an unknown time. *Int. Econ. Rev.* **1998**, *39*, 1073–1100. [CrossRef]
43. Perron, P.; Vogelsang, T.J. Nonstationarity and level shifts with an application to purchasing power parity. *J. Bus. Econ. Stat.* **1992**, *10*, 301–320. [CrossRef]
44. Perron, P.; Vogelsang, T.J. Testing for a unit root in a time series with a changing mean: Corrections and extensions. *J. Bus. Econ. Stat.* **1992**, *10*, 467–470. [CrossRef]
45. Gregory, A.; Hansen, B. Residual-based tests for cointegration in models with regime shifts. *J. Econom.* **1996**, *70*, 321–335. [CrossRef]
46. Zellner, A. An efficient method of estimating seemingly unrelated regressions and tests for aggregation bias. *J. Am. Stat. Assoc.* **1962**, *57*, 348–368. [CrossRef]
47. Theil, H. *Theory and Measurement of Consumer Demand*; North-Holland: Amsterdam, The Netherlands, 1975.
48. Huang, J.; Xiang, Y.; Duan, X.; Du, M. Digital infrastructure construction and energy efficiency: A quasi-natural experiment with double machine learning. *Emerg. Mark. Financ. Trade* **2026**, *advance online publication*. [CrossRef]
49. United Nations. *Energy Statistics Yearbook 2023*; United Nations: New York, NY, USA, 2023. Available online: https://unstats.un.org/unsd/energystats/pubs/yearbook/ (accessed on 29 November 2024).
50. OECD. *Korea 2020: Energy Policy Review*; OECD Publishing: Paris, France, 2020. Available online: https://www.oecd.org/en/publications/korea-2020-energy-policy-review_2f15bd8f-en.html (accessed on 29 November 2024).
51. Chow, G.C.; Lin, A.-L. Best Linear Unbiased Interpolation, Distribution, and Extrapolation of Time Series by Related Series. *Rev. Econ. Stat.* **1971**, *53*, 372–375. [CrossRef]
52. de Boor, C. *A Practical Guide to Splines*; Springer: New York, NY, USA, 1978.
53. Fritsch, F.N.; Carlson, R.E. Monotone Piecewise Cubic Interpolation. *SIAM J. Numer. Anal.* **1980**, *17*, 238–246. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.