

## Where Does ASEAN+3 Stand on the Emissions–Development Relationship?<sup>1</sup>

May 25, 2026

*This note benchmarks where ASEAN+3 economies stand on the emissions–development relationship and discusses implications for medium-term growth. Econometric estimates using a STIRPAT framework suggest emissions are most strongly associated with income, population scale, and energy use, while EKC-based turning points should be interpreted as comparative benchmarks rather than country-specific thresholds. To synthesize cross-economy exposure and transition pressure, the note introduces a Composite Environment–Development Risk Index spanning emissions scale, emissions growth, EKC positioning, energy use per capita, and renewables shares. The results point to uneven vulnerabilities across the region.*

### I. Introduction

**1. Balancing development with decarbonization remains a central challenge for the ASEAN+3 region.** Over the past few decades, ASEAN+3's share of global emissions has increased at a faster pace than its share of global GDP. Figure 1 shows that the region's share of global emissions rose steadily from about 24 percent in the early 1990s to above 60 percent by the early 2020s, with particularly strong increases after the mid-2000s. Over the same period, the region's GDP share increased more modestly, from around 15 percent in 1990 to about 30 percent in 2024. This widening gap is consistent with emissions in ASEAN+3 rising faster than output on a production basis, and highlights the importance of understanding the drivers of emissions intensity in the region.

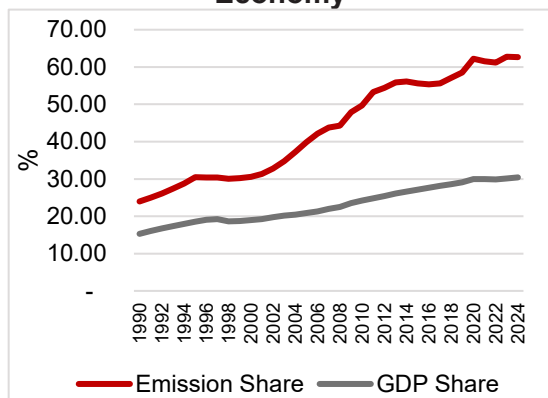
**2. A sectoral breakdown of emissions provides further insight into the drivers of this divergence.** Figure 2 shows that emissions in the region are dominated by the industry and energy sectors, which together account for around 80 percent of total emissions in the period. The combined share of these sectors rises notably from the mid-2000s, while transport and other sectors remain smaller contributors. This persistent concentration of emissions in carbon-intensive production and energy use suggests that sectoral composition has been an

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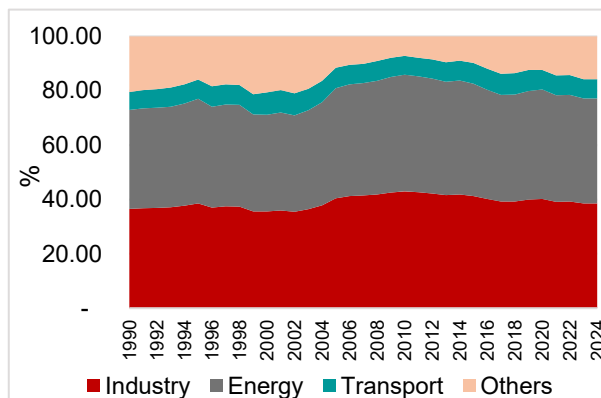
important correlate of emissions outcomes. As incomes rise and consumption patterns evolve, demand may gradually shift toward less emissions-intensive activities and support higher energy efficiency, but the pace and extent of improvement will depend on technology adoption and policy choices. Finally, transition exposure in ASEAN+3 is closely tied to energy supply and industrial production, supporting the emphasis in later sections on energy use and energy-mix indicators when benchmarking cross-economy exposure and transition pressure.

**Figure 1. Emissions and Size of the Economy**



Source: Crippa et al. (2025); World Bank (2025), AMRO staff calculation

**Figure 2. Sectoral Emissions Shares**



Source: Crippa et al. (2025); AMRO staff calculation

Note: Emissions share is defined as total emissions from ASEAN+3 countries relative to total global emissions. Emissions data are extracted from the Emissions Database for Global Atmospheric Research (EDGAR) constructed by Crippa et al. (2025). The emissions dataset covers CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, and F-gases. Others include agriculture, building, domestic aviation, domestic shipping, indirect, offshore, and waste emissions. GDP share is defined as total GDP (constant PPP, USD) of ASEAN+3 relative to total world GDP (constant PPP, USD). GDP dataset is extracted from World Bank (2025).

**3. Against this backdrop, this note has three objectives and makes a distinct contribution.** First, it estimates how emissions respond to income and other structural factors using the Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) framework.<sup>2</sup> Second, it uses the implied Environmental Kuznets Curve (EKC) turning point to benchmark economies' positions along the emissions–development path.<sup>3</sup> Third, it summarizes cross-economy exposure and forward-looking pressures using a newly constructed Composite Environment–Development Risk Index that combines emissions levels, emissions growth, EKC positioning, energy use per capita, and renewable energy consumption shares. Beyond standard emissions-income or EKC, the note contributes by integrating multifactor elasticities from a common STIRPAT estimation, turning-point benchmarking used for cross-economy positioning, and a composite risk index as a set of signals on exposure and transition pressure. In particular, the STIRPAT estimates are used to identify the monitoring indicators included in the Composite Environment–Development Risk Index.

**4. The empirical approach combines a STIRPAT specification with EKC-style nonlinearity to benchmark cross-economy positioning.** The STIRPAT framework relates emissions to population, affluence (income per capita), and technology/ structural factors (including energy use, urbanization, and renewables). A quadratic income term allows for EKC-type curvature, while quantile estimates help assess whether nonlinearities differ across the emissions distribution. These estimates are best interpreted as conditional associations rather than causal effects, given potential endogeneity between emissions, growth, energy

<sup>2</sup> Further explanation on the STIRPAT framework can be found in Appendix A.

<sup>3</sup> The EKC turning point is a hypothesis under which emissions initially rise with income but decouple at higher development levels (Dinda, 2004; Grossman & Krueger, 1994).

use, and policy choices. This setup supports a consistent regional comparison, while recognizing that structural and policy differences can lead to diverse transition paths.

**5. The composite risk index complements the econometric results by converting estimated relationships into an operational cross-economy monitoring tool.** The STIRPAT estimates identify broad correlates of emissions and caution against interpreting EKC turning points as automatic decoupling thresholds. The index then is constructed by selecting several variables based on the STIRPAT estimates. In particular, the index then aggregates current exposure (emissions scale, energy use per capita) and transition pressure (emissions growth, distance to the turning point, renewables gap) into comparable scores that can be updated regularly and decomposed by component. This allows surveillance to flag economies where emissions pressures are rising faster than in regional peers, distinguish whether risks stem mainly from scale, growth momentum, or energy-mix vulnerabilities, and track whether policy and structural changes are shifting an economy's risk profile even when short-run econometric coefficients remain stable.

## II. Emissions and Development Paths

**6. Emissions have gone hand-in-hand with development in ASEAN+3, but the relationship is nonlinear and heterogeneous.** Figure 3 and Appendix B suggest that cross-economy differences in emissions are most strongly associated with scale and energy-use channels, while EKC-type curvature is not robust across quantiles. In the pooled estimates, a 1 percent increase in income per capita is associated with an increase of about 1.6 percent in CO<sub>2</sub> emissions, conditional on energy use and other controls.<sup>4</sup> The negative value of the squared income term is consistent with EKC-type curvature, implying that the fitted emissions–income slope tends to flatten as income rises. In principle, low- and high-emitting countries could exhibit different estimates for the squared income term, reflecting various levels of development. However, in both in OLS and quantile estimates this curvature is not statistically significant across quantiles. The results should therefore not be treated as evidence of a robust income threshold at which emissions are expected to decline.

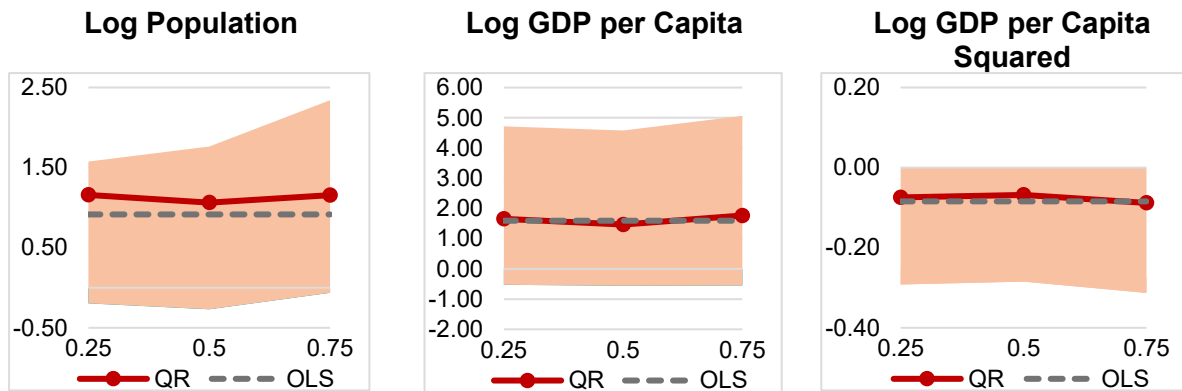
**7. Most ASEAN+3 economies remain below the common turning-point threshold.** Based on the pooled parameters of income and income squared (Figure 3 and Appendix B), this note estimates a common turning point<sup>5</sup> of around USD46,793 in GDP per capita (constant PPP) across economies. This pooled turning point should be interpreted as a stylized reference point for cross-economy positioning rather than a precise country-specific threshold, since turning points can differ with energy mix, industrial structure, and policy regimes. Applying this benchmark to current income levels suggests that many ASEAN+3 economies, such as Cambodia, China, Indonesia, Lao PDR, Malaysia, Myanmar, the Philippines, Thailand, Timor-Leste, and Vietnam, sit below the turning point range. For these economies, further income gains could bring rising emissions unless offset by gains in energy efficiency, structural change, and mitigation policies.

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<sup>4</sup> There may be substantial correlation between income and energy use, which could reduce coefficient precision and interpretation. Even though energy use is already included as one of the control variables, the estimated coefficient on income should be interpreted with caution.

<sup>5</sup> The turning point of the EKC is obtained by computing  $\exp\left(-\frac{\beta_2}{2\beta_3}\right)$ . The derivation can be found in Appendix A.

**Figure 3. Determinants of Emissions (Dependent Variable = Log CO<sub>2</sub> Emissions)**



Source: AMRO staff calculation

Note: The observation period is 2000 to 2023. Log CO<sub>2</sub> emissions refers to the natural logarithm of carbon emissions. Log Population refers to the natural logarithm of population. Log GDP per capita and Log GDP per capita squared refer to the natural logarithm and its square of GDP per capita (constant PPP, USD). The dashed lines report average estimates of ordinary least square (OLS) regression coefficients. The solid lines report point estimates of quantile regression (QR) coefficients shown at selected conditional quantiles ( $\tau = 0.25, 0.50, \text{ and } 0.75$ ). Shaded bands indicate the corresponding 95 percent confidence intervals (CI). CI around the estimated coefficients, particularly for income, are relatively wide, indicating uncertainty around the magnitude of the estimated effects. All data is extracted from the World Development Indicators of the World Bank. The complete OLS estimation with quantile estimation can be found in Appendix B.

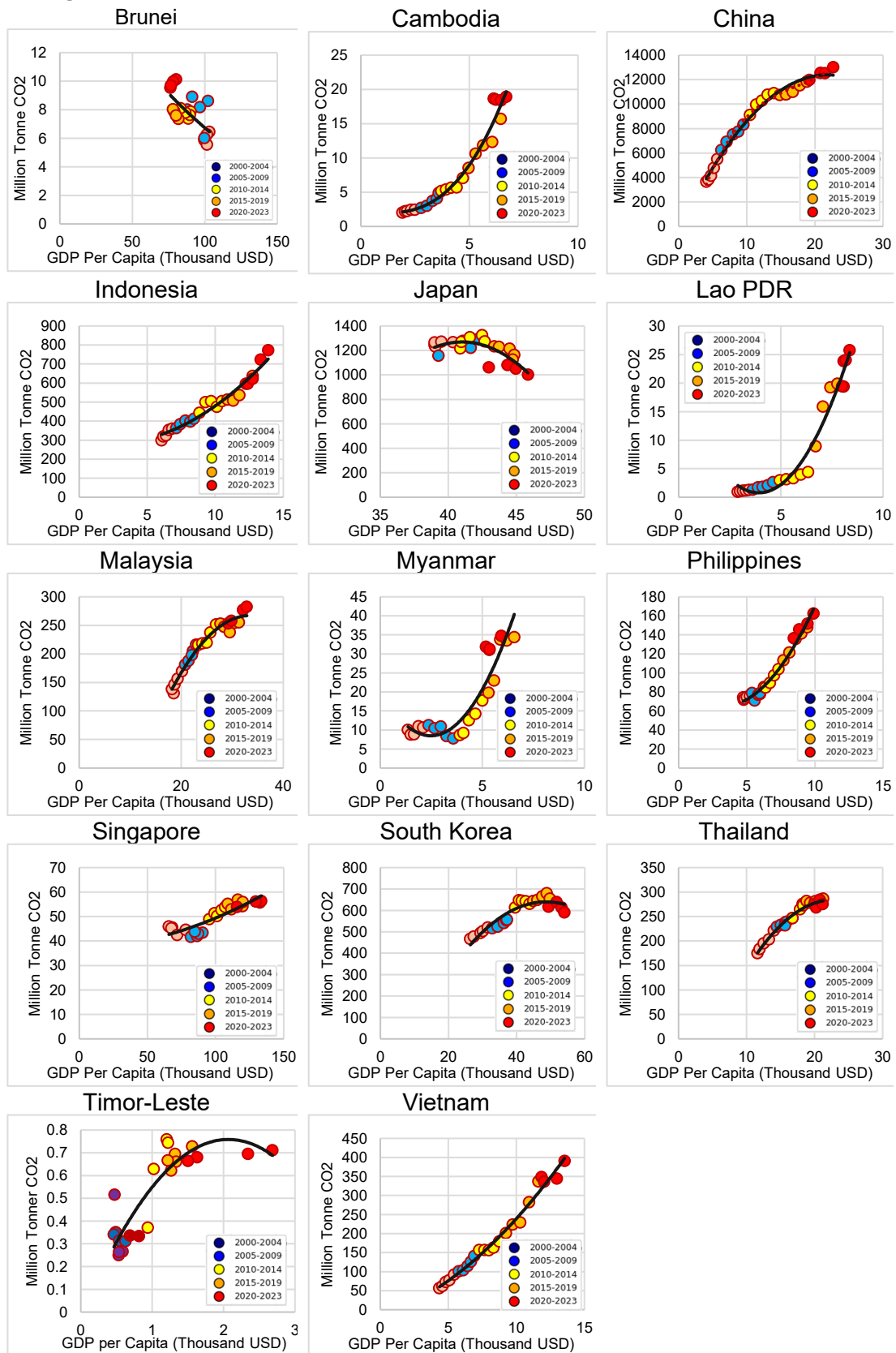
**8. Population scale and energy use per capita are strongly associated with emissions in the estimates.** Population elasticities remain close to or above unity across quantiles, consistent with demographic scale effects being an important correlation of aggregate emissions. Energy use per capita is also positive and statistically significant across the conditional distribution, with larger elasticities in the lower quantiles compared to Q75. This pattern suggests that baseline energy demand and energy-intensive economic structures are particularly salient among lower-emitting economies, although the estimates should be interpreted as conditional associations given potential two-way links between energy use, growth, and policy.

**9. Other structural variables play a more limited role than scale and energy channels.** Urbanization is associated with small and statistically insignificant effects across quantiles, suggesting its influence on emissions likely operates indirectly through production structure and energy use rather than as an independent driver in the specification. The renewables share enters with a negative sign (Appendix B), consistent with lower emissions where clean energy penetration is higher—though the estimated magnitude is small and statistical significance varies across specifications. Given that renewables deployment itself responds to income, energy security, and policy, these coefficients should be interpreted cautiously. Overall, the results suggest that income, population, energy use, and renewables share explain much of the within-sample variation in emissions across ASEAN+3.

### III. Turning Points and Country Positioning

**10. The fitted emissions–income curves of EKC reveal three broad patterns across the ASEAN+3 region.** Figure 4 indicates that advanced economies such as Japan, South Korea, and Singapore show flat or declining emissions at high income levels. In contrast, in several upper-middle-income economies such as China, Malaysia, and Thailand, emissions show some flattening but continue on rising paths. Finally, other middle-income economies such as Vietnam and Indonesia display steeper upward slopes. This dispersion in fitted patterns at broadly similar income levels underscores the importance of combining EKC positioning with indicators of emissions growth, energy demand, and energy-mix readiness.

**Figure 4. The Environmental Kuznets Curve (EKC) for ASEAN+3 Economies**



Source: Crippa et al. (2025); World Bank (2025); AMRO staff calculation

Note: Emissions data are extracted from the Emissions Database for Global Atmospheric Research (EDGAR) constructed by Crippa et al. (2025). The emissions dataset covers CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, and F-gases. The GDP per capita (constant PPP, USD) dataset is extracted from World Bank (2025). The trendline for each country is a polynomial function and should be interpreted as a descriptive fit; qualitative patterns may vary with alternative smoothing choices and sample windows.

**11. Advanced economies show flatter or declining fitted emissions paths at high income levels.** Japan, South Korea, and Singapore sit on the flatter or downward portion of the fitted emissions–development curve in Figure 4, where higher GDP per capita is associated with stable or falling emissions within the sample. This pattern is consistent with patterns expected beyond an EKC-type turning point, as mature energy demand, efficiency gains, tighter environmental regulation, and shifts toward cleaner energy and less emissions-intensive activity can help offset scale effects from further income growth. As the trendlines are based on polynomial fits, these patterns should be interpreted as descriptive rather than definitive evidence of causal decoupling.

**12. In upper-middle-income economies, emissions growth appears to be slowing but is not reversing.** The flatter slopes for China, Malaysia, and Thailand are consistent with improving energy intensity and wider deployment of cleaner technologies, but continued growth in manufacturing, construction, and mobility keeps with emissions rising in absolute terms. The timing of an eventual downturn is likely to hinge on how quickly coal and gas are displaced in power generation, and how rapidly efficiency gains and electrification spread through industry and transport.

**13. In many middle-income economies, development remains tightly linked to emissions.** Vietnam and Indonesia show steep upward trajectories, consistent with strong scale effects from industrial expansion, urbanization, and infrastructure investment. With fossil fuels still central to power and transport, emissions tend to rise quickly as incomes grow. These patterns point to the importance of accelerating grid investment, renewables deployment, and efficiency policies to reduce the risk of carbon-intensive capital from being locked in during the catch-up phase.

#### **IV. Where Does ASEAN+3 Stand Now?**

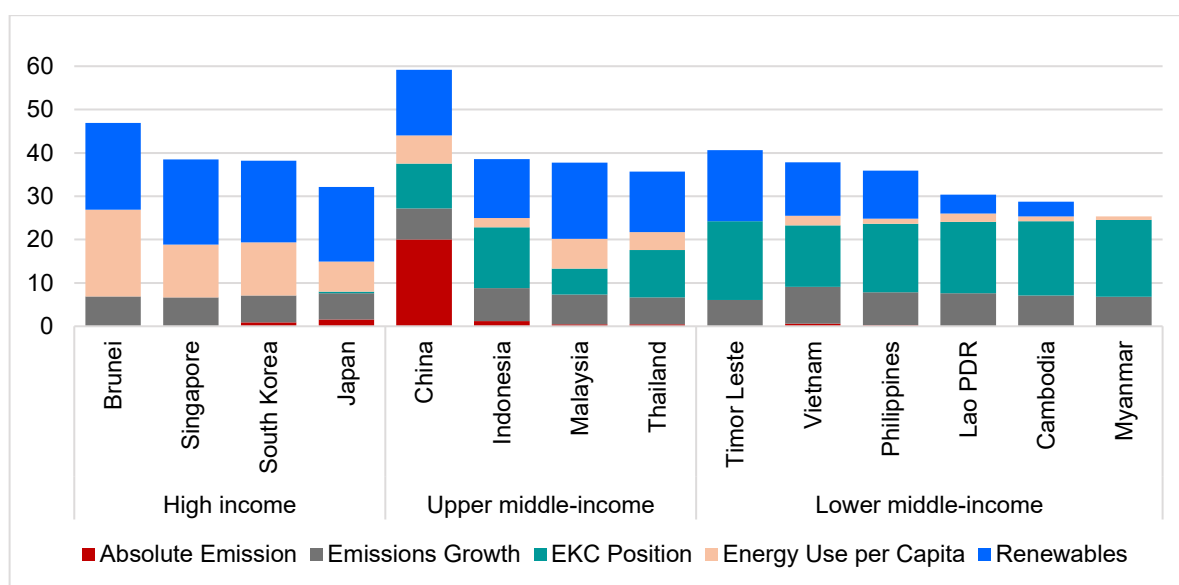
**14. To compare ASEAN+3 economies consistently, this note introduces a Composite Environment–Development Risk Index.** The index is designed as a parsimonious surveillance tool that captures two broad dimensions that matter for transition risk, namely current exposure and forward-looking pressure. It draws on five variables that align with these two dimensions and draw on data that are widely available and comparable across ASEAN+3 economies. The current exposure captures two variables: absolute emissions and energy use per capita. The last three variables—emissions growth, distance to the EKC turning point, and renewables shares—capture transition pressure. As composite indicators can be sensitive to scaling choices and weights, index rankings should be interpreted together with underlying component scores rather than as precise league-table results.

**15. Each index component links to a distinct macro-financial channel.** A high level of absolute emissions is correlated with a higher risk of repricing carbon-intensive assets, while being far below the turning point is correlated with the possibility of growth still being accompanied by substantial emissions in the absence of stronger mitigation. Faster emissions growth can correlate with larger future adjustment costs as policies tighten, while higher energy use per capita is correlated with greater exposure to energy-price shocks and may be associated with inflation and external balance pressures. Finally, a low share of renewables (or high fossil-fuel dependence) is correlated with greater vulnerability to carbon

pricing, fuel-import shocks, and stranded-asset risks in the power sector as the transition accelerates.

**16. The Composite Environment–Development Risk Index reveals substantial heterogeneity across ASEAN+3 economies, including within country income groupings.** Figure 5 shows that several advanced economies (Brunei, Singapore, South Korea, and Japan) score relatively low overall because their EKC position scores are at or near zero (post turning), and their absolute emissions scores are low. However, these economies still exhibit notable exposure through other components such as relatively high energy use per capita and lower renewables shares, which are still important drivers of their overall scores.

**Figure 5. The 2023 Composite Environment–Development Risk Index**



Source: AMRO staff calculation

Note: Country income category is based on the World Bank’s classification. The Composite Environment–Development Risk Index is a composite indicator summarizing economies’ positions along the emissions–development relationship. It combines standardized measures of absolute emissions, emissions growth, position relative to the Environmental Kuznets Curve (EKC) turning point, energy use per capita, and renewables shares to total energy supply. Each component is scaled from 0 to 100, with higher values indicating greater emissions exposure along that dimension. The overall index score is an equal-weighted average of these five components, reflecting the absence of a single agreed weighting scheme and the fact that each captures distinct but complementary channels relevant for monitoring. In practice, alternative weights (for example, placing more weight on forward-looking pressure components such as emissions growth and renewables, or more weight on scale and energy-use exposure) would shift some marginal rankings, but would be unlikely to overturn the broad grouping of economies into higher-exposure, higher-pressure, and lower-risk clusters when component patterns are pronounced. Similarly, alternative scaling choices (for example, z-score standardization versus min–max scaling) can affect dispersion and rank sensitivity at the tails. Therefore, the results should be interpreted together with underlying component scores. Further detail on the index’s construction can be found in Appendix C.

**17. Upper middle-income economies exhibit mixed risk profiles, with China’s index score dominated by scale effects and other economies’ scores reflecting diverse combinations of forward-looking and structural pressures.** China ranks highest overall, driven mainly by its high level of absolute emissions, high energy use per capita, and lower renewables share. By comparison, its emissions growth and EKC position components are more moderate, indicating that current exposure rather than forward-looking pressure is the main driver. The other economies in this group such as Indonesia, Malaysia, and Thailand differ in composition. Indonesia’s score is driven largely by emissions growth and its below–turning point EKC position, pointing to forward-looking pressures as the economy expands. Malaysia shows relatively higher contributions from energy use per capita and the renewables component, indicating structural exposure linked to energy demand and energy mix. Thailand presents a more balanced profile across components, but remains below the turning point,

suggesting that continued growth could still add to emissions in the absence of stronger mitigation.

**18. Lower middle-income economies face transition risks, driven primarily by forward-looking pressures linked to their distance from the EKC turning point and ongoing emissions growth.** Figure 5 shows that Timor-Leste, Vietnam, the Philippines, Lao PDR, Cambodia, and Myanmar exhibit moderate to relatively high index values despite low absolute emissions and low energy use per capita. This reflects substantial contributions from the EKC position and emissions growth, as these economies remain below the turning point and are expected to experience rising emissions alongside continued income growth.

**19. High EKC-position scores are a key driver of risk scores in lower middle-income countries.** Timor-Leste combines very low emissions with a large distance to the turning point and elevated renewables-risk, signaling rising transition pressure as growth accelerates. Vietnam and the Philippines stand out high overall scores, driven by a combination of below-turning point EKC positioning, strong emissions growth, and low renewable shares, indicating pronounced forward-looking pressure. Lao PDR and Cambodia sit in the middle of the distribution despite low absolute emissions and low energy use per capita mainly because they remain far below the turning point. Lao PDR's lower renewables-risk score points to higher clean-energy penetration, while Cambodia shows higher exposure through the growth and renewables components. Across lower-middle-income economies, this illustrates how EKC positioning can shape the overall risk signal, making the component breakdown essential for distinguishing whether transition pressure stems mainly from growth momentum, baseline energy demand, or energy-mix readiness.

## V. Conclusions

**20. Climate transition dynamics in ASEAN+3 operate through multiple macro-financial channels and pose material risks to medium-term growth.** For economies below the turning point, emissions-intensive growth is often associated with an expansion in industrial activity and energy demand—raising exposure to future policy tightening, including stricter emissions standards, carbon pricing, fossil-fuel subsidy reform, and related regulatory measures along with adjustment costs and investment reallocation risks. As these economies converge toward higher income levels, stronger mitigation requirements may weigh on capital formation, productivity growth, and sectoral employment if transition policies are delayed or implemented abruptly.

**21. For economies near or beyond their estimated turning points, growth risks arise from structural rigidities and policy execution than from scale effects.** In these economies, insufficient progress in energy efficiency, fuel switching, or technological upgrading can translate into higher production costs, reduced competitiveness, and vulnerability to energy price shocks. Delayed transition in hard-to-abate sectors may also drag potential growth by locking in carbon-intensive capital and slowing investment in emerging low-carbon industries.

**22. This note underscores the importance of early, differentiated monitoring of transition-related risks across ASEAN+3.** Policymakers could use the STIRPAT estimates to identify the main emissions channels, the EKC turning point to benchmark where an economy sits on the emissions–development path, and the composite risk index as a decomposable indicator to monitor transition risks, prioritize vulnerabilities, and calibrate the

pace and sequencing of mitigation policies. Economies below the turning point must pay close attention to emissions growth and energy use as development accelerates, while those approaching the turning point require a careful assessment of policy credibility and reform momentum. For economies beyond the turning point, it is increasingly likely growth will be closely associated with the pace of structural adjustment and the ability to absorb transition-related shocks without undermining investment and productivity. Throughout, EKC-based turning points and index rankings should be treated as benchmarks for surveillance and prioritization, and complemented with country-specific diagnostics.

## Appendix A. The Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT)

This analysis applies the STIRPAT (Stochastic Impacts by Regression on Population, Affluence, and Technology) framework to examine the structural drivers of carbon emissions across ASEAN+3 economies. STIRPAT is an econometric reformulation of the IPAT identity that allows statistical estimation and hypothesis testing of how population, income, and technology jointly influence environmental pressure (Dietz & Rosa, 1997; Liddle, 2014; York et al., 2003).

Formally, emissions are modeled as a multiplicative function of population, affluence, and technology, which can be expressed in log-linear form as:

$$\ln E_{it} = \alpha_i + \beta_1 \ln Pop_{it} + \beta_2 \ln Y_{it} + \beta_3 \ln Y_{it}^2 + \gamma Z_{it} + \varepsilon_{it}$$

Where  $i$  denotes country,  $t$  denotes year,  $E_{it}$  denotes carbon emissions,  $Pop_{it}$  denotes population,  $Y_{it}$  denotes GDP per capita,  $Z_{it}$  denotes a vector of control variables capturing technology and structural characteristics (such as energy use per capita, urbanization, and trade openness, and renewable shares on energy supply).

Including a quadratic income term allows the framework to capture non-linear emissions–income dynamics consistent with the Environmental Kuznets Curve (EKC) hypothesis, under which emissions initially rise with income but decouple at higher development levels (Dinda, 2004; Grossman & Krueger, 1994).

The estimated income coefficients can be used to derive a turning point, interpreted as the income level (GDP per capita) at which the fitted EKC slope changes sign. In this note, a common turning point is applied across economies as a transparent benchmark for comparability and due to data and sample limitations; however, country-specific turning points can differ with energy mix, industrial structure, and policy regimes. Taking the first-order condition (FOC) of the STIRPAT equation with respect to GDP per capita yields:

$$\frac{\partial \log E}{\partial \log Y} = \beta_2 + 2 \beta_3 \log Y$$

When the FOC is zero, the turning point can be defined as:

$$\log Y = - \frac{\beta_2}{2\beta_3}$$
$$Y = \exp\left(- \frac{\beta_2}{2\beta_3}\right)$$

The STIRPAT results should be interpreted with caution, as technology is proxied indirectly and EKC turning points may reflect structural change and policy effects rather than automatic decoupling (Kaika & Zervas, 2013; Stern, 2004).

## Appendix B. Regression Results

### Dependent Variable: Log CO<sub>2</sub> Emissions

Independent Variable	OLS			Q25			Q50			Q75		
	Coeff.	SE	P	Coeff.	SE	P	Coeff.	SE	P	Coeff.	SE	P
Intercept	-27.995	9.759	0.004	-27.014	10.937	0.013	-25.809	13.344	0.013	-28.086	15.201	0.013
Log Pop	0.915	0.491	0.062	1.159	0.491	0.087	1.063	0.577	0.100	1.157	0.632	0.073
Log GDP	1.593	0.890	0.074	1.657	1.565	0.287	1.468	1.579	0.167	1.766	1.830	0.147
Log GDP sq.	-0.084	0.052	0.102	-0.074	0.082	0.340	-0.068	0.086	0.207	-0.088	0.098	0.140
Log Energy	1.247	0.485	0.010	0.551	0.366	0.000	0.705	0.530	0.000	0.737	0.534	0.000
Urbanization	-0.003	0.009	0.745	-0.002	0.008	0.927	-0.001	0.010	0.973	-0.001	0.011	0.980
Renewables	-0.020	0.007	0.003	-0.019	0.010	0.033	-0.016	0.010	0.040	-0.017	0.011	0.047

Source: AMRO staff estimation

Note: The observation period is from 2000 to 2023. Log CO<sub>2</sub> emissions refers to the natural logarithm of carbon emissions. Log Pop refers to the natural logarithm of population. Log GDP and Log GDP sq refer to the natural logarithm and its square of GDP per capita (constant PPP, USD). Log Energy refers to the natural logarithm of energy usage per capita. Urbanization refers to the share of the urban population to total population. Renewables refers to renewable energy consumption to total energy consumption. Coeff.= coefficient, SE= standard error, P=P-value. OLS=Ordinary Least Square estimates using country fixed effects and clustered standard errors. Q25, Q50, and Q75 indicate conditional quantile regression estimates using country fixed effects for each quantile, respectively. Bootstrap is used to obtain statistical inference (Standard Errors and P-Value) for quantile regression coefficient. All estimates using country fixed effect and clustered standard errors. All data is extracted from the World Development Indicators of the World Bank. Adjusted R-squared is 0.996 with F-statistic and Probability of F-statistic are 3.111 and 0.037, respectively.

## Appendix C. Constructing the Composite Environment–Development Risk Index

The Composite Environment–Development Risk Index combines five dimensions: (i) absolute level CO<sub>2</sub> emissions, capturing scale-related exposure; (ii) emissions growth, reflecting forward-looking transition pressure; (iii) the distance from the EKC turning point, capturing environment–development positioning; (iv) energy use per capita, capturing baseline energy demand associated with consumption patterns, transport intensity, climate conditions, and industrial structure; and (v) renewables' share in total energy consumption, capturing the extent of fossil-fuel dependence in the energy consumption. Each component is normalized to a 0–100 scale and aggregated using a weighted average (OECD, 2008).

### 1. Absolute Emissions Level

The first component captures the relative level of current CO<sub>2</sub> emissions across economies. For each country  $i$ , emissions are scaled using min–max normalization across the sample:

$$\text{Absolute Emission}_i = \frac{\text{CO}_{2i} - \min(\text{CO}_2)}{\max(\text{CO}_2) - \min(\text{CO}_2)} \times 100$$

This measure assigns a higher index component score to economies with higher absolute emissions, reflecting greater exposure to transition pressures associated with emissions-reduction policies.

### 2. Emissions Growth Trajectory

The second component captures emissions dynamics over time. Let  $g_i$  denote the emissions growth rate of economy  $i$ , measured relative to its base year level. Emissions growth dynamics are constructed in two steps.

First, emissions growth rates are standardized using a z-score transformation:

$$z_i = \frac{g_i - \mu_g}{\sigma_g}$$

where  $\mu_g$  and  $\sigma_g$  denote the cross-economy mean and standard deviation of emissions growth rates, respectively. This transformation measures each economy's emissions growth relative to the regional average in units of standard deviation.

Second, the standardized scores are then linearly rescaled to obtain the emissions growth index component:

$$\text{Emissions}_i^{\text{growth}} = 50 + \lambda \left[ \frac{g_i - \mu_g}{\sigma_g} \right]$$

where  $\lambda$  is a scaling parameter that controls dispersion. This centered rescaling ensures that economies with above-average emissions growth receive higher index component scores, while preserving the continuous distribution of growth dynamics without imposing arbitrary bounds.

### 3. Position Relative to the EKC Turning Point

The third component reflects the economy's distance from the estimated EKC turning point, based on the ratio of current income to the EKC threshold. Economies below the turning point

are assigned higher index component scores, reflecting greater upward pressure on emissions as income growth continues.

$$\text{EKC Position}_i = \min \left( 100, \max \left( 0, (1 - \text{Ratio\_to\_TP}_i) \times 100 \right) \right)$$

#### 4. Energy Use per Capita

The fourth component measures energy use per capita as a proxy for baseline energy demand associated with consumption patterns, transport intensity, climate conditions, and industrial structure. As with emissions levels, the indicator is normalized using a 0–100 min–max scaling:

$$\text{Energy Intensity}_i = \frac{\text{Energy Intensity}_i - \min(\text{Energy Intensity})}{\max(\text{Energy Intensity}) - \min(\text{Energy Intensity})} \times 100$$

Higher values indicate higher baseline energy demand per person, which can increase exposure to demand-side adjustment pressures and energy-price shocks during the transition.

#### 5. Renewables Index Score

The fifth component measures the share of renewable energy consumption to total energy consumption as a proxy for the extent to which an economy's energy system remains dependent on fossil fuels. As with the other indicators, the variable is normalized using a 0–100 min–max scaling:

$$\text{Renewables}_i = 100 - \left( \frac{\text{Renewables}_i - \min(\text{Renewables})}{\max(\text{Renewables}) - \min(\text{Renewables})} \times 100 \right)$$

Higher values indicate a lower share of renewables (greater fossil fuel dependence), which increases exposure to carbon pricing, fuel-import shocks, and policy tightening during the transition.

#### 6. Composite Risk Index Score

The overall risk index score is computed as an equal weighted average of the five components described above.

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