 DOI: 10.35382/TVUJS.16.2.2026.167

DRIVERS OF CARBON EMISSION REDUCTION IN ECONOMIC DEVELOPMENT: AN EXPERT-BASED ANALYTIC HIERARCHY PROCESS STUDY

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Abstract – *Carbon emission reduction poses a growing challenge for subnational governments that must reconcile economic growth with climate commitments under conditions of limited data and constrained resources. Provincial policymakers, therefore, require transparent tools to prioritize emission reduction drivers that reflect local institutional, technological, and social contexts. This study applies an expert-based analytic hierarchy process to identify and rank the key drivers of carbon emission reduction in Thai Nguyen Province, Vietnam, within the context of provincial economic development. An analytic hierarchy process comprising the overall goal, five main criteria, and twenty subcriteria was constructed. Pairwise comparison judgments were collected from 15 experts representing government, enterprises, and academia during July and August 2025. The results indicate that institutions and public governance (weight = 0.292), community and society (0.250), and science, technology, and human resources (0.202) are the most influential dimensions. At the subcriterion level, policy implementation and enforcement, research and development infrastructure, community environmental awareness, and clean technology adoption emerge as the highest priorities. The priority structure is highly concentrated, with the top-ranked drivers accounting for more than 70% of total importance. This study presents a replicable decision-support framework for designing provincial low-carbon policies and provides transferable insights for other subnational contexts in emerging economies.*

Keywords: analytic hierarchy process (AHP), carbon emission reduction, economic development, expert judgment, multi-criteria decision making, provincial policy.

I. INTRODUCTION

Reducing carbon emissions while sustaining economic development has become a central policy challenge for subnational governments worldwide. In Vietnam, national climate commitments under COP26 have placed increasing responsibility on provincial governments to translate mitigation targets into concrete development policies [1]. As industrialization, urbanization, and energy demand intensify at the local level, provinces are increasingly responsible for translating national climate commitments into concrete actions. In this context, carbon emission reduction is no longer viewed solely as an environmental objective but as an integral component of development quality, competitiveness, and long-term resilience. The establishment of a national carbon market further reinforces the need for provinces to strengthen governance capacity, monitoring systems, and institutional readiness for market-based mitigation instruments [2]. However, achieving emission reductions without undermining economic performance remains particularly challenging for industrializing regions where growth pressures are strong, and policy capacity is uneven. Recent policy developments further highlight the growing importance of provincial implementation capacity in carbon emission reduction. In Vietnam, Decision No. 232/QD-TTg, which approves the Scheme on the establishment and development of a carbon market, has introduced new requirements for emissions

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Received date: 3 February 2026; Revised date: 29 June 2026; Accepted date: 30 June 2026

monitoring, reporting, verification, and market-based mitigation instruments [2].

A key difficulty faced by provincial policy-makers lies in prioritization, as carbon mitigation involves multiple interacting institutional, technological, economic, enterprise-related, and social drivers [3–6]. Under conditions of limited budgets and incomplete local data, decision-makers must determine which drivers should be addressed first to achieve the greatest policy impact. While national and sectoral studies provide important evidence on the relationship between economic growth, industrial structure, energy consumption per capita, and carbon emissions [7, 8], such analyses often provide limited guidance for subnational policy design, where local institutional capacity, governance quality, and social dynamics play a decisive role. Recent studies and policy assessments, including IPCC [9], OECD [10], and Zhang et al. [11], have increasingly emphasized the importance of governance quality, policy implementation capacity, and social participation in determining the effectiveness of mitigation efforts. However, many macro-level and policy-instrument studies rely primarily on quantitative indicators and may not fully capture context-specific factors such as enforcement credibility, technological diffusion capacity, or community pressure [7, 8, 12–15]. As a result, there remains a methodological gap in providing provincial governments with transparent and operational tools to systematically prioritize drivers of emission reduction when conventional data sources are insufficient or fragmented.

This study addresses this gap by applying an expert-based analytic hierarchy process (AHP) to prioritize the drivers of carbon emission reduction in the context of economic development at the provincial level. The analysis uses Thai Nguyen Province, Vietnam, as a case study. Thai Nguyen was selected for three main reasons. First, rapid industrialization and export-oriented manufacturing have made the tension between economic growth and emission reduction particularly visible. Second, the province has an important innovation and human-resource base, supported by Thai Nguyen University and its network of member universities, affiliated schools, institutions, and research/service units. Third, Thai Nguyen represents a subnational context in which provincial authorities must translate national climate commitments and emerging carbon-market requirements into concrete local policy priorities under data and resource constraints. These characteristics make the province a relevant setting for examining how governance, technology, enterprise behavior, economic structure, and social dynamics interact in shaping subnational mitigation priorities.

By eliciting and aggregating judgments from experts drawn from government, industry, and academia, this study constructs a multi-level priority structure that reflects local development conditions and implementation realities. The objective is not only to rank emission reduction drivers, but also to provide a decision-support framework that can inform policy sequencing and resource allocation. The study contributes to the literature by operationalizing a governance–technology–society perspective on carbon mitigation at the provincial level and by demonstrating the applicability of expert-based AHP as a practical tool for subnational low-carbon policy design in emerging economies.

Although previous multi-criteria decision-making (MCDM) and AHP studies have been widely applied to environmental management, energy planning, and sustainability assessment [3–6, 16], their applications have mainly focused on national, sectoral, project-level, or technology-selection problems. This study extends the use of AHP to the provincial policy context, where mitigation priorities are shaped not only by technical feasibility but also by governance capacity, social pressure, enterprise behavior, and local economic structure. By integrating these dimensions into a single prioritization framework and validating the ranking through expert judgment and sensitivity analysis, the study provides a practical decision-support approach for subnational low-carbon policy design in data-constrained settings.

II. LITERATURE REVIEW

A substantial body of literature has examined the relationship between carbon emission reduction and economic development, highlighting the tension between growth-driven increases in energy consumption and environmental sustainability. Early studies focused on emission intensity and the environmental Kuznets curve, suggesting a nonlinear relationship between income growth and environmental degradation [17, 18]. More recent research emphasized structural change, energy transition, and technological upgrading as key mechanisms for decoupling economic growth from carbon emissions [19, 20]. At the macro level, national and sectoral studies provided important insights into how GDP growth, industrial structure, and energy mix influence emissions [7, 8]. However, these studies are largely explanatory and data-driven, focusing on identifying statistical relationships rather than supporting concrete policy prioritization. As a result, their applicability to subnational decision-making is limited, particularly in contexts where local institutional capacity, governance quality, and social dynamics differ substantially across regions.

Another important strand of research focuses on governance quality and policy instruments as key determinants of carbon mitigation outcomes. Research on environmental regulation consistently shows that regulatory stringency and enforcement credibility significantly influence firms' emission behavior and technology adoption [21, 22]. International assessments further emphasized that effective mitigation requires coordinated policy mixes combining regulatory, market-based, and enabling instruments, especially at subnational levels where implementation occurs [9, 23]. Empirical studies on carbon pricing and emissions trading schemes indicated that market-based instruments can reduce emissions by altering cost structures and incentivizing cleaner production, although their effectiveness depends heavily on institutional design and enforcement capacity [12, 13]. Evidence from pilot emissions trading programs in emerging economies showed heterogeneous impacts across regions, suggesting that governance capacity and local implementation conditions play a decisive role [14, 15, 24]. Nevertheless, most existing studies assess governance effects indirectly through econometric models, offering limited guidance on how policymakers should prioritize governance-related drivers relative to other mitigation factors.

Beyond formal regulation, technological capability, social drivers, and firm behavior have been increasingly recognized as important factors shaping emission-reduction outcomes. Studies on innovation-based mitigation emphasized the role of research and development (R&D), human capital, and university–industry linkages in enabling firms to adopt low-carbon technologies [25, 26]. In parallel, research on sustainability transitions highlighted the influence of social pressure, community awareness, and demand-side preferences in shaping corporate environmental behavior [27, 28]. Firm-level analyses often identify internal capabilities and compliance behavior as determinants of emission outcomes [29]. These studies frequently treat governance, technology, and social factors as external or control variables rather than integrating them into a unified analytical framework. Consequently, the relative importance of these drivers and their interaction at the provincial level remains insufficiently explored, particularly in developing and emerging economies. Given the multidimensional and context-specific nature of carbon emission reduction, MCDM methods have gained increasing attention in environmental and energy policy research. Reviews of MCDM applications showed their usefulness in synthesizing economic, environmental, technological, and social criteria into coherent decision-support frameworks [3, 4]. Among MCDM methods, the AHP is widely used due to its ability to combine qualitative and quantitative judgments, incorporate expert knowledge, and assess consistency in decision-making [5, 6]. AHP has been applied in energy planning, environmental management, and sustainability assessment [16]. However, its application to prioritizing carbon emission reduction drivers at the provincial level, particularly through an integrated framework that explicitly includes governance, technological capacity, economic structure, enterprise behavior, and social dynamics, remains limited.

Recent developments in carbon governance, ESG transition, and subnational climate policy provide additional support for an integrated analytical framework. OECD [10] argued that climate targets should be operationalized through mission-oriented and multi-level governance arrangements that strengthen coordination, execution, resources, and accountability. Similarly, Zhang et al. [11] emphasized that climate policy implementation for carbon neutrality goals must be examined not only at the national level but also across subnational levels and non-state actors. Recent evidence from carbon emissions trading also showed that market-based instruments can improve regional green total factor productivity, but their effectiveness depends on market maturity, policy stabilization, regional conditions, and implementation capacity [30]. At the firm level, recent ESG studies indicated that ESG performance can influence corporate carbon emissions through mechanisms such as green technological innovation and external oversight [31], while green innovation and digital transformation are increasingly recognized as strategic channels for improving ESG performance and supporting corporate low-carbon transition [32]. Taken together, these studies suggest that carbon emission reduction should be analyzed as an integrated governance–technology–society process rather than as a purely technological or firm-level issue.

The existing literature reveals two key gaps. First, while national and sectoral studies identify broad emission determinants, they offer limited operational guidance for subnational policymakers who must prioritize mitigation drivers under data and resource constraints. Second, although governance, technological, enterprise, and social factors are widely acknowledged as important, they are rarely integrated into a single, transparent prioritization framework that reflects local development conditions. This study addresses these gaps by applying an expert-based AHP framework to prioritize carbon emission reduction drivers in the context of economic development at the provincial level. Using Thai Nguyen Province in Vietnam as a case study, the research integrates institutional, technological, economic, firm-level, and social dimensions into a coherent decision support structure. This contributes both methodologically and empirically to the literature on subnational carbon mitigation and provides policy-relevant insights for emerging economies by conceptualizing provincial carbon mitigation as a system-level process, in which governance credibility, social pressure, and innovation capacity jointly shape firm behavior, rather than treating firms or industrial structure as autonomous drivers.

Figure 1 presents the conceptual framework of the study, illustrating how carbon emission reduction in provincial economic development is shaped by the interaction of governance, technology, economic structure, enterprise behavior, and social factors. Institutions and public governance create the regulatory and enforcement environment, while science, technology, and human resources provide the capacity for firms to adopt low-emission solutions. Community awareness and social pressure further encourage environmental compliance, whereas the economic structure determines the extent to which emission reduction depends on industrial transformation and reduced fossil energy dependence. Overall, the framework positions enterprise behavior and mitigation actions as the central mechanism through which these drivers contribute to carbon emission reduction at the provincial level.

III. RESEARCH METHODS

A. *Research design*

This study employs an expert-based AHP to prioritize the drivers of carbon emission reduction in the context of economic development at the provincial level. AHP is used because it supports multi-criteria prioritization where some determinants are qualitative, context-specific, and difficult to quantify consistently using secondary

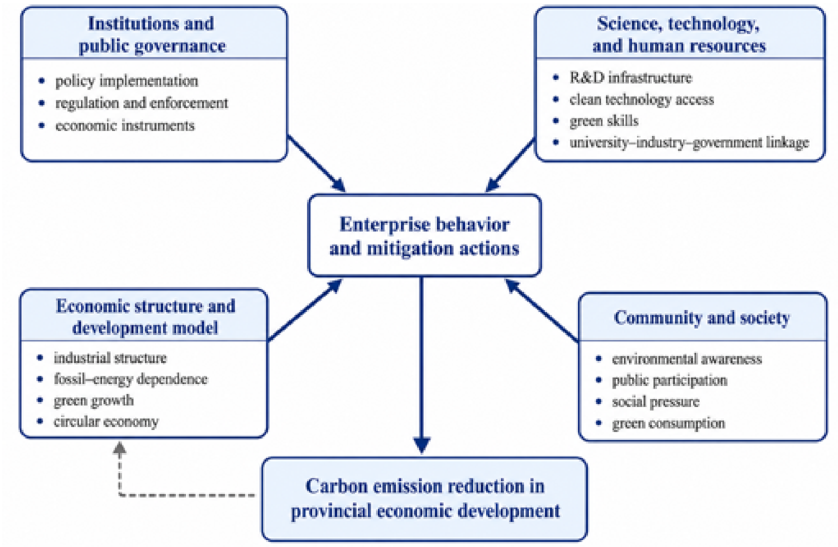

Fig. 1: Conceptual framework of carbon emission reduction in provincial economic development

data alone. AHP is particularly appropriate in this context because several key drivers of carbon emission reduction, such as governance effectiveness, enforcement credibility, and social pressure, are difficult to measure quantitatively and are best captured through structured expert judgment rather than secondary data.

The AHP model is defined in three levels: goal (Level 0), main criteria (Level 1), and subcriteria (Level 2). The goal is to determine the relative priority of factor groups affecting emissions during provincial economic development. Level 1 consists of five main criteria (C1–C5) capturing the major mechanisms that drive carbon emission reduction within economic development. Level 2 consists of twenty subcriteria (four under each main criterion), representing specific policy levers and implementation factors (C1.1–C5.4). Figure 2 presents the AHP hierarchy developed for this study. The hierarchy links the overall research goal with five main criteria and twenty subcriteria, thereby providing a structured basis for expert pairwise comparisons and subsequent priority-weight calculation.

The criteria were developed through a review of relevant literature on emission reduction drivers and local economic development, and contextual adaptation to provincial conditions. To ensure content validity, each subcriterion was defined with a short description to guide expert judgments and reduce ambiguity during pairwise comparisons.

B. Questionnaire design, data collection, and evaluation method

Data were collected during July and August 2025 through offline consultation using a structured AHP questionnaire. A total of 15 experts participated in the survey. The selection of experts was considered appropriate for this expert-based AHP study because AHP prioritizes informed judgments, respondent expertise, and matrix consistency rather than statistical representativeness based on large sample size [5, 6]. The use of expert consultation was appropriate because several drivers of carbon emission reduction are context-dependent and cannot be fully captured by secondary data alone. Experts were selected based on three criteria: demonstrated expertise in economic development, energy, environment, or climate-related policy; practical experience in policy design, implementation, en-

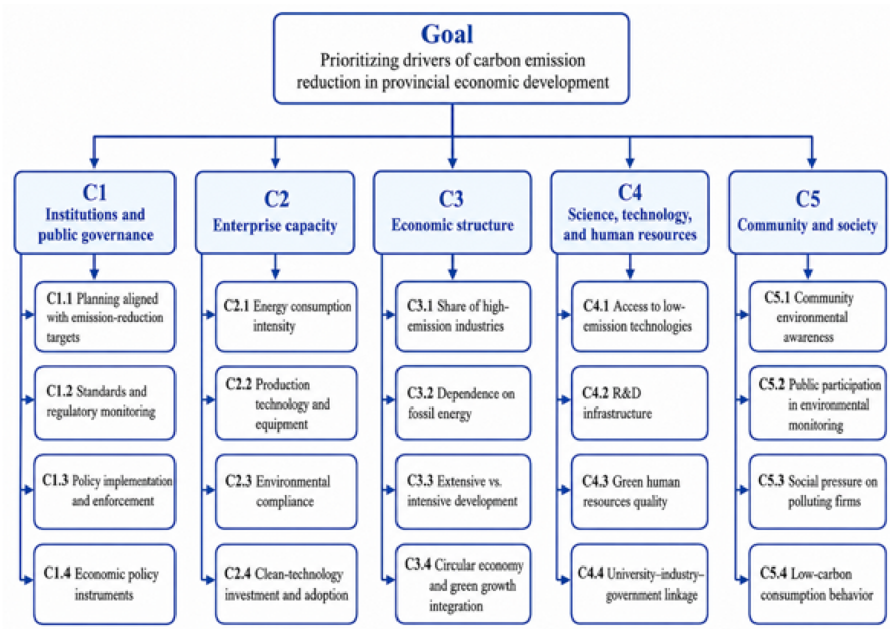

Fig. 2: AHP hierarchy for prioritizing drivers of carbon emission reduction

terprise management, or applied research; and familiarity with provincial development conditions. All participants had at least five years of relevant professional experience, and most had more than ten years. To reduce single-group bias, the panel was diversified across stakeholder categories, including public administration, enterprises or industry-related organizations, and academic or research institutions.

Table 1: Profile and composition of the expert consultation panel

Expert group	Number	Main background	Relevant experience
Government	5	Economic management, environmental governance, provincial development	Policy design, planning, regulation, implementation
Enterprises	5	Manufacturing, industrial management, environmental management	Compliance, technology adoption, investment decisions
Academia	5	Development economics, environmental studies, technology research	Applied research, policy analysis, advisory work

Source: Author's compilation from expert survey data, 2025

The expert panel size is appropriate for the expert-based AHP design of this study. The AHP questionnaire was structured into six pairwise comparison tasks, including one 5×5 matrix for comparisons among the main criteria (C1–C5) and five 4×4 matrices for comparisons among subcriteria within each main criterion. The 100% consistency pass rate across all matrices indicates that the selected panel provides reliable and coherent evaluations.

Experts provided pairwise judgments using the Saaty scale 1–3–5–7–9 and reciprocals, where 1 indicates equal importance, and 9 indicates extreme importance of one element over another. Respondents completed the survey independently. Before answering, experts received brief instructions and an example to ensure consistent understanding of the scale and the meaning of pairwise comparisons. Because the study aims to obtain a collective priority structure, individual pairwise judgments were aggregated into a group comparison matrix using the geometric mean for each element, as in Equation (1).

$$\overline{a_{ij}} = \left(\prod_{k=1}^{m} a_{ij}^{(k)}\right)^{1/m} \qquad (1)$$

The geometric mean is used because it preserves the reciprocal property of AHP pairwise comparison matrices and is the standard aggregation method for combining individual judgments on a ratio scale. Where m = 15 is the number of experts, and $a_{ij}^{(k)}$ is the judgment of expert k. This approach preserves the reciprocal property of AHP matrices and reflects the central tendency of expert opinions on a ratio scale.

For each aggregated matrix, the priority vector w was derived using the standard AHP approximation procedure: normalize each column by its column sum, and compute the average of each row to obtain relative weights. Weights were then normalized to sum to one. Local weights for subcriteria were computed within each 4×4 matrix. Global weights for subcriteria were obtained by multiplying each subcriterion's local weight by the corresponding main criterion weight, which can be determined by Equation (2).

$$w_{sub}^{global} = w_{main}^{(L1)} \, x \, w_{sub\,main}^{(L2)} \quad (2)$$

The global weights were used to rank drivers of carbon emission reduction across all subcriteria. To ensure reliability of pairwise judgments, consistency was evaluated for each matrix using the maximum eigenvalue λ_{max}, the consistency index (CI), and the consistency ratio (CR), which were presented as Equation (3) and Equation (4).

$$CI = \frac{\lambda_{max} - n}{n-1} \ (3), \qquad CR = \frac{CI}{RI} \qquad (4)$$

Where n is the matrix size, and RI is the random index. Consistency was considered acceptable when CR $\leq$ 0.10 for the 5×5 matrix and CR $\leq$ 0.09 for each 4×4 matrix. If any matrix had failed to meet the consistency threshold, the corresponding judgments would have been reviewed for potential inconsistencies. In the final dataset, all matrices satisfied the required consistency thresholds. To describe the extent of consensus, the dispersion of expert judgments was summarized for pairwise comparison elements using descriptive statistics (e.g., minimum, maximum, and standard deviation) and/or geometric dispersion indicators based on log-transformed ratios. This step complements CR by indicating whether experts converge strongly or show polarized views on specific comparisons. Sensitivity analysis was conducted by varying the weight of the leading Level-1 criterion, C1, by $\pm$10%. When C1 was increased or decreased, the remaining Level-1 weights were proportionally rescaled so that the total weight remained equal to one. Additional scenarios beyond $\pm$10% were not examined because the purpose was to test ranking stability under reasonable perturbations rather than extreme weighting assumptions.

C. *Ethical considerations*

Participation in the expert consultation was voluntary and anonymous. Before completing the questionnaire, all experts were informed about the purpose of the study, the academic use of the collected data, and the aggregated reporting of the results. Completing and returning the questionnaire was considered informed consent to participate in the study. No personally identifiable information was collected or disclosed in the manuscript. The collected responses were used solely for academic research purposes and were analyzed only at the group level. Responses were collected anonymously and analyzed in aggregate to reduce social desirability and dominance effects. The resulting local and global weights are interpreted as relative priorities, indicating the comparative importance of each driver in guiding provincial policy sequencing and resource allocation rather than as precise quantitative effect sizes. As with all expert-based methods, the results depend on the composition of the expert panel and reflect perceived priorities rather than observed emission outcomes. However, the use of a diversified expert group, strict consistency checks, and sensitivity analysis enhances the robustness and credibility of the findings.

IV. RESULTS AND DISCUSSION

A. *Results*

The results indicate that institutions and public governance have the highest Level-1 weight, followed by community and society and science, technology, and human resources. This suggests that experts assign greater priority to system-level drivers than to firm-internal or structural factors. In such a context, improvements in implementation capacity are perceived as yielding greater marginal emission reduction impacts than the introduction of additional regulations.

Table 2 confirms the reliability of expert judgments. All pairwise comparison matrices satisfy the consistency requirement (CR below the corresponding thresholds), with mean CR values around 0.025 for the Level-1 matrix and approximately 0.030–0.034 for the Level-2 matrices, yielding a 100% pass rate. The analysis included 15 individual expert matrices; the aggregated group matrix was computed separately using the geometric mean and was not counted as an additional respondent.

Table 2: Consistency summary by matrix (mean CR, max CR, pass rate)

Matrix	Threshold	N (records)	Mean CR	Max CR	Pass rate (%)
L1	0.10	15	0.0252	0.0727	100.0
C1	0.09	15	0.0320	0.0693	100.0
C2	0.09	15	0.0330	0.0806	100.0
C3	0.09	15	0.0338	0.0766	100.0
C4	0.09	15	0.0323	0.0766	100.0
C5	0.09	15	0.0299	0.0688	100.0

Source: Author's compilation from expert survey data, 2025

For the Level-1 (C1–C5) matrix, the mean CR = 0.0252 and max CR = 0.0727, both comfortably below the 0.10 threshold. This suggests that experts were particularly consistent when prioritizing the five main criteria, strengthening confidence in the Level-1 ranking and the downstream global weights.

Across the five Level-2 matrices (C1–C5), the mean CR ranges from 0.0299 to 0.0338, and the maximum CR ranges from 0.0688 to 0.0806, all below the 0.09 threshold. These values indicate that experts maintained stable and consistent judgments even when making finer comparisons among subcriteria.

Among Level-2 matrices, C2 has the highest max CR (0.0806) and a mean CR of 0.0330. Although still well within the acceptance threshold, this pattern may reflect that enterprise-related subcriteria are relatively harder to compare (e.g., experts may hold more diverse views due to differences in operational experience or sector exposure). Importantly, the values remain far from the threshold, so this does not threaten reliability.

Table 3: Level-1 criteria weights and ranking (C1–C5)

Code	Criterion	Global weight	Rank
C1	Institutions and public governance	0.2919	**1**
C5	Community and society	0.2502	2
C4	Science, technology, and human resources	0.2018	3
C2	Enterprise capacity	0.1388	4
C3	Economic structure	0.1174	5

Source: Author's compilation from expert survey data, 2025

Building on this validated foundation, Table 3 shows that institutions and public governance (C1) has the highest Level-1 priority weight (0.2919), followed by community and society (C5: 0.2502), and science, technology, and human resources (C4: 0.2018). Together, these three highest-ranked Level-1 criteria account for 74.4% of total importance, indicating that system-level governance, societal engagement, and technological capability are perceived as the dominant dimensions of provincial carbon emission reduction.

This pattern is further clarified in Table 4, which reports the ten highest-ranked Level-2 subcriteria based on global weights. Policy implementation and enforcement (C1.3) is the most important subcriterion, indicating the central role of implementation credibility and compliance enforcement. Other highly ranked subcriteria are concentrated in technology-related factors under science, technology, and human resources, including R&D infrastructure (C4.2) and access to low-emission technologies (C4.1), as well as community-related factors under community and society, including community environmental awareness (C5.1), social pressure on polluting firms (C5.3), and low-carbon consumption behavior (C5.4). This confirms the coherence of the AHP hierarchy across levels, as governance capacity, technological readiness, and societal pressure jointly support carbon emission reduction at the provincial level.

The high ranking of community-related drivers can be explained by the growing role of social awareness and informal pressure in Vietnam, where public opinion, community monitoring, and reputational concerns increasingly influence firm behavior. In Thai Nguyen, this effect is reinforced by dense residential–industrial proximity and the presence of universities and civil society actors, which amplify social scrutiny of environmental performance.

The strong position of science, technology, and human resources is closely linked to Thai Nguyen's role as a regional education and research hub. The concentration of universities and research institutions enhances firms' access to technical knowledge and applied research, thereby increasing the feasibility of adopting low-emission technologies once regulatory and social pressures are in place.

Table 4: The ten highest-ranked subcriteria by global weights

Rank	Subcriterion	Global weight	Cumulative (%)
1	C1.3 – Policy implementation and enforcement	0.144	14.39
2	C4.2 – R&D infrastructure	0.083	22.66
3	C5.1 – Community environmental awareness	0.072	29.84
4	C5.3 – Social pressure on polluting firms	0.071	36.93
5	C4.1 – Access to low-emission technologies	0.069	43.79
6	C5.4 – Low-carbon consumption behavior	0.068	50.57
7	C1.4 – Economic policy instruments	0.062	56.82
8	C3.2 – Dependence on fossil energy	0.059	62.61
9	C3.1 – Share of high emission industries	0.052	67.77
10	C1.2 – Standards and regulatory monitoring	0.046	72.37

Source: Author's compilation from expert survey data, 2025

The cumulative contribution indicates a highly concentrated priority structure: the three leading subcriteria, namely policy implementation and enforcement (C1.3), R&D infrastructure (C4.2), and community environmental awareness (C5.1), collectively account for 29.84% of total importance. The six leading subcriteria account for 50.57%, while the ten leading subcriteria account for 72.37%, supporting a focused policy intervention strategy rather than dispersed efforts. Table 4 identifies the ten highest-ranked subcriteria by global weight (Level-1 × local weight), revealing the most influential drivers in the AHP model. The strongest factor is C1.3 (implementation and enforcement) with a global weight of 0.1439, indicating that experts consider execution capacity and compliance enforcement the key leverage point. The remaining top-ranked items cluster mainly under C1 (governance tools and standards), C5 (community awareness, social pressure, green consumption), and C4 (research capacity and clean technology adoption), with smaller contributions from C3 (energy dependence and industrial structure). Overall, the ten highest-ranked subcriteria account for 72.37% of total priority, implying that policy efforts can focus on a compact set of high-impact levers.

Table 5: Comparison of Level-1 weights by expert group (n = 5 per group)

Code	Criterion	Government	Enterprises	Academia	Overall
C1	Institutions and public governance	0.2584	0.2863	0.3184	0.2919
C2	Enterprise capacity	0.1252	0.1527	0.1430	0.1388
C3	Economic structure	0.1176	0.1385	0.1025	0.1174
C4	Science, technology, and human resources	0.2379	0.1834	0.1866	0.2018
C5	Community and society	0.2609	0.2390	0.2494	0.2502

Source: Author's compilation from expert survey data, 2025

Table 5 reveals clear but coherent differences in priority perceptions across stakeholder groups. Government experts place the highest emphasis on community and society (0.2609) and institutions and public governance (0.2584), reflecting a policy perspective that combines regulatory capacity with social acceptance. Enterprise respondents prioritize institutions and public governance (0.2863) most strongly, indicating their reliance on clear, predictable rules to guide investment and operational decisions. In contrast, academic experts assign the greatest weight to institutions and public governance (0.3184), underscoring the central role of governance quality in shaping system-wide outcomes.

Despite these differences, all three groups consistently rank institutions and public governance among the top priorities, while economic structure (C3) receives the lowest weight across groups.

Table 6: Sensitivity of five highest-ranked subcriteria to changes in Level-1 weights

Scenario	C1 −10%	Baseline	C1 +10%
Rank 1	C1.3	C1.3	C1.3
Rank 2	C4.2	C4.2	C4.2
Rank 3	C5.1	C5.1	C5.1
Rank 4	C5.3	C5.3	C5.3
Rank 5	C4.1	C4.1	C4.1

Source: Author's compilation from expert survey data, 2025

Table 6 shows that the five highest-ranked subcriteria remain unchanged when the Level-1 weight of the leading criterion is varied by ±10%. In all tested scenarios, policy implementation and enforcement retain the first position, followed by the same set of high-priority subcriteria. This stability indicates that the ranking is robust to reasonable changes in criteria weights and is not driven by a single weighting assumption. Consequently, the identified top drivers can be regarded as reliable priorities for interpretation and policy discussion.

Taken together, the dominance of governance, social, and technological drivers suggests that carbon emission reduction at the provincial level is primarily a system-level process, in which firm behavior is shaped by institutional credibility, societal expectations, and enabling innovation capacity rather than by firm internal factors alone.

B. Discussion

The findings first suggest that institutions and public governance constitute the primary enabling condition for carbon emission reduction at the provincial level. This does not imply that regulation alone is sufficient; rather, the results emphasize the importance of implementation credibility, monitoring capacity, and enforcement effectiveness. This finding is consistent with previous studies showing that environmental policy outcomes depend not only on the existence of formal regulations but also on the capacity of public institutions to implement and enforce them effectively [21, 22]. In the context of Thai Nguyen, this result is particularly relevant because the province is experiencing rapid industrial development, where the effectiveness of environmental governance can directly influence firms' incentives to comply with regulations and invest in cleaner production. Compared with national- and sectoral-level econometric studies that examine emission drivers through indicators such as GDP growth, industrial structure, energy mix, environmental regulation, and carbon-market instruments [7, 8, 12, 13], as well as studies of emissions trading schemes in emerging economies [14, 15, 24], this study highlights governance as a locally perceived and operational policy priority within a provincial decision-making framework.

In addition to governance, science, technology, and human resources play a critical role in converting regulatory pressure and social expectations into practical mitigation actions. Regulatory requirements and social expectations can encourage firms to reduce emissions, but actual implementation depends on access to low-emission technologies, research and development infrastructure, skilled human resources, and university–industry–government linkages. This finding is consistent with the literature on innovation-driven mitigation, which emphasizes that firms' environmental responses depend on technological capability, knowledge diffusion, and human capital [25, 26]. In Thai Nguyen, the presence of universities and research institutions strengthens the local innovation ecosystem and creates favorable conditions for technology transfer, applied research, and green workforce development. Therefore, technological and human resource factors should be understood not as isolated drivers, but as enabling capacities that allow firms and local authorities to translate low-carbon policy objectives into concrete actions.

Community and society factors also serve as an important complementary mechanism that reinforces formal governance and influences enterprise behavior. Environmental awareness, public participation, social pressure on polluting firms, and low-carbon consumption behavior can influence enterprise behavior through reputational effects, stakeholder scrutiny, and demand-side expectations. This finding aligns with sustainability transition studies that emphasize the role of social pressure and public awareness in shaping corporate environmental behavior [27, 28]. In emerging economies, where formal enforcement capacity may vary across sectors and localities, community-based monitoring and social expectations can reinforce compliance and encourage firms to adopt cleaner practices. Thus, the role of community and society should not be interpreted merely as a behavioral dimension, but as a complementary mechanism that strengthens the effectiveness of formal environmental governance.

The comparatively lower priority assigned to enterprise capacity and economic structure should not be interpreted as evidence that these factors are unimportant. Firms are the direct actors that consume energy, adopt technologies, and generate emissions, while economic structure determines the long-term emission profile of the province. However, the AHP results suggest that experts perceive these factors as being strongly conditioned by broader system-level drivers. Enterprise-level change is more likely to occur when firms face credible regulation, have access to suitable technologies, and respond to social and market pressure. Similarly, structural transformation toward greener and less carbon-intensive development requires institutional coordination, innovation capacity, and long-term policy commitment. This interpretation is consistent with firm-level evidence showing that internal capabilities alone may be insufficient to produce substantial emission reductions without external incentives and enabling conditions [29]. Overall, the discussion indicates that provincial carbon emission reduction should be viewed as a system-level process in which governance credibility, technological capacity, community pressure, enterprise behavior, and structural change interact rather than operate independently.

V. CONCLUSION AND IMPLICATIONS

This study applied an expert-based analytic hierarchy process to identify and prioritize the key drivers of carbon emission reduction in the context of economic development at the provincial level, using Thai Nguyen Province in Vietnam as an empirical case. By integrating governance, technological, economic, enterprise-related, and social dimensions into a unified prioritization framework, the analysis provides a structured understanding of how different drivers contribute to emission reduction under local development constraints.

The results highlight a clear dominance of system-level drivers. Institutions and public governance, particularly policy implementation and enforcement, emerge as the most influential dimension, followed by community and society factors, and science, technology, and human resources. At the subcriterion level, implementation capacity, research and development infrastructure, community environmental awareness, and clean technology adoption account for a large share of total priority weight. The highly concentrated priority structure suggests that focused interventions targeting a limited set of high-impact drivers are likely to be more effective than dispersed, firm-centered measures. From a theoretical perspective, the study contributes to the literature on carbon mitigation by extending governance and institution-centered explanations to the provincial level and by explicitly integrating social and technological drivers into a single decision-support framework. Rather than treating these factors as auxiliary or contextual variables, the AHP results reveal their relative importance and interaction as core mechanisms shaping subnational mitigation outcomes in emerging economies.

Although the empirical analysis is grounded in the specific context of Thai Nguyen, the proposed framework and methodological approach are not province-specific. The criteria system, expert-based prioritization logic, and interpretation of global weights can be adapted to other provinces in Vietnam and to comparable subnational contexts in emerging and developing economies, with appropriate contextual calibration. In settings where detailed emission data are limited but expert knowledge is available, the approach offers a practical and transparent tool for policy sequencing and resource allocation.

From a policy perspective, the findings suggest that provincial carbon mitigation strategies should prioritize system-level interventions rather than isolated firm-level measures. Strengthening implementation and enforcement capacity is likely to yield the greatest immediate impact, particularly when complemented by investments in research infrastructure and mechanisms that enhance community awareness and social pressure. Rather than expanding the number of regulatory instruments, policymakers may achieve greater effectiveness by improving coordination, credibility, and sequencing among governance, technological, and social drivers.

Certain limitations should be acknowledged. First, the study relies on a purposively selected expert panel of 15 respondents. Although this sample size is appropriate for an expert-based AHP design that emphasizes informed judgment and consistency of pairwise comparisons, the findings should be interpreted as expert-perceived priorities rather than statistically representative estimates. Second, the AHP approach identifies the relative importance of mitigation drivers but does not estimate their causal effects on actual emission outcomes. Third, the single-case design limits direct generalization to all Vietnamese provinces. Future research should expand the expert sample, apply the proposed AHP framework to multiple industrial provinces, and integrate expert-based priorities with quantitative emission inventories, longitudinal data, or firm-level carbon information.

ACKNOWLEDGMENTS

The authors would like to sincerely thank Thai Nguyen University of Economics and Business Administration – Thai Nguyen University for its contribution. This research belongs to the University-level Science and Technology Project 2025, code number DH2025- TN08-01.

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