

Article

Regionalized Well-to-Wheel Mechanism Diagnosis of Low-Carbon Bus Transition Across Northwest China's Electricity–Hydrogen Systems

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Abstract

The low-carbon bus transition depends on the electricity and hydrogen pathways that support vehicle operation. This study develops a regionalized WTW mechanism diagnosis for six provincial electricity–hydrogen–bus systems in Northwest China and an adjacent energy-output region. Localized GREET pathway intensities, fleet-level aggregation, Logarithmic Mean Divisia Index (LMDI) decomposition, B0-upstream HFCB exposure tests, local A/B/C perturbations and HFCB intensity-sensitivity checks are combined to evaluate greenhouse gas (GHG) emissions, primary-energy consumption and primary-water burden. The results show that B0–S1 fleet-level GHG reductions range from 9.86% in Shaanxi to 73.81% in Qinghai, while Gansu records the largest absolute decrease, from 126.52 to 41.21 kg CO₂-eq/hkm. GHG, primary-energy and primary-water responses diverge: in Qinghai, S1–S2 GHG intensity decreases by 28.76%, while primary-energy consumption and primary-water burden increase by 1.99% and 21.31%, respectively. LMDI results reveal different attribution mechanisms, including dual-driver reduction in Gansu and a counter-acting composition effect in Shaanxi. Exposure, perturbation and sensitivity tests indicate that hydrogen-related outcomes depend on pathway intensity, fleet share and break-even margins. The findings support pathway-conditioned screening that coordinates BEB and HFCB expansion with electricity decarbonization, renewable-hydrogen availability and multi-indicator burden assessment.

Keywords: low-carbon bus transition; electricity–hydrogen system; LMDI decomposition; Northwest China; primary-water burden



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1. Introduction

Road-transport decarbonization has become an essential component of climate-mitigation strategies worldwide [1]. Public buses are intensively used urban transport assets, and their long annual operating distances make them important targets for fleet decarbonization. The transition from diesel buses (DBs) to battery electric buses (BEBs) and hydrogen fuel cell buses (HFCBs) is increasingly regarded as an important pathway for reducing GHG emissions while maintaining public transport services [2–5]. However, the environmental implications of bus decarbonization extend beyond vehicle technologies themselves. The benefits achieved by BEB and HFCB deployment depend not only on fleet electrification or hydrogen adoption, but also on the upstream energy systems that supply electricity and hydrogen for vehicle operation. A WTW perspective is necessary for

evaluating how low-carbon bus transition shifts GHG, primary-energy and primary-water burdens across the energy chain.

Recent WTW and LCA studies have compared DBs, BEBs and HFCBs by tracing environmental burdens across fuel production, energy delivery, vehicle operation and, in some cases, vehicle production and infrastructure stages [2–5]. A consistent finding is that BEBs and HFCBs can reduce WTW or life-cycle GHG emissions relative to conventional DBs, while the magnitude of reduction depends strongly on the adopted system boundary and upstream energy-pathway assumptions [2–4]. Recent work on public-bus LCA uncertainty further shows that comparative results are sensitive to life-cycle impact assessment methods, inventory databases, modeling approaches, energy-carrier consumption and lifetime assumptions, reinforcing the need to state assumptions clearly and interpret deterministic comparisons as condition-dependent results [6]. BEB outcomes are particularly sensitive to electricity-generation mix, grid carbon intensity, charging configuration and operational conditions [2,6–10]. Recent materials-level hydrogen-generation studies, including work on air-stable expanded graphite and magnesium-based composites, further illustrate the continuing diversification of hydrogen-generation technologies [11]. For transport LCA, however, such technological options need to be translated into pathway-level energy inputs, material requirements, supply conditions and delivery assumptions before their fleet-level implications can be assessed. HFCB outcomes vary with hydrogen-production route, electricity input, delivery conditions and refueling assumptions [2–5,12]. China-specific hydrogen studies further show that hydrogen-transition uncertainty and sectoral demand contexts affect the environmental and economic competitiveness of hydrogen pathways [13–15]. Recent research has also moved beyond GHG emissions to examine primary energy consumption, primary-water burden and broader environmental trade-offs, showing that no single bus technology consistently outperforms all alternatives across indicators and operating contexts [2,16–18]. These findings indicate that vehicle labels alone provide an incomplete basis for environmental comparison. For bus-transition assessment, the relevant analytical unit is therefore not only the vehicle type, but the vehicle–energy pathway through which substitution from DBs to BEBs or HFCBs changes WTW GHG, primary-energy and primary-water burdens.

Electricity and hydrogen pathway studies further explain why upstream conditions are central to low-carbon bus assessment. For BEBs, life-cycle studies of urban bus decarbonization indicate that the GHG advantage of electrification depends on the electricity mix that supplies charging energy [8]. BEB scheduling and grid-integration studies further show that BEB deployment is connected with photovoltaic generation, energy storage, power-grid constraints and bus-to-grid services [9,10]. These studies suggest that BEB performance should not be inferred from zero tailpipe emissions alone, because charging-related electricity demand is embedded in the carbon intensity, renewable-integration capacity and operational flexibility of the power system. Hydrogen pathway studies provide a parallel implication for HFCBs. Systematic reviews of hydrogen-production LCA show large variation in life-cycle GHG intensity across steam reforming, fossil-fuel gasification, biomass-based pathways and water electrolysis [12]. China-specific studies further indicate that grid-connected electrolysis is not automatically low-carbon; hydrogen pathway competitiveness depends on provincial electricity conditions, system configuration, sectoral demand contexts and transition uncertainty [13–15]. Global prospective LCA and green-hydrogen studies also show that low-carbon hydrogen can reduce GHG emissions relative to fossil-based pathways, but may introduce energy, water, land and supply-chain trade-offs [16–19]. These findings indicate that hydrogen cannot be treated as a uniform low-carbon input. For HFCB assessment, the relevant question is which hydrogen pathway

is used, how it is powered, and what resource burdens are generated along the production, delivery and refueling chain.

These pathway findings have an important regional implication. Regional energy-transition and sustainability-transition studies have emphasized that low-carbon technologies are shaped by spatially uneven resource endowments, infrastructure conditions, industrial structures and institutional settings [20–22]. Low-carbon transport technologies therefore cannot be evaluated independently of the electricity and hydrogen systems in which they are deployed. Regional differences in electricity carbon intensity, renewable-resource conversion, power-system position, hydrogen-production conditions and water-related constraints can change the WTW performance of the same nominal bus-transition pathway [13,16–22]. National-average electricity or hydrogen assumptions may therefore conceal the mechanism through which upstream pathway conditions shape fleet-level outcomes. For bus-transition assessment, regional heterogeneity shapes the pathway intensities attached to BEB charging and HFCB hydrogen supply. Northwest China provides a suitable setting for examining this regional mechanism. The empirical setting covers six provincial electricity–hydrogen–bus systems in Northwest China and an adjacent energy-output region—Inner Mongolia, Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang. These systems share a broad national low-carbon transition context but differ sharply in electricity carbon intensity, electricity-system position, renewable-resource conversion conditions and hydrogen-supply assumptions. Some are major electricity-production and power-delivery systems, while others have lower-carbon electricity structures or stronger renewable-regulation conditions. These differences allow the same DB, BEB and HFCB transition settings to be compared across heterogeneous electricity–hydrogen conditions. The region is therefore used as a diagnostic setting for examining why the same vehicle-composition change may produce different fleet-level GHG, primary-energy and primary-water outcomes across heterogeneous electricity–hydrogen systems.

Methodologically, existing studies have used decomposition and scenario-based approaches to move beyond aggregate emission estimates. Decomposition analysis has been widely applied to attribute changes in energy use and emissions to predefined drivers such as activity, structure, energy intensity and emission intensity [23]. In transport-related applications, recent studies have examined how energy intensity, energy structure, production linkages, final demand and vehicle-category changes shape CO₂ emissions from transport sectors and on-road transportation systems [24,25]. These studies demonstrate the value of decomposition methods for identifying aggregate emission drivers, but they mainly explain macro-sectoral or road-transport emissions and rarely decompose bus-fleet WTW GHG changes into pathway-intensity and vehicle-composition effects. Fleet-scenario studies provide another relevant methodological stream. Recent research has examined bus fleet replacement, charging-infrastructure planning and mixed BEB–hydrogen-bus operation under constraints such as depot capacity, charging availability, refueling flexibility and operational scheduling [26,27]. These studies show that low-carbon bus deployment depends on fleet composition, infrastructure configuration and operational constraints. Yet their main focus is deployment feasibility, scheduling or system operation. Less attention has been paid to whether clean-electricity improvement, green-hydrogen improvement and HFCB share expansion generate comparable fleet-level WTW signals under the same regional baseline. This gap is especially relevant when clean-electricity improvement, green-hydrogen improvement and HFCB share expansion occur simultaneously but enter fleet-level WTW burdens through different mechanisms.

Taken together, existing studies provide important foundations for bus WTW accounting, electricity- and hydrogen-pathway assessment, decomposition analysis, fleet-scenario comparison and regional transition analysis. These strands, however, are rarely

integrated into a regional fleet-level framework that explains how electricity–hydrogen heterogeneity is translated into WTW burden outcomes. Bus WTW studies show that vehicle performance depends on upstream energy pathways, but less often trace how regional electricity and hydrogen conditions shape fleet-level GHG emissions, primary-energy consumption and primary-water burden. Decomposition studies identify aggregate emission drivers, but they rarely separate WTW pathway-intensity effects from vehicle-composition effects within bus-fleet transition. Fleet-scenario studies examine deployment and operational outcomes, but they seldom compare how equal local changes in clean-electricity condition, green-hydrogen share and HFCB vehicle share become visible at the fleet level. This gap motivates a regionalized WTW mechanism diagnosis of electricity–hydrogen–bus transition.

This study addresses this gap by developing a regionalized WTW diagnostic framework for electricity–hydrogen–bus systems. The analysis asks three linked questions. First, how are regional electricity–hydrogen pathway conditions translated into fleet-level GHG, primary-energy and primary-water outcomes under comparable bus-transition settings? Second, when fleet-level GHG changes occur, how much is generated by pathway-intensity improvement, vehicle-composition change or counteracting movement between the two? Third, how do clean-electricity improvement, green-hydrogen improvement and HFCB vehicle-share expansion appear in fleet-level WTW outcomes, and how stable are HFCB-related GHG results under pathway-intensity variation?

To answer these questions, the study combines localized GREET-based WTW pathway intensities, fleet-level aggregation, additive LMDI decomposition and diagnostic scenario tests. This design links regional pathway conditions with burden profiles, attribution structures, fleet-level pathway visibility and HFCB stability margins.

This study makes three contributions. First, it extends bus-oriented LCA from vehicle or fuel-pathway comparison to regional mechanism diagnosis. Second, it links pathway intensity attribution with fleet composition effects through LMDI decomposition. Third, it evaluates multi-indicator burden alignment and HFCB stability margins under regional electricity–hydrogen heterogeneity. The proposed diagnostic approach provides an environmental screening basis for interpreting BEB and HFCB deployment under regionally differentiated pathway conditions.

2. Materials and Methods

2.1. Regional Scope, Structural Gradients and Parameter Basis

This study focuses on six provincial electricity–hydrogen–bus systems in Northwest China and an adjacent energy-output region: Inner Mongolia, Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang. The cases form a purposive provincial contrast set rather than a statistical sample. They are selected to span high-, intermediate- and low-carbon electricity positions, differentiated hydrogen-development contexts and contrasting bus-transition conditions. The provincial scale is used because electricity generation, hydrogen planning and bus-fleet parameters are mainly reported and parameterized at this level, allowing a consistent regional WTW comparison across the six systems.

The selection is designed to examine a specific regional problem: how low-carbon bus pathways perform when they are embedded in energy-production systems where coal-based electricity, renewable-resource conversion and hydrogen development coexist. This distinguishes the study region from eastern demand-side metropolitan regions, southern hydropower-dominant regions and purely urban vehicle-substitution cases. Including those regions would shift the analysis from a mechanism-oriented regional diagnosis toward a broader national comparison involving additional market, urban-demand and infrastructure-readiness factors.

The six provincial systems jointly cover the main pathway contrasts required by the study. Qinghai provides a low-carbon electricity reference with strong clean-electricity and green-hydrogen potential. Gansu represents an intermediate electricity-system case with renewable-resource endowment and upstream transition constraints. Inner Mongolia, Shaanxi, Ningxia and Xinjiang represent energy-producing systems with stronger coal-power or fossil-energy foundations, while also participating in wind–solar expansion and hydrogen-development planning. Ningxia and Xinjiang further provide energy–chemical or refining interfaces for hydrogen use, whereas Inner Mongolia provides a stronger heavy-transport and energy-logistics contrast. These differences allow the same DB/BEB/HFCB transition settings to be compared across low-carbon, intermediate and high-carbon electricity conditions as well as differentiated hydrogen-supply assumptions.

The structural indicators used for parameter localization support this contrast. The six systems span a pronounced grid-carbon gradient, with Qinghai positioned at the low-carbon end, Gansu occupying an intermediate position and Inner Mongolia representing the high-carbon end. Shaanxi, Ningxia and Xinjiang remain closer to the high-carbon side of the gradient. They also differ in electricity-system position: Inner Mongolia, Shaanxi, Gansu, Ningxia and Xinjiang have electricity generation exceeding local consumption, whereas Qinghai is closer to balance. The six systems are therefore used as a coherent regional contrast set for examining whether renewable-resource advantages, coal-based electricity structures, hydrogen-production assumptions and transport-energy demand translate into different fleet-level WTW outcomes. The corresponding structural indicators, GREET localization treatments, numerical scenario settings and scenario-parameter derivation notes are reported in Supplementary Tables S1, S2 and S4a,b.

Figure 1 summarizes the conceptual and methodological framework of the regionalized WTW mechanism diagnosis. It shows how regional electricity–hydrogen conditioning is translated into fleet-level WTW burdens through pathway-intensity formation and fleet-composition weighting.

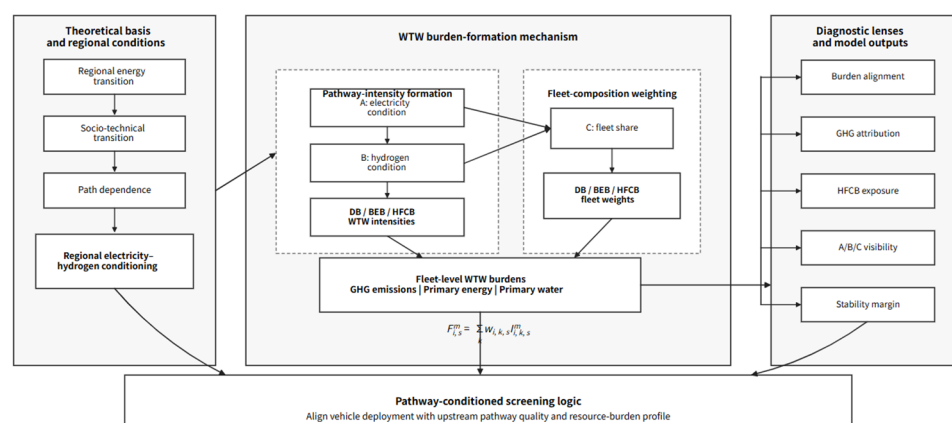


Figure 1. Regionalized WTW mechanism-diagnosis framework for electricity–hydrogen–bus transition.

2.2. LCA Boundary

LCA provides a structured approach for evaluating environmental burdens associated with products and technological systems. Following the general LCA logic of goal and scope definition, inventory analysis, impact assessment and interpretation, this study defines its goal as diagnosing operational energy-chain burdens of DB, BEB and HFCB pathways under regionally differentiated electricity and hydrogen conditions [28,29].

This study adopts a WTW fuel-cycle boundary to evaluate DB, BEB and HFCB pathways. The boundary includes well-to-pump (WTP) energy-supply processes, such as fuel, electricity and hydrogen production, delivery, storage, charging or refueling, and pump-

to-wheel (PTW) vehicle operation. Vehicle-cycle stages, including vehicle manufacturing, component production, infrastructure construction and end-of-life treatment, are outside the calculation boundary. This boundary is consistent with public bus energy-pathway studies that use WTW analysis to examine how fuel supply, electricity mix, hydrogen production and vehicle operation shape operational GHG and resource burdens [2,5,30–32]. The WTW boundary is used to isolate the operational energy-chain mechanism through which regional electricity and hydrogen pathways affect bus operation. The results are interpreted as WTW energy-chain outcomes.

DBs, BEBs and HFCBs differ in powertrain, but they also depend on different upstream energy chains. The DB pathway includes petroleum extraction, refining, distribution and direct diesel combustion during vehicle operation. The BEB pathway links vehicle operation to electricity generation, transmission and charging-related electricity use. The HFCB pathway links vehicle operation to hydrogen production, electricity inputs embedded in hydrogen supply, hydrogen delivery and refueling. BEBs and HFCBs are treated as having zero direct GHG emissions at the point of vehicle operation, while their upstream burdens are captured through the electricity and hydrogen pathways.

The functional unit is 100 vehicle-kilometers, denoted as hkm, which supports a vehicle distance-based comparison of fleet-pathway burden intensity rather than passenger-service efficiency. Three WTW burden indicators are evaluated: GHG emissions, primary energy consumption and primary-water burden. GHG emissions are expressed as kg CO₂-eq/hkm. Primary energy consumption is expressed as J/hkm. Primary-water burden is expressed as m³/hkm.

Pathway intensities are constructed using GREET-based WTW parameters localized with provincial inputs where available. GREET 2024 is used as the base fuel-cycle model. Provincial localization is implemented as a regional pathway parameterization of the energy-chain links that are most relevant to bus WTW outcomes. It focuses on electricity inputs for BEB operation and hydrogen production, hydrogen-production mix and green-hydrogen availability, hydrogen delivery and refueling assumptions, pathway-specific water factors for cooling, mining-related and process water, and fleet-composition parameters. Where province-specific evidence is available, default parameters are replaced with localized or scenario-defined values. These replacements are screened for source traceability, unit consistency, cross-provincial comparability and consistency with the GREET 2024 baseline before being used in the WTW calculation. Other non-localized fuel-cycle parameters and harmonized vehicle energy-use assumptions are retained from GREET 2024 or treated consistently across provinces to reduce route-level operating heterogeneity. Detailed engineering assumptions, parameter treatments and data sources are reported in Supplementary Table S2, with scenario source documents and derivation notes summarized in Supplementary Table S4b. The resulting parameterization is deterministic and source-traceable rather than probabilistic, and the stability of the main diagnostic claims is examined through the structured scenario contrasts and sensitivity modules described in Section 2.3.

Primary-water burden is defined as upstream energy-chain water consumption within the adopted WTW boundary. It includes cooling-water consumption, mining-related water consumption and process-water consumption associated with fuel, electricity and hydrogen pathways. The indicator represents energy-chain water consumption and is not a scarcity-weighted measure of local water stress. Water results are interpreted as WTW energy-chain water burdens. The pathway-specific water factors, units, sources and dominant components are reported in Supplementary Table S3.

2.3. Scenario Design and Diagnostic Modules

The scenario design links upstream electricity–hydrogen pathway conditions with downstream bus-fleet composition. Regional electricity and hydrogen parameters determine the pathway intensities of DB, BEB and HFCB operation, while vehicle-composition settings determine how these pathway profiles are expressed in fleet-level outcomes. The design combines a full-region B0–S1–S2 comparison with additional diagnostic modules for GHG attribution, B0-upstream HFCB exposure, local A/B/C visibility and HFCB pathway-intensity stability. The B0–S1–S2 comparison is applied to all six provinces and provides the main cross-provincial evidence. The additional modules are used to isolate specific mechanisms that the full-region comparison cannot identify directly: HFCB pathway exposure under fixed upstream conditions, the fleet-level visibility of equal local A/B/C perturbations around S1, and the stability of HFCB-related GHG outcomes under pathway-intensity variation.

Three parameters organize the scenario settings. Parameter A denotes the clean-electricity condition of the provincial electricity pathway. Parameter B denotes the green-hydrogen share in the hydrogen supplied to the modeled HFCB refueling pathway, rather than the green-hydrogen share in total provincial hydrogen production. Parameter C denotes the HFCB vehicle share in the bus fleet. B0 represents the 2023 benchmark, with electricity-system and bus-fleet inputs based on observed 2023 data where available. S1 and S2 are future-oriented, planning-informed 2035 diagnostic settings constructed under the common modeling treatment described in Section 2.2, with harmonized HFCB vehicle-share anchors of 5% and 15%, respectively. The numerical A/B/C settings, source documents and derivation notes are reported in Supplementary Table S4a,b.

The allocation of additional diagnostic modules follows the structural gradients identified in Section 2.1. Table 1 summarizes the logic. The B0-upstream HFCB exposure test uses three systems positioned along the grid-carbon gradient. Inner Mongolia represents the high-carbon end of the gradient, Gansu provides an intermediate electricity-system case, and Qinghai provides the low-carbon electricity-system reference. This design is used to examine how the HFCB pathway behaves when exposed under different upstream electricity conditions. The M-series uses three low-A cases around S1 with differentiated green-hydrogen settings: Xinjiang combines low clean-electricity share with a high green-hydrogen assumption, Ningxia combines low clean-electricity share with a medium green-hydrogen assumption, and Shaanxi combines low clean-electricity share with a constrained green-hydrogen assumption. This design allows the local visibility of clean-electricity improvement, green-hydrogen improvement and HFCB vehicle-share expansion to be compared under upstream-constrained electricity conditions.

In the B0-upstream HFCB exposure test, the electricity–hydrogen pathway conditions are fixed at the B0 benchmark setting while the HFCB vehicle share is set to full exposure for diagnostic purposes. It is an upper-bound diagnostic setting designed to magnify the WTW burden profile of the modeled B0 HFCB pathway and compare it with the B0 fleet benchmark.

The M-series tests local pathway visibility around S1. M1 increases (A) by five percentage points, M2 increases (B) by five percentage points, and M3 increases (C) from 5% to 10%, while the remaining S1 conditions are held fixed. The five-percentage-point step is used as an equal finite local perturbation around S1 to compare the fleet-level visibility of A, B and C changes. This step is large enough to generate observable fleet-level responses but small enough to remain a local diagnostic perturbation. It is not interpreted as a policy-realistic transition magnitude, a policy-priority ranking or a cost-effectiveness ranking. The three implemented cases share low clean-electricity conditions around S1 but differ in green-hydrogen assumptions, which makes them suitable for comparing how

electricity improvement, green-hydrogen improvement and HFCB vehicle-share expansion enter WTW outcomes under upstream-constrained conditions.

Table 1. Diagnostic-module allocation logic.

Module	Analytical Role	Allocation Criterion	Implemented Cases
B0–S1–S2 comparison	Full-region burden comparison	Applied to all six systems	Inner Mongolia, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang
B0-upstream HFCB exposure test	Upper-bound exposure of the HFCB pathway under B0 upstream conditions	High–intermediate–low positions along the grid-carbon gradient	Inner Mongolia, Gansu, Qinghai
M-series local perturbation test	Local visibility of A, B and C changes around S1	Low-A cases with differentiated green-hydrogen settings	Xinjiang, Ningxia, Shaanxi
HFCB pathway-intensity sensitivity	Boundary-condition check for HFCB -related GHG conclusions	Applied to HFCB exposure and HFCB-share perturbation cases	T1 and M3 cases

Note: This table reports the allocation logic of the diagnostic modules. The complete province-specific A/B/C values for B0, S1 and S2, and additional diagnostic settings are reported in Supplementary Table S4a, while source documents, derivation rules, and source notes are reported in Supplementary Table S4b.

Technology-specific hydrogen-production routes are not modeled as separate stand-alone engineering scenarios. The main analysis represents hydrogen-supply differences at the HFCB pathway-intensity level through parameter B and the HFCB pathway-intensity sensitivity test. This treatment is consistent with the diagnostic purpose of the study, which compares how regional electricity–hydrogen pathway conditions are translated into fleet-level WTW outcomes rather than estimating plant-level hydrogen-production technology scenarios. The HFCB pathway-intensity sensitivity test varies HFCB pathway GHG intensity by $\pm 20\%$ while holding fleet composition and non-HFCB pathway intensities unchanged. The $\pm 20\%$ range is used as a moderate one-way stress amplitude informed by published evidence on hydrogen pathway GHG-intensity variability across production routes, system-boundary choices and China-specific transition assumptions [12,14]. It is not interpreted as a probabilistic uncertainty interval or as the full uncertainty range of hydrogen supply. The test examines whether HFCB-related GHG conclusions remain directionally stable under pathway-intensity variation and identifies the distance from the GHG break-even condition. The break-even condition is interpreted within the fleet-aggregation calculation and not as a system-level equilibrium threshold.

2.4. Calculation Methods and Diagnostic Metrics

2.4.1. Technology-Specific WTW Intensity

Based on the WTW boundary and pathway parameterization described in Section 2.2, technology-specific pathway intensities are calculated for each province, bus technology, scenario and burden category. For province i , bus technology k , scenario s , and burden category m , the intensity is calculated as:

$$I_{i,k,s}^m = I_{i,k,s}^{m,WTP} + I_{i,k,s}^{m,PTW} \quad (1)$$

where $I_{i,k,s}^m$ denotes the intensity of burden category m , $I_{i,k,s}^{m,WTP}$ denotes the upstream well-to-pump intensity, and $I_{i,k,s}^{m,PTW}$ denotes the pump-to-wheel intensity. The burden categories include GHG emissions, primary energy consumption and primary-water burden.

Primary-water burden is calculated as an upstream energy-chain water-consumption indicator within the adopted WTW boundary.

$$I_{i,k,s}^W = W_{i,k,s}^{cool} + W_{i,k,s}^{min} + W_{i,k,s}^{proc} \quad (2)$$

where $I_{i,k,s}^W$ denotes the primary-water burden, $W_{i,k,s}^{cool}$ denotes cooling-water consumption, $W_{i,k,s}^{min}$ denotes mining-related water consumption, and $W_{i,k,s}^{proc}$ denotes process-water consumption.

2.4.2. Fleet-Level Aggregation and Burden-Change Convention

Technology-specific WTW intensities are aggregated using vehicle-composition shares:

$$F_{i,s}^m = \sum_k w_{i,k,s} I_{i,k,s}^m \quad (3)$$

where $F_{i,s}^m$ denotes the fleet-level WTW burden intensity, $w_{i,k,s}$ is the share of technology k in province i under scenario s , and $\sum_k w_{i,k,s} = 1$. $I_{i,k,s}^m$ denotes the pathway-specific WTW intensity.

Scenario changes are reported using a unified burden-change convention:

$$BC_i^m(s|r) = \frac{F_{i,s}^m - F_{i,r}^m}{F_{i,r}^m} \times 100, m \in \{G, E, W\} \quad (4)$$

where r denotes the reference setting and s denotes the comparison setting. Negative values indicate burden reductions, while positive values indicate burden increases. B0 is used as the reference for B0–S1 and the exposure module, S1 is used as the reference for S1–S2 and the M-series perturbations.

2.4.3. LMDI Decomposition

To identify how fleet-level GHG changes are generated, the study applies additive LMDI decomposition to the GHG burden change [33]. For each pathway k , its contribution to fleet-level WTW GHG burden is defined as:

$$C_{i,k,s} = w_{i,k,s} I_{i,k,s}^G \quad (5)$$

The total GHG burden between reference scenario r and comparison scenario s is:

$$\Delta F_i^G(s|r) = F_{i,s}^G - F_{i,r}^G \quad (6)$$

Under this sign convention, $\Delta F_i^G(s|r) < 0$ indicates a reduction in fleet-level WTW GHG burden, while $\Delta F_i^G(s|r) > 0$ indicates a burden increase.

The change is decomposed into a pathway-intensity effect and a vehicle-composition effect:

$$\Delta F_i^G(s|r) = \Delta F_{i,int}^G(s|r) + \Delta F_{i,comp}^G(s|r) \quad (7)$$

The pathway-intensity effect is calculated as:

$$\Delta F_{i,int}^G = \sum_{k \in K} L(C_{i,k,s}, C_{i,k,r}) \ln \left(\frac{I_{i,k,s}^G}{I_{i,k,r}^G} \right) \quad (8)$$

The vehicle-composition effect is calculated as:

$$\Delta F_{i,comp}^G = \sum_{k \in K} L(C_{i,k,s}, C_{i,k,r}) \ln \left(\frac{w_{i,k,s}}{w_{i,k,r}} \right) \quad (9)$$

where $L(x, y)$ is the logarithmic mean:

$$L(x, y) = \begin{cases} \frac{x-y}{\ln x - \ln y}, & x > 0, y > 0, x \neq y \\ x, & x = y > 0 \end{cases} \quad (10)$$

The intensity effect reflects changes in pathway-specific WTW GHG intensities, while the composition effect reflects changes in DB, BEB and HFCB vehicle shares.

LMDI decomposition is applied to fleet-level GHG changes because this module is designed for decarbonization attribution. Mathematically, the same additive form can be extended to other additive burden indicators, including primary energy consumption and primary-water burden. In this study, however, primary energy consumption and primary-water burden are interpreted as burden-profile and trade-off indicators rather than as the main attribution targets. For primary-water burden, the analysis traces the component structure of pathway-specific water factors, including cooling-water, mining-related and process-water contributions. This component trace is used to identify the source of the Qinghai water increase, whereas the LMDI module is retained for GHG pathway-intensity and vehicle-composition attribution. This treatment keeps the decomposition analysis aligned with the decarbonization objective while using energy and water indicators to evaluate resource-burden trade-offs.

For technology entry or exit, zero-share terms are handled using the limiting-value treatment in additive LMDI [33]. When a pathway enters or leaves the fleet through a change from or to zero vehicle share, the corresponding entry or exit contribution is assigned to the vehicle-composition component. Additive consistency is checked by verifying that the sum of the intensity and composition effects equals the total GHG change.

2.4.4. Exposure, Perturbation and Sensitivity Calculations

The B0-upstream HFCB exposure test and the M-series perturbations are evaluated using the burden-change convention defined above. For the exposure test, B0 is used as the reference. For the M-series, S1 is used as the reference.

For the M-series, visibility ratios are calculated from absolute GHG burden-change magnitudes:

$$R_{i,A/B}^G = \frac{|BC^G(M1|S1)|}{|BC^G(M2|S1)|} \quad (11)$$

$$R_{i,C/B}^G = \frac{|BC^G(M3|S1)|}{|BC^G(M2|S1)|} \quad (12)$$

These visibility ratios are interpreted as local WTW expression measures under equal percentage-point perturbations; they are not used as measures of cost-effectiveness, implementation feasibility or policy-priority ranking across electricity, hydrogen and vehicle-deployment measures.

The HFCB pathway-intensity sensitivity test varies HFCB GHG intensity by a multiplier μ :

$$I_{i,H,s}^G(\mu) = \mu I_{i,H,s}^G \quad (13)$$

where (H) denotes the HFCB pathway. The tested values are $\mu = 0.8, 1.0$ and 1.2 . Fleet composition and non-HFCB pathway intensities are held unchanged.

The break-even multiplier is the value of μ at which the GHG burden change equals zero:

$$F_{i,s}^G(\mu) = F_{i,r}^G \quad (14)$$

For a setting with positive HFCB vehicle share, this value is calculated as:

$$\mu^* = \frac{F_{i,r}^G - \sum_{k \neq H} w_{i,k,s} I_{i,k,s}^G}{w_{i,H,s} I_{i,H,s}^G} \quad (15)$$

The break-even multiplier is obtained by scaling the modeled HFCB pathway GHG intensity while holding fleet composition and non-HFCB pathway intensities fixed; it marks the sign-reversal threshold of the fleet-level GHG difference within the WTW aggregation.

3. Results

3.1. Full-Region Transition Burden Changes

The B0–S1–S2 comparison shows that provincial bus decarbonization produces differentiated WTW burden profiles, Figure 2. From B0 to S1, fleet-level GHG intensity decreases in all six provinces, but the scale and meaning of the reduction differ across regions. Qinghai records the largest proportional B0–S1 GHG reduction, decreasing from 29.39 to 7.70 kg CO₂-eq/hkm, or 73.81%. Gansu records the largest absolute reduction, falling from 126.52 to 41.21 kg CO₂-eq/hkm, a decrease of 85.31 kg CO₂-eq/hkm, or 67.43%. The smallest reduction occurs in Shaanxi, where GHG intensity decreases from 127.13 to 114.60 kg CO₂-eq/hkm, or 9.86%.

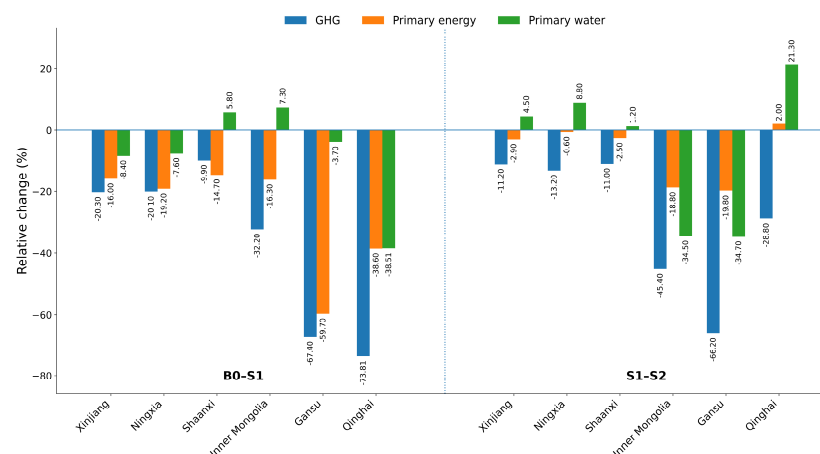


Figure 2. Multi-indicator fleet-level WTW burden changes under B0–S1 and S1–S2.

This contrast shows that proportional reduction and absolute burden reduction should be interpreted separately. Gansu's large absolute decline reflects its higher B0 GHG base-line and the marked decline in S1 electricity- and hydrogen-linked pathway intensities. The reduction is therefore generated by the gap between a relatively high benchmark burden and substantially lower transition-pathway intensities under S1. Qinghai represents a different pattern: its proportional reduction is the largest, but its absolute GHG burden remains much lower than the other provinces throughout the sequence. This low-GHG outcome should be interpreted together with the accompanying primary-energy and primary-water burdens. In the later S1–S2 and HFCB-exposure comparisons, Qinghai's low-GHG profile is accompanied by increases in primary energy and/or primary-water burden, indicating an energy-chain trade-off within the adopted WTW accounting boundary rather than a local water-scarcity assessment. The full absolute fleet-level intensities for GHG emissions, primary energy consumption and primary-water burden are reported in Supplementary Table S6a.

The technology-specific pathway intensities explain why these cross-provincial differences persist. In Xinjiang, Ningxia and Shaanxi, the B0 BEB pathway remains more

GHG-intensive than the corresponding DB pathway. In these B0 cases, BEB operation does not reduce WTW GHG intensity relative to the DB pathway because the electricity pathway remains high-GHG. Gansu occupies an intermediate position in the B0 grid-carbon gradient: its B0 BEB intensity is lower than its DB pathway, but remains high at 102.91 kg CO₂-eq/hkm; under S1 and S2, the BEB pathway falls sharply to 43.21 and 16.10 kg CO₂-eq/hkm. Qinghai is the low-GHG reference case, with much lower BEB and HFCB pathway intensities. These contrasts indicate that the same bus category can have different WTW GHG implications when paired with different electricity and hydrogen pathways. The relevant comparison is the vehicle–energy pathway through which each technology is operated.

The S1–S2 comparison further clarifies the role of remaining transition space. GHG reductions continue in all provinces, but the magnitude differs. Gansu again records the largest additional reduction, falling from 41.21 to 13.91 kg CO₂-eq/hkm, a reduction of 66.25%. Inner Mongolia also shows a substantial additional reduction, from 63.23 to 34.53 kg CO₂-eq/hkm. By contrast, Shaanxi decreases from 114.60 to 101.97 kg CO₂-eq/hkm, indicating that accelerated vehicle transition remains constrained when upstream electricity and hydrogen pathways remain high-GHG. Shaanxi therefore represents a high-upstream-burden case in which cleaner vehicle composition alone cannot fully offset the GHG intensity carried by the electricity–hydrogen supply chain. Qinghai decreases further from 7.70 to 5.48 kg CO₂-eq/hkm, but from an already low S1 level. The comparison separates two effects: provinces with high remaining upstream burdens retain high absolute GHG intensity, while provinces closer to a lower-GHG pathway have less remaining GHG-reduction space.

Primary-energy results reveal a different mechanism from GHG emissions. From B0 to S1, all six provinces reduce total primary-energy intensity, but the S1–S2 transition is not uniformly energy-saving. Qinghai is the clearest case: GHG intensity decreases by 28.76% from S1 to S2, while total primary energy increases by 1.99%. This divergence shows that GHG intensity and energy-chain efficiency are not equivalent. Additional hydrogen production, delivery and fuel-cell conversion steps can increase upstream energy requirements even when the associated pathway has a lower GHG intensity.

Primary-water burden results add a further burden dimension. The direction of water change differs across provinces and transition stages. In the S1–S2 comparison, Inner Mongolia and Gansu reduce both GHG emissions and primary-water burden, whereas Qinghai, Ningxia, Xinjiang and Shaanxi show further GHG reductions accompanied by higher primary-water burdens. Qinghai provides the most visible example: from S1 to S2, its GHG intensity falls from 7.70 to 5.48 kg CO₂-eq/hkm, but primary-water burden increases by 21.31%. In Qinghai, the S1–S2 primary-water burden increase is mainly driven by the process-water component under the adopted pathway-specific water factors, with process-water accounting for about three quarters of the calculated increase. This component trace indicates that the Qinghai water increase is mainly associated with hydrogen-related process-water assumptions.

Overall, the full-region comparison answers the first diagnostic question by showing that GHG, primary-energy and primary-water burden outcomes do not move as a single bundle. B0–S1 confirms broad GHG reduction across all provinces, but the absolute burdens and response patterns differ sharply. S1–S2 shows that additional GHG reduction can be accompanied by weaker energy-efficiency gains or higher energy-chain water consumption. Low-carbon bus transition is best understood as a pathway-conditioned burden assessment.

3.2. GHG Attribution

For the B0–S1 transition, the six provinces show distinct attribution patterns, Figure 3. In Xinjiang and Ningxia, the GHG reduction is mainly associated with pathway-intensity improvement, indicating that changes in upstream electricity–hydrogen pathway conditions account for most of the observed decline. This pattern is consistent with provinces where the initial upstream burden remains high enough for pathway-intensity improvement to be more visible than small changes in vehicle composition. Shaanxi shows a more constrained mechanism: the pathway-intensity effect reduces GHG emissions by 15.13 kg CO₂-eq/hkm, but the vehicle-composition effect adds 2.60 kg CO₂-eq/hkm. This positive composition effect offsets about 17% of the intensity-driven reduction and helps explain why Shaanxi records the smallest B0–S1 GHG reduction among the six provinces.

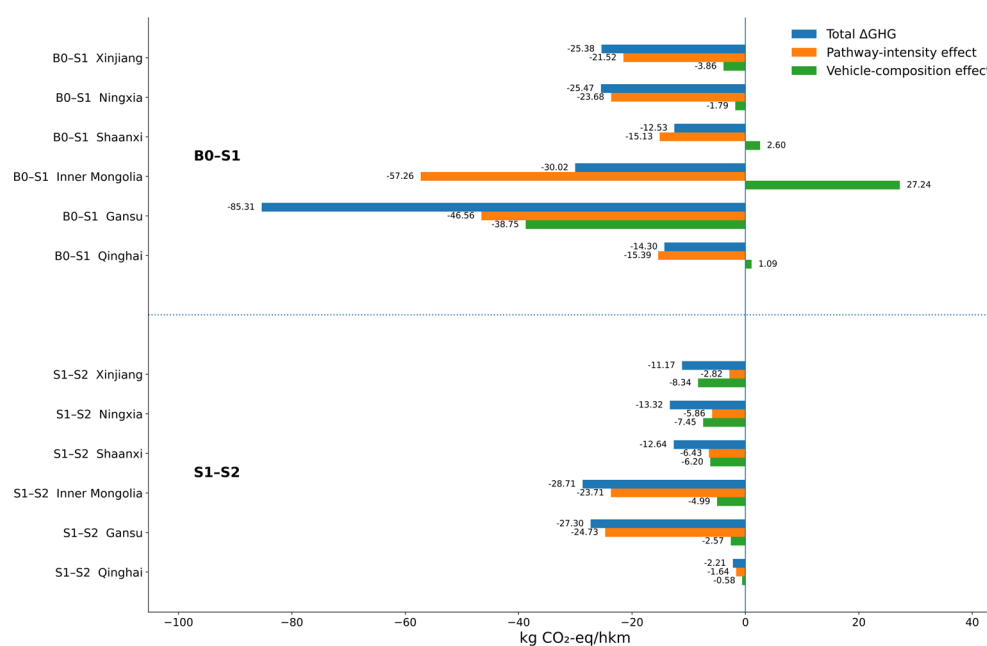


Figure 3. LMDI decomposition of fleet-level WTW GHG changes under B0–S1 and S1–S2.

Gansu provides a dual-driver case. Its B0–S1 GHG reduction is generated by both pathway-intensity improvement and vehicle-composition change. The pathway-intensity effect is approximately -46.56 kg CO₂-eq/hkm, while the vehicle-composition effect is approximately -38.75 kg CO₂-eq/hkm. This means that the large aggregate reduction in Gansu is not attributable to vehicle substitution alone or to upstream pathway improvement alone. It reflects the joint effect of cleaner pathway intensities and a shift away from higher-GHG fleet components.

The S1–S2 comparison shows a clearer role for pathway-intensity improvement in several provinces. In Gansu, fleet-level GHG intensity decreases by 27.30 kg CO₂-eq/hkm, of which about -24.73 kg CO₂-eq/hkm comes from pathway-intensity improvement and about -2.57 kg CO₂-eq/hkm from vehicle-composition change. This indicates that further reduction after S1 is mainly produced by cleaner BEB and HFCB pathway intensities. Inner Mongolia follows a similar direction, with its S1–S2 reduction also dominated by pathway-intensity improvement.

Xinjiang and Ningxia show a different S1–S2 mechanism. Their additional GHG reductions are more closely linked to vehicle-composition change, because the higher HFCB vehicle share allows the lower-GHG HFCB pathway to become more visible in the fleet average. Shaanxi shows a more limited and balanced reduction, consistent with its continued upstream GHG intensity. Qinghai has a smaller absolute S1–S2 GHG change

because its S1 fleet-level GHG intensity is already low; the main issue in Qinghai shifts from further GHG reduction to the accompanying energy and water implications identified in Section 3.1.

Overall, the LMDI results show that aggregate GHG reductions conceal different attribution structures across provinces.

3.3. B0-Upstream HFCB Exposure Test

Figure 4 reports the B0-upstream HFCB exposure results, expressed as burden changes relative to each province's B0 fleet benchmark.

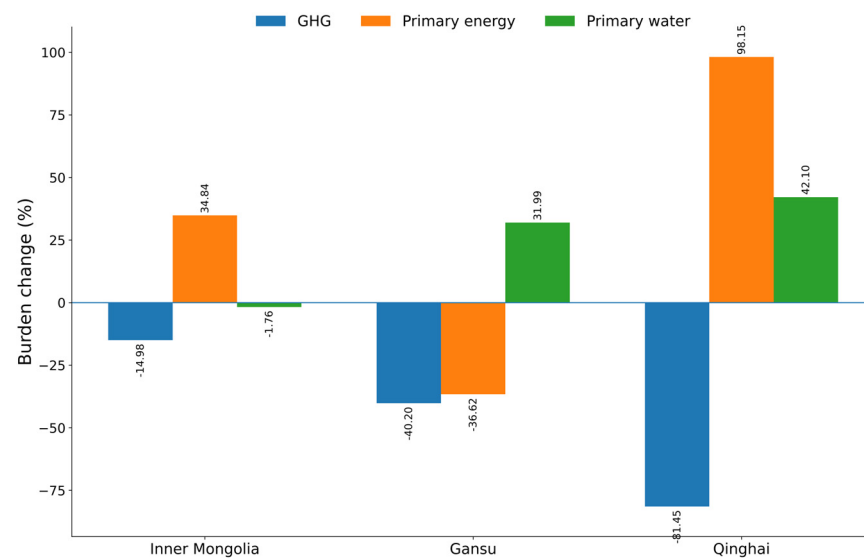


Figure 4. T1 B0-upstream full-HFCB exposure burden changes relative to B0.

Inner Mongolia shows a GHG-reducing but energy-intensive exposure profile. Full HFCB exposure reduces GHG intensity by 14.98% and primary-water burden by 1.76%, but increases primary energy by 34.84% relative to B0. The HFCB pathway is GHG-reducing relative to the B0 fleet benchmark, but it carries a higher primary-energy burden under the B0 upstream setting. This result indicates that GHG reduction and energy-chain efficiency can diverge in the exposure comparison.

Gansu shows a GHG- and energy-reducing exposure profile with a water trade-off. Full HFCB exposure reduces primary energy by 36.62% and GHG emissions by 40.20%, but increases primary-water burden by 31.99%. The exposed HFCB pathway is therefore favorable relative to the B0 fleet benchmark in energy and GHG terms, while carrying a higher WTW primary-water burden. This result shows that HFCB exposure can be GHG-reducing and energy-saving while still shifting part of the burden to energy-chain water consumption.

Qinghai shows a GHG-reduction-dominant exposure profile accompanied by large primary-energy and primary-water burden increases. Full HFCB exposure reduces GHG intensity by 81.45%, but increases primary energy by 98.15% and primary-water burden by 42.10%. This profile is analytically different from Gansu. In Qinghai, the exposed HFCB pathway is very low in GHG intensity, but it is much more energy- and water-intensive than the B0 fleet benchmark. The mechanism is the additional electricity–hydrogen–vehicle conversion chain: hydrogen production and use can increase upstream energy and primary-water burdens even when the associated GHG intensity remains low.

Taken together, the T1 results show that full HFCB exposure does not produce a uniform burden profile. The three cases differ in whether GHG reduction is accompanied by lower primary energy, lower primary-water burden, or additional energy-chain burdens.

The exposure module identifies which burdens become visible when the B0-upstream HFCB pathway is magnified.

3.4. Local A/B/C Visibility

Figure 5 shows that equal five-percentage-point perturbations in A, B and C are not expressed equally at the fleet level. The difference is not caused by the nominal size of the perturbation, which is held constant, but by where the perturbation enters the electricity–hydrogen–bus chain. Around S1, the fleet remains BEB-dominant and the HFCB share remains small. This makes clean-electricity improvement highly visible, green-hydrogen improvement weakly visible, and HFCB share expansion conditionally visible.

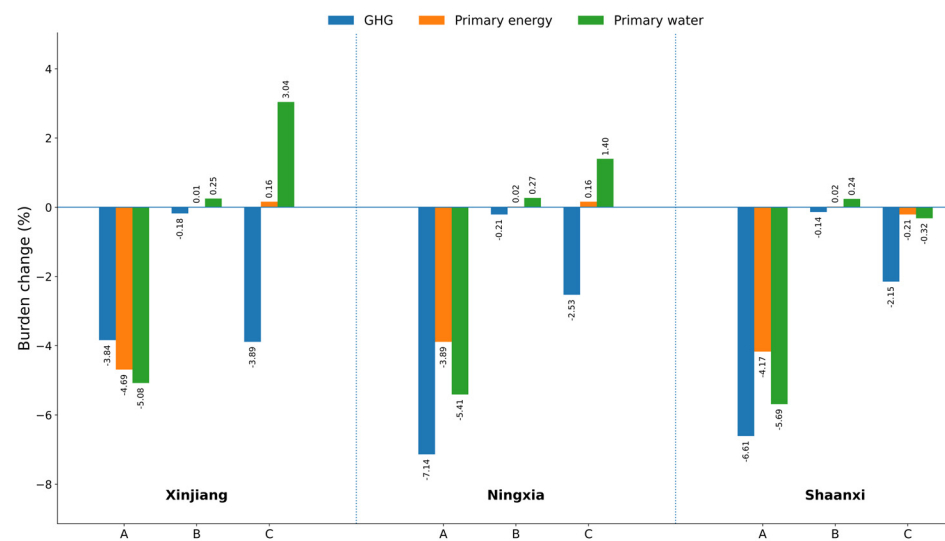


Figure 5. Multi-indicator burden changes under local A, B and C perturbations.

The A perturbation has the strongest and most consistent fleet-level expression. Its GHG reduction ranges from 3.84% in Xinjiang to 7.14% in Ningxia, and it also reduces primary energy and primary-water burden in all three cases. The mechanism is straightforward: clean-electricity improvement affects the electricity pathway that supports the dominant BEB component of the fleet. In this setting, A is not only an upstream parameter; it is attached to the pathway carrying most of the fleet-level burden. This explains why a local improvement in clean electricity is transmitted strongly into all three WTW indicators.

The B perturbation shows the opposite pattern. Increasing the green-hydrogen share produces only very small GHG reductions, between 0.14% and 0.21%, while primary-energy changes are negligible and primary-water burdens increase slightly. This does not mean that green hydrogen is environmentally unimportant. It means that, under the S1 vehicle composition, the hydrogen pathway has limited fleet-level reach. Because HFCBs account for only a small share of the fleet, improvements in hydrogen quality are diluted in the fleet average. The weak B response is a visibility problem caused by low downstream exposure, not evidence that hydrogen quality is irrelevant.

The C perturbation makes the hydrogen pathway more visible by increasing the HFCB share from 5% to 10%. This produces GHG reductions in all three cases, ranging from 2.15% in Shaanxi to 3.89% in Xinjiang. However, the multi-indicator response is less stable than under A. Primary-energy changes remain small, while primary-water burden increases in Xinjiang and Ningxia and decreases slightly in Shaanxi. This shows that increasing HFCB share does not only scale a GHG benefit; it also scales the full WTW burden profile of the hydrogen pathway. The GHG effect depends on the GHG advantage of the HFCB pathway, whereas the energy and water effects depend on the pathway's broader resource

burden. The conditional visibility of C therefore reflects the interaction between HFCB share and HFCB pathway intensity: C becomes more visible when the HFCB pathway differs sufficiently from the fleet pathway it replaces.

Table 2 summarizes the visibility gap. For the same five-percentage-point perturbation, the GHG effect of A is 21–47 times that of B, while the effect of C is 12–22 times that of B. These ratios should be read as local WTW expression measures, not as cost-effectiveness or policy-priority rankings. In this S1-based local setting, green-hydrogen improvement has limited fleet-level expression when HFCB share is low, while increasing HFCB share makes hydrogen-pathway quality more consequential and also exposes its energy and water trade-offs.

Table 2. GHG visibility ratios for local A/B/C perturbations.

Province	A Perturbation GHG Change (%)	B Perturbation GHG Change (%)	C Perturbation GHG Change (%)	A/B Visibility Ratio	C/B Visibility Ratio
Xinjiang	−3.84	−0.18	−3.89	21.0	21.3
Ningxia	−7.14	−0.21	−2.53	34.3	12.2
Shaanxi	−6.61	−0.14	−2.15	46.1	15.0

3.5. HFCB Pathway-Intensity Sensitivity

HFCB pathway GHG intensity is varied by $\pm 20\%$ as a bounded one-way stress test, with fleet composition and non-HFCB pathway intensities held unchanged. The test is applied to the T1 exposure cases and the M3 HFCB-share perturbation cases. The complete sensitivity results are reported in Supplementary Table S9a,b.

Table 3 summarizes the break-even multipliers for the T1 and M3 cases. The T1 results show that the three exposure profiles differ in their GHG stability margins. Qinghai remains far from the GHG sign-reversal threshold and Gansu remains stable within the tested $\pm 20\%$ range. Inner Mongolia is closer to the threshold: although its baseline T1 result is GHG-reducing, the GHG advantage is sensitive to upward variation in HFCB pathway intensity. This refines the T1 interpretation in Section 3.3 by showing that Inner Mongolia's GHG-reducing exposure profile has a narrower stability margin than the Qinghai and Gansu cases.

Table 3. HFCB GHG break-even multipliers under T1 and M3.

Module	Case	Baseline GHG Change (%)	Break-Even Multiplier
T1	Inner Mongolia	−14.98	1.18×
T1	Gansu	−40.20	1.67×
T1	Qinghai	−81.45	5.39×
M3	Xinjiang	−3.89	2.49×
M3	Ningxia	−2.53	1.49×
M3	Shaanxi	−2.15	1.36×

The M3 results show that local HFCB-share expansion around S1 remains GHG-reducing in Xinjiang, Ningxia and Shaanxi within the tested range. However, the break-even multipliers indicate different margins. Xinjiang is farthest from the sign-reversal threshold, while Shaanxi is closest. The Shaanxi result does not overturn the M3 finding, but it shows that the GHG benefit of local HFCB-share expansion is more sensitive when the HFCB pathway has a smaller GHG advantage over the displaced fleet pathway.

Overall, HFCB-related GHG reductions are more directionally stable when the hydrogen pathway remains below the relevant benchmark or displaced pathway. They become more sensitive as the pathway-intensity margin narrows. The GHG benefit of HFCB expansion depends not only on vehicle share, but also on the margin between HFCB pathway intensity and the fleet pathway it replaces.

4. Discussion

4.1. From Vehicle Ranking to Pathway-Conditioned Assessment

The bus-transition burden profile is best understood as a pathway-conditioned burden assessment. BEB and HFCB performance is produced through the electricity and hydrogen pathways that support operation and through the fleet composition that translates pathway intensity into system-level burdens. This study links those pathway conditions to fleet-level burden formation across heterogeneous provincial electricity–hydrogen systems.

Vehicle substitution becomes analytically meaningful after the supporting electricity and hydrogen pathways are specified. The full-region comparison separates GHG reduction from primary-energy and primary-water burden responses. GHG-reducing pathways may still carry energy-chain or water burdens when conversion chains lengthen or hydrogen-related processes become more resource-demanding. This distinction is central for regions where renewable-resource abundance, electricity-system structure and water constraints coexist.

Percentage changes require absolute burden anchors. A large proportional reduction may indicate substantial transition space and a high residual burden. A low absolute burden may indicate a system already close to a lower-GHG pathway and expose energy or water constraints on further scalability. Regionalized WTW assessment should combine relative change, absolute intensity and multi-indicator burden profiles.

Aggregate GHG reduction masks the attribution structure behind the transition effect. GHG reduction can arise from pathway-intensity improvement, vehicle-composition change or their interaction. WTW accounting gains diagnostic value when it identifies how upstream pathway improvement and downstream fleet composition jointly produce fleet-level outcomes.

This interpretation extends vehicle- or fuel-pathway comparison by treating regional pathway intensity and fleet composition as linked sources of fleet-level WTW burden formation. The study advances WTW assessment from pathway comparison toward regionalized mechanism diagnosis. The diagnostic logic links pathway intensity, fleet composition, burden alignment, attribution structure, pathway exposure, local visibility and stability margin within one assessment design.

4.2. Deployment Sequencing Under Electricity–Hydrogen Pathway Constraints

Regional bus-transition governance can use the proposed diagnostic logic as an environmental screening framework alongside deployment targets. BEB and HFCB expansion can be assessed through three linked conditions: the upstream pathway assigned to each technology, the fleet share through which that pathway enters operation and the resulting GHG, primary-energy and primary-water burden profile.

BEB-oriented transition depends on electricity-pathway decarbonization. In BEB-dominant systems, clean-electricity improvement is transmitted strongly into fleet-level WTW outcomes. The results suggest that the WTW GHG benefit of bus electrification is more clearly supported when it is paired with electricity-pathway decarbonization, grid-emission monitoring and clean-electricity integration. High-GHG electricity systems shift part of the burden upstream when vehicle replacement proceeds faster than electricity-pathway improvement.

HFCB-oriented transition depends on coordination between green-hydrogen supply and downstream fleet expansion. Green-hydrogen improvement has limited fleet-level expression at low HFCB share and becomes more consequential as the hydrogen pathway expands. The environmental value of HFCB expansion therefore depends on whether hydrogen quality improves as fleet share increases.

The T1 and sensitivity modules add a stability criterion to HFCB deployment. Inner Mongolia, Gansu and Qinghai all show baseline GHG reductions under T1 exposure, with sharply different energy and water profiles. HFCB pathways can scale GHG benefits together with broader energy-chain burdens. Break-even distance adds a further screening criterion: HFCB-related GHG reductions are more directionally stable when the modeled HFCB pathway remains farther below the benchmark or displaced pathway and become more sensitive as the intensity margin narrows. This metric should be interpreted within the fleet-level WTW aggregation rather than as a system-level equilibrium threshold for hydrogen supply, infrastructure expansion or cost adjustment.

The screening logic can be organized in three steps: verify electricity and hydrogen pathway intensity; screen GHG gains against primary-energy and primary-water burden implications; and inform BEB or HFCB deployment sequencing according to pathway quality, fleet share and stability margin. The implication is that vehicle deployment should be aligned with the pathway quality and resource-burden profile attached to the fleet.

4.3. Boundary Conditions, Transferability and Future Research

Several boundaries define the use and transferability of the results. First, the study is limited to a WTW fuel-cycle boundary. The analysis focuses on fuel production, energy delivery and vehicle operation, while vehicle-cycle stages are outside the calculation boundary. The results should therefore be interpreted as WTW energy-chain diagnostics rather than cradle-to-grave technology rankings. Future research could extend the framework by adding vehicle-cycle inventories, battery and fuel-cell replacement assumptions, infrastructure allocation and end-of-life treatment.

Second, the primary-water burden indicator captures energy-chain water consumption within the adopted WTW boundary. The Qinghai water result should be interpreted as a conditional WTW water-burden signal under the adopted pathway-specific water factors. The component trace shows that the S1–S2 increase is mainly associated with process-water contributions, but the exact magnitude of the increase and the process-water share may change under alternative cooling-water, electrolysis-water and process-water coefficients. The result supports the existence of a GHG–water trade-off within the adopted WTW accounting framework rather than a water factor-invariant estimate of local water burden. Its implication for local water scarcity would require additional watershed-level or basin-level assessment. Future research can connect WTW water accounting with water-scarcity assessment, especially in regions where hydrogen expansion intersects with ecological constraints and water allocation pressure.

Third, the scenarios and parameters are diagnostic. B0 provides the benchmark setting. S1 and S2 provide comparable transition settings; T1 exposes the B0-upstream HFCB pathway; the M-series tests local visibility around S1. The regionalized GREET parameterization is deterministic and source-traceable rather than probabilistic. The scenario contrasts and sensitivity modules should therefore be interpreted as structured diagnostic checks rather than statistical uncertainty propagation. Future work could test broader parameter distributions or scenario ensembles, especially for hydrogen-production intensity, delivery assumptions, vehicle energy-use assumptions and water-consumption factors.

Fourth, the analysis does not include economic variables. Hydrogen cost, electricity tariffs, vehicle purchase cost, battery or fuel-cell replacement, infrastructure investment,

station utilization, subsidies and carbon pricing could affect deployment feasibility and sequencing even when a pathway appears environmentally favorable. The conclusions should therefore be interpreted as environmental WTW pathway diagnostics rather than techno-economic deployment recommendations. Future work could combine the present framework with life-cycle cost, total cost of ownership or multi-criteria decision analysis.

Finally, transferability depends on reparameterization. The diagnostic logic can be applied to other regions as an assessment structure linking pathway intensity, fleet composition and multi-indicator burden formation. However, applications to countries or regions with different electricity-market structures would need to rebuild BEB electricity inputs, hydrogen-production electricity inputs and delivery assumptions according to local market design, dispatch patterns, power-trading rules, cross-border electricity exchange and marginal or average emission accounting.

5. Conclusions

This study developed a regionalized WTW mechanism diagnosis of low-carbon bus transition across six provincial electricity–hydrogen–bus systems in Northwest China and an adjacent energy-output region. Combining localized GREET pathway intensities, fleet-level aggregation, LMDI attribution and diagnostic scenario tests, local A/B/C perturbations and HFCB pathway-intensity sensitivity checks, the analysis examined how regional electricity–hydrogen conditions are translated into fleet-level GHG, primary-energy and primary-water burdens. Three conclusions can be drawn.

First, low-carbon bus transition is a multi-indicator burden-alignment problem. Under the common B0–S1 transition setting, all six provinces reduce fleet-level GHG intensity. The largest proportional reduction occurs in Qinghai, where GHG intensity decreases from 29.39 to 7.70 kg CO₂-eq/hkm, or 73.81%. Gansu records the largest absolute reduction, falling from 126.52 to 41.21 kg CO₂-eq/hkm, or 67.43%. Energy and water responses further show that GHG reduction is only one dimension of transition performance. In Qinghai, S1–S2 GHG intensity decreases by 28.76%, while primary-energy consumption and primary-water burden increase by 1.99% and 21.31%, with the calculated water increase mainly associated with the process-water component. This result highlights the importance of evaluating GHG, primary energy and primary-water as a combined burden profile.

Second, fleet-level GHG reduction is generated through different mechanisms across provinces. The LMDI results show that aggregate GHG reduction may be driven by pathway-intensity improvement, vehicle-composition change or the joint movement of both. Gansu's B0–S1 reduction is a dual-driver case, with a pathway-intensity effect of −46.56 kg CO₂-eq/hkm and a vehicle-composition effect of −38.75 kg CO₂-eq/hkm. Shaanxi presents a constrained pattern: pathway-intensity improvement reduces GHG by 15.13 kg CO₂-eq/hkm, while the vehicle-composition effect adds 2.60 kg CO₂-eq/hkm, offsetting about 17% of the intensity-driven reduction. These attribution results show why regional transition assessment requires mechanism diagnosis. Similar aggregate reductions may reflect different combinations of upstream pathway improvement and downstream fleet-composition change.

Third, HFCB-related outcomes depend on pathway exposure, fleet share and GHG-stability margins. The T1 exposure test identifies three hydrogen-pathway profiles under B0 upstream conditions. Inner Mongolia is GHG-reducing but energy-intensive, with GHG decreasing by 14.98% and primary energy increasing by 34.84%. Gansu is GHG- and energy-reducing with a water trade-off, with GHG and primary energy decreasing by 40.20% and 36.62%, while primary-water burden increases by 31.99%. Qinghai shows a GHG-reduction-dominant profile, with GHG decreasing by 81.45% while primary energy and primary-water burden increase by 98.15% and 42.10%. The M-series results further

show that equal five-percentage-point perturbations have different fleet-level visibility. Clean-electricity improvement produces 21–47 times the GHG effect of green-hydrogen improvement, while HFCB-share expansion produces 12–22 times the GHG effect of green-hydrogen improvement.

Overall, the results support a pathway-conditioned screening logic for BEB and HFCB deployment. Regional bus-transition assessment should coordinate vehicle deployment with electricity-pathway decarbonization, renewable-hydrogen availability and multi-indicator burden profiles. BEB-oriented transition is more closely tied to electricity-pathway decarbonization, while HFCB-oriented transition depends on hydrogen-pathway quality, fleet-share expansion and stability margins. For both pathways, GHG reduction should be assessed together with primary-energy consumption and primary-water burden.

This interpretation is bounded by the adopted WTW fuel-cycle framework. The analysis does not include vehicle manufacturing, infrastructure construction, end-of-life stages, water-scarcity weighting or techno-economic feedback on factors such as hydrogen cost, electricity tariffs, vehicle purchase cost and infrastructure utilization. The scenarios are deterministic diagnostic settings designed for mechanism interpretation. Future research could integrate full vehicle-cycle burdens, water-scarcity factors, city-level bus operation, charging and refueling constraints, and dynamic deployment pathways.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su18146961/s1>, Table S1: Regional structural indicators; Table S2: GREET localization parameters and data sources; Table S3: Water-boundary factors and component definitions; Table S4: (a) Scenario A/B/C settings, (b) Source documents and derivation notes for scenario parameters; Table S5: Pathway-specific WTW intensities; Table S6: (a) Fleet-level B0-S1-S2 burdens and burden changes, (b) T1 B0-upstream full-HFCB exposure results, (c) M-series burden changes around S1; Table S7: (a) GHG LMDI decomposition and residual checks, (b) Zero-share treatment in the GHG LMDI decomposition; Table S8: GHG visibility ratios for A/B/C perturbations; Table S9: (a) HFCB pathway-intensity sensitivity for T1 exposure cases, (b) HFCB pathway-intensity sensitivity for M3 local perturbation cases, (c) Break-even multipliers for HFCB pathway GHG intensity.

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