

# Using Cross-Impact Balance Analysis to Quantify the Internal Consistency of Energy Transition Scenarios Towards Carbon Neutrality<sup>#</sup>

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## ABSTRACT

Scenario-based approaches are widely used to explore long-term energy transitions under deep uncertainty. Integrated assessment and energy system models provide quantitative insights but often combine technological, policy, institutional, and social assumptions without checking their consistency, which can produce numerically coherent yet internally contradictory scenarios that weaken policy relevance. Cross-Impact Balance (CIB) analysis can serve as a front-end screening tool to identify internally consistent scenario configurations before quantitative modelling. Applications in energy and sustainability studies demonstrate that CIB reduces arbitrary assumption combinations, enhances transparency, and links qualitative narratives with quantitative inputs, thereby strengthening the reliability of scenario-based energy and climate policy analysis.

**Keywords:** Energy transition, Scenario analysis, Cross-Impact Balance, Internal consistency, Energy modelling, Policy-oriented analysis

## NONMENCLATURE

### Abbreviations

CIB	Cross-Impact Balance (analysis)
IAMs	Integrated Assessment Models

## 1. INTRODUCTION

Scenario-based approaches are commonly used to explore long-term energy transitions under uncertainty. Energy system models and integrated assessment models (IAMs) provide internally consistent numerical results based on predefined assumptions, offering insights into system feasibility, technology deployment,

and emissions trajectories[13][16]. These models play a central role in informing energy and climate policy discussions.

Energy transition scenarios typically combine assumptions across technological, policy, institutional, and social domains. Although individual assumptions may be supported by empirical evidence or expert judgement, their combination is not always examined for mutual compatibility. Studies show that scenarios can appear coherent numerically while embedding tensions that may limit real-world implementation[3][11].

This challenge is particularly relevant in policy-oriented energy analysis. Many decarbonisation pathways assume rapid deployment of low-carbon technologies alongside stable policies, effective governance, and public acceptance. In reality, infrastructure expansion, regulatory adaptation, and social acceptance often lag behind technological ambition[8][10]. When these gaps remain unexamined, scenario results may overstate feasibility or overlook critical barriers.

Existing quantitative models primarily explore cost-effective or technically feasible pathways rather than whether the underlying assumptions are mutually consistent[5][11]. Qualitative scenario narratives rely on expert judgement but often lack formal procedures for assessing coherence. As a result, structurally inconsistent configurations can enter quantitative analysis unchecked.

Cross-Impact Balance (CIB) analysis offers a complementary approach. It evaluates whether combinations of system assumptions are mutually supportive or contradictory using structured assessments of cross-impacts among key drivers[14][15].

<sup>#</sup> This is a paper for the 17th International Conference on Applied Energy (ICAE2025), 8-12 December 2025, Bangkok, Thailand.

Rather than predicting or optimising future states, CIB functions as a front-end screening tool to filter out internally inconsistent configurations before they are used in quantitative models (Fig. 1).

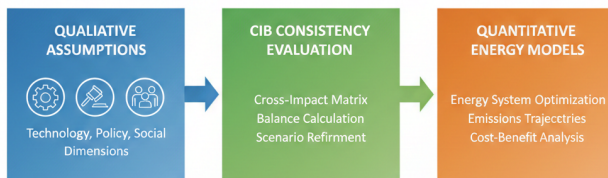


Fig. 1 Conceptual positioning of CIB

## 2. INTERNAL CONSISTENCY CHALLENGES IN ENERGY TRANSITION SCENARIOS

### 2.1 Cross-domain assumptions in energy scenario construction

Energy transition scenarios typically combine assumptions across multiple domains, including technological development, economic conditions, policy ambition, institutional capacity, and social acceptance. In quantitative energy system models and IAMs, these assumptions are often represented as exogenous inputs or constraints, such as technology cost trajectories, carbon prices, or demand growth rates[13][16]. This enables systematic exploration of long-term pathways, but implicitly assumes that inputs from different domains are mutually compatible.

In practice, assumptions are often developed independently, reflecting disciplinary boundaries or modelling conventions. Consequently, scenario configurations may embed combinations of assumptions whose internal coherence is not explicitly assessed. This issue arises from simplifications of complex socio-technical transitions[11].

### 2.2 Technological and system-level interdependencies

Technological assumptions can introduce inconsistencies in energy scenarios. High shares of variable renewable energy require coordinated developments in grid infrastructure, storage technologies, and operational practices[3]. Electrification of transport, heating, and industry further reshapes demand profiles and increases pressure on electricity networks.

Scenarios assuming rapid deployment of end-use technologies without corresponding infrastructure expansion may underestimate system constraints, even when generation technologies are cost-competitive[2][9]. These inconsistencies are often hidden by aggregate indicators, such as installed capacity

or emissions trajectories, while underlying system interactions remain implicit.

### 2.3 Institutional and governance-related inconsistencies

Institutional and governance assumptions add another layer of potential inconsistency. Many long-term decarbonisation scenarios assume stable, effective policy frameworks that support sustained investment and coordinated infrastructure development over decades. Empirical evidence shows that policy implementation is often fragmented, contested, and subject to political reversal, especially in energy and transport sectors[1][6].

When ambitious policy targets are combined with weak or unspecified governance capacity, scenarios may rely on institutional conditions that are unlikely to materialise. Quantitative models typically treat policy ambition as an exogenous input, without capturing these institutional dynamics[3].

### 2.4 Social acceptance and behavioural assumptions

Public acceptance and behavioural responses can further affect scenario consistency. Opposition to infrastructure projects, concerns about distributional impacts, and regional differences in acceptance influence technology deployment rates and transition pathways[10][12]. Energy models often simplify or omit these factors, implicitly assuming high levels of social compliance.

Scenario narratives may overestimate the speed and scale of implementation, especially for infrastructure-intensive solutions like renewable energy expansion or transmission networks. Including social and behavioural dimensions is therefore essential for internal consistency, even when scenarios are not intended as predictions[8].

### 2.5 Internal consistency as a distinct quality dimension

Despite growing awareness of these challenges, tools for systematically identifying internal inconsistencies at early stages are limited. Optimisation-based models focus on cost-effectiveness or emissions reduction under assumed conditions, while qualitative scenario exercises often rely on expert judgement without formal consistency checks[5][11].

Internal consistency represents a separate dimension of scenario quality, distinct from feasibility, optimality, or likelihood. Assessing consistency does not resolve uncertainty or prescribe pathways, but it helps exclude structurally incoherent configurations before

they are used as inputs to quantitative models. Cross-Impact Balance analysis provides a method for addressing this issue in energy scenario development[7][14].

### 2.6 Positioning CIB among energy scenario methods

Energy transitions are studied using diverse methods, including optimisation-based energy system models, IAMs, probabilistic uncertainty analysis, and data-driven forecasting. Optimisation and simulation models are effective at assessing system costs, emissions trajectories, and technology deployment under predefined assumptions[13][16]. Probabilistic approaches, such as Monte Carlo simulations, characterise uncertainty by assigning likelihoods to parameter ranges or outcomes[5].

These methods address feasibility, cost-effectiveness, or likelihood, but they offer limited means to evaluate whether qualitative assumptions—policy ambition, institutional capacity, social acceptance—are mutually compatible. Data-driven approaches rely heavily on historical trends and are constrained when analysing structural changes or unprecedented policy targets[8].

Cross-Impact Balance analysis occupies a distinct role. Rather than assigning probabilities or optimising outcomes, CIB examines the logical consistency of scenario assumptions across domains. It does not evaluate likelihood or cost-effectiveness, but identifies combinations of technological, institutional, and social conditions that can coherently coexist. CIB complements quantitative and probabilistic methods by addressing scenario consistency, distinct from feasibility or likelihood.

## 3. APPLIED LOGIC OF CROSS-IMPACT BALANCE ANALYSIS

### 3.1 Conceptual logic of CIB for energy scenario analysis

Cross-Impact Balance (CIB) analysis is a qualitative and semi-quantitative method designed to assess the internal consistency of systems with interdependent drivers and deep uncertainty[14]. Unlike optimisation or simulation models, CIB does not aim to identify optimal solutions or predict future states. Instead, it evaluates whether assumed system configurations are mutually supportive based on structured judgments of cross-impacts among key descriptors.

In energy transition analysis, CIB examines whether assumptions across technological, institutional, and

social domains form coherent scenario narratives. By treating these assumptions as interacting elements within a system, CIB helps identify internally inconsistent configurations before they are used as inputs for quantitative energy models[7][11].

### 3.2 Defining descriptors and states in energy applications

Applying CIB begins with defining descriptors that represent key drivers of the energy transition. Descriptors can include technological variables (e.g., renewable energy penetration, electrification level), policy and governance factors (e.g., climate policy stringency, regulatory stability), and social dimensions (e.g., public acceptance, behavioural change). Each descriptor is represented by a limited set of discrete states reflecting qualitatively distinct conditions[15].

The selection of descriptors should align with the scope of the scenario exercise and the intended linkages to quantitative models. To maintain analytical tractability, the number of descriptors is usually constrained, prioritising variables that are both influential and uncertain. This process also enhances transparency by clarifying which aspects of the transition are considered central.

### 3.3 Assessing cross-impacts and consistency

Once descriptors and states are defined, CIB evaluates the influence of each state on the states of other descriptors using a cross-impact matrix. These influences are typically assessed through expert judgement and expressed on an ordinal scale, indicating whether a state supports, constrains, or has little effect on another state[14].

CIB identifies internally consistent scenarios as configurations in which each descriptor state is supported by the combined influence of all other states. Configurations with mutually contradictory assumptions are excluded. In energy scenario applications, this systematic screening reduces implausible or arbitrary combinations of assumptions[7][12](Fig. 2).

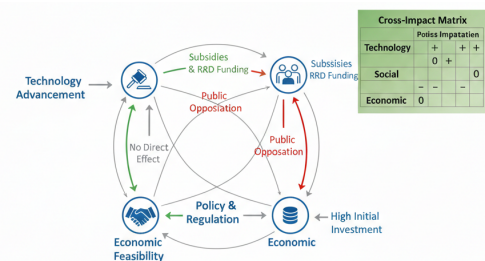


Fig. 2 Consistency evaluation mechanism in CIB

### 3.4 Role of CIB in applied energy analysis

CIB does not replace quantitative energy models or assess detailed system performance. Its main strength is structuring qualitative knowledge and expert judgement in a transparent, reproducible manner. By identifying which assumptions can coexist coherently, CIB supports more robust scenario design and facilitates communication across interdisciplinary teams[3].

In applied energy analysis, CIB functions as an intermediate method between narrative scenario development and quantitative modelling. This role is particularly valuable during early scenario construction, where methodological choices shape downstream modelling outcomes but are seldom systematically reviewed.

### 3.5 CIB in relation to probabilistic and data-driven approaches

CIB differs from probabilistic and data-driven approaches in how it treats uncertainty. Probabilistic methods quantify uncertainty by assigning likelihoods to variables or outcomes based on historical data or assumed distributions. These approaches are effective for parametric uncertainty in relatively stable systems but are less suited to deep uncertainty and qualitative change typical of long-term energy transitions[5].

CIB does not assign probabilities or determine the most likely future. Instead, it evaluates whether a configuration is internally consistent given expert assessments of cross-impacts. Consistent scenarios may be politically challenging or unlikely, while inconsistent scenarios may appear attractive from cost or emissions perspectives. This distinction is relevant when analysing transitions with unprecedented targets that cannot be meaningfully assessed using probability-based reasoning alone.

CIB also relies on structured expert knowledge rather than historical data. Expert judgements capture vagueness, ambiguity, and potential conflicts inherent in long-term transitions[15]. Ordinal or semi-quantitative scales are commonly used to represent these judgements, prioritising transparency and logical coherence over precise statistical inference.

## 4. INTEGRATING CIB INTO ENERGY MODELLING WORKFLOWS

### 4.1 CIB as a front-end screening tool

CIB can be applied as a front-end screening tool before quantitative energy modelling. In this approach,

qualitative scenario narratives or sets of assumptions are first evaluated for internal consistency using CIB before being translated into numerical inputs for energy system models or IAMs[7](Fig. 3).

Filtering out inconsistent configurations early reduces the risk that quantitative models explore pathways based on structurally incompatible assumptions. This enhances the interpretability of modelling results by ensuring that numerical outputs are grounded in coherent scenario logics[11].

### 4.2 Linking CIB outcomes with quantitative model inputs

Internally consistent configurations identified by CIB can be mapped to parameter ranges or qualitative settings in quantitative models. For example, different policy and governance states consistent under CIB may correspond to alternative carbon pricing trajectories, technology support schemes, or infrastructure deployment rates[13]

The mapping does not require a one-to-one correspondence between descriptors and model variables. Instead, CIB provides a structured rationale for selecting and combining model inputs, improving transparency in how qualitative assumptions influence quantitative outcomes. This is especially important when generating multiple scenarios to explore uncertainty rather than to identify a single optimal pathway[16].

### 4.3 Supporting exploratory and policy-oriented scenario analysis

Beyond technical integration, CIB supports exploratory and policy-oriented scenario design. Rather than focusing on a small set of predefined pathways, it enables systematic exploration of alternative internally consistent futures that reflect different combinations of technological ambition, policy capacity, and social acceptance[5].

This capability is valuable for policy discussions, where understanding trade-offs, risks, and conditional dependencies is more relevant than selecting a single preferred solution. By making consistency constraints explicit, CIB allows policymakers and stakeholders to engage with scenario results more critically[12].

### 4.4 Limitations and scope of integration

While CIB improves scenario coherence, its outcomes depend on the selection of descriptors and the elicitation of cross-impact judgements, both of which involve subjective choices. Additionally, CIB does not provide quantitative system performance or economic

metrics, and it cannot replace detailed energy modelling[15].

CIB should therefore be seen as a complementary tool that strengthens the coherence and transparency of scenario design rather than providing standalone policy prescriptions. When applied appropriately, it enhances the robustness of energy transition analysis under conditions of deep uncertainty[3].

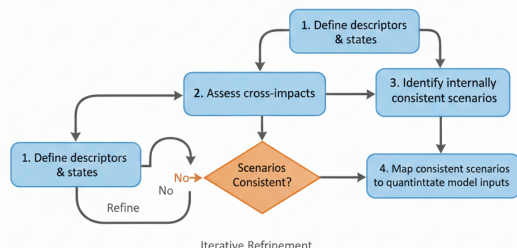


Fig. 3 Iterative workflow of CIBs

## 5. IMPLICATIONS FOR ENERGY ANALYSIS AND POLICY PRACTICE

### 5.1 Improving transparency in scenario design

CIB enhances transparency in scenario development by explicitly structuring assumptions and their interdependencies. This clarity makes the qualitative logic underlying scenario narratives visible, which is particularly valuable in policy-oriented analysis where stakeholders come from diverse disciplinary backgrounds[11].

By showing which combinations of assumptions are explored and which are excluded, CIB helps interpret modelling results more accurately and reduces the risk that scenarios are seen as arbitrary or opaque.

### 5.2 Supporting robust policy-relevant insights under uncertainty

Energy policy decisions often occur under deep uncertainty regarding technological development, institutional capacity, and social responses. In such contexts, the goal of scenario analysis is typically to explore a range of plausible and internally consistent futures rather than identify a single optimal pathway[5].

CIB filters out inconsistent configurations, providing a clearer basis for stress-testing policy options. It helps identify the conditions under which ambitious technological transitions are feasible, highlighting dependencies on institutional and social factors[3].

### 5.3 Enhancing linkage between qualitative narratives and quantitative models

CIB offers a structured intermediate step between narrative scenario assumptions and quantitative energy models. By translating qualitative assumptions into internally consistent sets of model inputs, it bridges a well-documented gap in energy scenario research[7][13].

This approach strengthens scenario consistency without substantially increasing computational complexity and complements existing modelling practices, reinforcing the credibility of scenario-based policy analysis.

### 5.4 Scope and limitations for applied use

Although CIB improves coherence, it does not eliminate uncertainty or resolve political and normative debates about energy transitions. Its results depend on the choice of descriptors and expert judgements, which should be documented transparently. CIB also does not provide quantitative performance metrics and cannot replace detailed energy system modelling[15].

When used appropriately, CIB functions as a support tool that strengthens scenario design rather than as a standalone decision-making framework.

### 5.5 Methodological relevance for energy transition analysis

The value of CIB lies in its alignment with challenges specific to energy transition analysis. Long-term transitions involve multiple interacting domains and policy objectives that often exceed historical patterns. Internal consistency is a prerequisite for assessing the feasibility of policies, costs, and implementation pathways.

By clarifying which combinations of technological, policy, institutional, and social conditions are consistent, CIB provides context for interpreting quantitative outputs. It makes implicit assumptions explicit, supporting more credible assessments of policy target attainability under deep uncertainty.

## 6. CONCLUSION

This paper has examined the use of Cross-Impact Balance analysis to improve internal consistency in energy transition scenarios. Scenario studies often combine assumptions across technological, institutional, and social domains, yet their mutual compatibility is rarely assessed, which can reduce interpretability and policy relevance.

Applying CIB as a front-end screening method allows analysts to systematically identify internally consistent

configurations before they are used in quantitative models. This enhances transparency, reduces arbitrary assumption combinations, and supports robust exploratory analysis under deep uncertainty.

CIB complements existing energy modelling frameworks by structuring qualitative knowledge and expert judgement in a reproducible manner. Integrating CIB into energy scenario workflows provides a practical approach to strengthening the credibility of scenario-based energy and climate policy analysis.

#### ACKNOWLEDGEMENT

This work is jointly supported by the Carbon Neutrality and Energy System Transformation (CNEST) Program led by Tsinghua University, National Natural Science Foundation of China (No.72243007), and the Tsinghua University Initiative Scientific Research Program (No. 20253080097; 20243100010; 20233080047).

#### AUTHOR CONTRIBUTIONS

Weize Song contributed to the conceptualisation of the study, the development of the methodological framework, and the review and revision of the manuscript. Qi Zhang contributed to the literature review, manuscript drafting, and subsequent modifications. Xi LU contributed to the discussion. Gemini supported visualisations and graphical elements. All authors reviewed and approved the final manuscript.

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