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Unraveling the Water–Energy Nexus (WEN): A Structured Analytical Framework and a Six-Pillar Extended Definition for Governance and Future Research

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Desentrañando el nexo agua–energía (WEN): un marco analítico estructurado y una definición extendida de seis pilares para la gobernanza y la investigación futura

Abstract

This study synthesizes peer-reviewed journal articles indexed in the Web of Science Core Collection (2018–2023) to clarify how the water–energy nexus is framed, measured, and governed. We derive nine analytical dimensions from key nexus variables 1) sectoral composition & interactions, 2) resource inputs and outputs, 3) social actors, 4) methodological frameworks, 5) problems and limitations, 6) geographic distribution, 7) operational nexus definitions, 8) territorial scales, and 9) study type. This classification reveals three structural bottlenecks: (i) methodological concentration on static environmentally extended input–output models; (ii) regional aggregation of case studies in data-rich China, which limits global transferability; and (iii) institutional narrowness, with multi-level governance and civil society underrepresented. Network analysis shows that conceptual framing predicts methodological choice and actor inclusion, and indicates limited methodological diversification—a relationship synthesized into the six pillars proposed below. Beyond existing WEN reviews, this combination of nine-dimension coding, cross-dimensional frequency analysis, and co-occurrence networks provides an empirical basis for the six pillars by linking how the nexus is defined to how it is measured and who is represented in the analysis. To support sustainable engineering decisions, we propose an extended water-energy nexus definition built around six interlocking pillars: high-resolution flow accounting; dynamic feedback modeling (rebound/tipping risks); explicit coupling with carbon, land, and waste; hybrid quantitative–qualitative analytics; inclusive multi-level collaborative governance; and interoperable open-data architectures. Together, these pillars translate fragmented case evidence into an engineering-ready, justice-sensitive systems framework, informing integrated water–energy infrastructure planning, evaluation of energy-transition pathways under water constraints, and prioritization of governance and data-architecture improvements required for interoperable nexus monitoring across sectors and scales.

Keywords: Resource management, Dynamic modeling, Multi-level and collaborative governance, Hybrid modeling, Input–Output analysis

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Resumen

Este estudio sintetiza artículos revisados por pares e indexados en la Web of Science Core Collection (2018–2023) para esclarecer cómo se conceptualiza, mide y gobierna el nexo agua–energía. A partir de las principales variables del nexo, derivamos nueve dimensiones analíticas: (1) composición sectorial e interacciones, (2) insumos y productos de los recursos, (3) actores sociales, (4) marcos metodológicos, (5) problemas y limitaciones, (6) distribución geográfica, (7) definiciones operativas del nexo, (8) escalas territoriales y (9) tipo de estudio. Esta clasificación destaca tres cuellos de botella estructurales: (i) concentración metodológica de modelos estáticos de insumo–producto ambientalmente extendidos; (ii) concentración regional de estudios de caso en China, favorecida por la disponibilidad de datos, lo que restringe la transferibilidad global; y (iii) una visión institucional estrecha, en la que la gobernanza multinivel y la sociedad civil aparecen subrepresentadas. El análisis de redes revela que el encuadre conceptual guía la elección metodológica y la inclusión de actores, e indica una escasa diversificación metodológica—relación que se sintetiza en los seis pilares propuestos a continuación. Más allá de revisiones previas del nexo, esta combinación de codificación en nueve dimensiones, análisis de frecuencia cruzada y redes de co-ocurrencia ofrece una base empírica para los seis pilares al vincular cómo se define el nexo con cómo se mide y quiénes son representados en el análisis. Con el fin de apoyar decisiones de ingeniería sostenibles, proponemos una definición ampliada del nexo estructurada en seis pilares interrelacionados: contabilidad de flujos a alta resolución; modelación dinámica con retroalimentaciones (efecto rebote y riesgos de puntos de inflexión); acoplamiento explícito con carbono, uso del suelo y residuos; enfoques híbridos cuantitativos–cualitativos (métodos mixtos); gobernanza colaborativa e inclusiva de múltiples niveles; y arquitecturas de datos abiertos interoperables. En conjunto, estos pilares integran evidencia fragmentada de estudios de caso en un marco sistémico aplicable a la ingeniería y sensible a consideraciones de justicia, informando la planificación integrada de infraestructura agua–energía, la evaluación de trayectorias de transición energética bajo restricciones hídricas, y la priorización de mejoras de gobernanza y arquitectura de datos necesarias para un monitoreo interoperable del nexo entre sectores y escalas.

Palabras clave: Gestión de recursos, Modelación dinámica, Gobernanza multinivel y colaborativa, Modelación híbrida, Análisis insumo–producto

INTRODUCTION

The water–energy nexus (WEN) refers to the two-way dependence between water and energy systems and the environmental and developmental implications of that coupling. Thermoelectric cooling, fossil-fuel extraction, and biofuel refining require substantial water, while every stage of water supply, treatment, and distribution demands energy [1]. Consequently, the WEN operates as a hard constraint on climate-mitigation and sustainable-development agendas, particularly in regions already facing water stress. Mitigation pathways—such as deep electrification (including power-sector expansion and hydrogen production) and large-scale desalination—increase electricity demand just as climate variability and hydrologic extremes reduce cooling-water availability and hydropower potential [2]. Effective WEN management therefore requires methods, data, and governance arrangements that respect thermodynamic, ecological, and institutional limits across scales and reconcile resource security with equity and environmental integrity.

The contemporary WEN landscape

Recent research establishes that water conservation policies and energy consumption exhibit complex, multi-scale interactions. Multiregional input–output (MR-IO) modeling shows that nominal water-saving measures can shift energy consumption spatially and raise embodied-carbon footprints due to rebound and supply-chain feedbacks [3]. When scarcity coefficients are embedded in MR-IO tables, demand changes propagate non-linear stresses across coupled water–energy–carbon systems, exposing trade-offs that single-resource assessments typically overlook [4]. At the urban scale, virtual-water accounting identifies core–periphery asymmetries: water, and energy, dependent cities externalize ecological burdens to their hinterlands, intensifying regional inequity [5]. Explicit representation of these hidden flows is thus required for infrastructure and land-use planning [6]. Integrated food–energy–water (FEW) assessments further underline the nexus' relevance for SDGs 6, 7, and 13, creating demand for frameworks that couple engineering, economic, environmental, and governance perspectives [7]. However, current scholarship remains fragmented, with limited cross-sectoral coverage, sparse methodological integration, and insufficient attention to actor and scale level interactions. A systematic appraisal of recent WEN studies is therefore needed to clarify the state of knowledge, identify persistent gaps, and support strategies that align energy-transition objectives with water-resource constraints while advancing environmentally sustainable development.

Gaps in current WEN research

Despite recent analytical advances, the field remains method-dominant rather than method-diverse. Quantitative studies rely on environmentally extended input–output (EE-IO) models [8, 9] which are frequently identified as the most practical tool for tracing embodied flows [10, 11]. EE-IO tables can represent exchanges at high resolution but lack dynamic capabilities, making them inadequate for modeling institutional feedbacks and governance processes in resource systems [12]. Hybrid approaches—combining IO, life-cycle assessment (LCA), ecological footprinting, and system dynamics (SD) simulations—remain limited to isolated case studies [13,14].

Empirical coverage is geographically skewed. More than half of recent WEN case studies are located in Asia, where provincial statistics and governmental support enable sophisticated econometric modeling [10, 15, 16, 17]. This concentration in a single regulatory and data context restricts the generalizability of findings to regions with fragmented information systems or differing policy regimes, complicating global comparisons.

Moreover, socio-institutional dimensions are understudied. Although multi-level governance and public participation are recognized as prerequisites for sustainable transitions [18, 19], only a small subset of WEN analyses explicitly examines civil society roles [20, 21, 22, 23]. Emerging scholarship highlights the importance of coordinated engagement across governmental, business, academic, and community actors [24] and identifies participatory legitimacy as a

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determinant of effective transitions [25, 26]. For instance, case evidence from the Colorado River Basin demonstrates how co-produced knowledge can strengthen adaptive water governance [27]. In parallel, critiques warn that technocratic framing of the nexus can mask underlying equity concerns [28, 29], and call for governance models that capture multi-level actor coordination [30, 31]. Addressing these methodological, geographic, and institutional shortcomings requires an integrative analytical structure capable of linking biophysical flows to governance processes across spatial and temporal scales [27] —an objective pursued in the subsequent sections of this review.

Aim and manuscript structure

This review pursues three linked objectives. (i) It maps the methodological landscape of WEN scholarship published between 2018 and 2023, quantifying the extent to which environmentally extended input–output (EE-IO) models continue to dominate over LCA, SD, and hybrid approaches. (ii) It compares competing conceptualizations of the nexus—from the traditional water-energy dyad to expanded frameworks that include carbon, land, and other variables—and tests whether particular definitions are associated with specific analytical tools. (iii) It assesses how geographic data asymmetries and actor representation shape modeling outcomes, with emphasis on the predominance of Chinese case studies and the limited treatment of civil society and local-scale governance. These objectives are operationalized through a nine-dimension analytical framework co-designed with five WEN specialists, refined using four seminal reviews (extended to twenty papers via snowballing), and applied to a rigorously screened corpus of seventy-one studies. The framework supports the following guiding questions:

1. **Methodological dominance** – To what degree does EE-IO modeling prevail over alternative or hybrid approaches, and is that dominance correlated with narrower definitions of interdependence?

2. **Spatial bias** – How has the concentration of data-rich case studies in specific regions influenced research priorities, and what gaps persist where statistical infrastructure is limited?

3. **Institutional representation** – How does the underrepresentation of civil society and local governance affect the identification of feedbacks and, by extension, the policy relevance of modeling results?

The Materials and methods section details the literature search in the Web of Science Core Collection (2018–2023), inclusion criteria, and procedures across the nine dimensions. The Results section presents quantitative distributions, cross-dimensional relationships, and a network analysis distinguishing research communities. The Discussion section interrogates findings through four analytical lenses: (i) methodological capabilities and limitations shaping current WEN modeling; (ii) multi-level governance barriers; (iii) our six-pillar framework—integrating dynamic feedbacks, multi-level governance, and interoperable data spines; and (iv) policy leverage points emerging from this synthesis.

Collectively, these contributions are intended to serve readers focused on engineering practice, environmental policy, and systems modeling by translating dispersed WEN evidence into decision-relevant guidance. For model development and engineering applications, the nine-dimension scaffold and cross-dimensional patterns clarify which system elements, actors, and variables are most consistently represented—and which are commonly omitted—so that nexus assessments can be designed more comprehensively. For policy and governance, the six-pillar extended definition highlights leverage points and institutional gaps (including governance and data architecture considerations) that condition whether technical solutions can be implemented, compared, and scaled.

A primary contribution of this manuscript is the six-pillar extended definition, which synthesizes the empirical patterns identified across the nine analytical dimensions into an actionable framework for governance and future research. Fig. 1 summarizes the nine-dimensional (9D) analytical framework used to code and compare studies in the corpus.

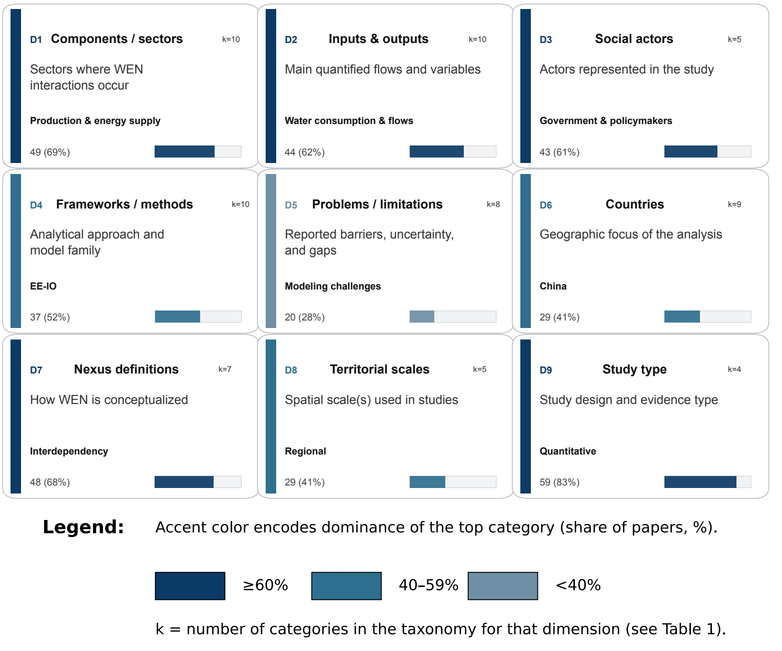

Figure 1. Nine-dimensional (9D) analytical framework and dominant signals in the coded corpus (n = 71). Each card summarizes the dimension's scope, its most frequent category, and the share of papers coded with that category.
Note: Accent color encodes the dominance of the top category (share of papers, %). *k* indicates the number of categories defined in the taxonomy for that dimension (see Table 1). Categories may co-occur within a dimension; therefore, percentages are not mutually exclusive.

MATERIALS AND METHODS

This review combined systematic literature mapping, directed content analysis, and network analytics. Procedures were organized into three steps: (i) corpus construction; (ii) development of a nine-dimension analytical framework; and (iii) sequential quantitative analyses that generated, respectively, a screened evidence base, a stable coding scaffold, and cross-dimensional patterns for interpretation.

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Corpus construction

The Web of Science Core Collection was selected for its long-term coverage and rigorous journal screening, which reduce the risk of predatory content [32, 33]. A topic search covering titles, abstracts, and keywords was conducted using the query reported below and the 2018–2023 time window, returning 116 records. Records were initially retained for screening to avoid prematurely excluding potentially relevant contributions, and titles/abstracts and full texts were then assessed to verify whether the water–energy nexus constituted the central analytical focus (rather than a tangential mention), yielding 56 eligible articles from the query-derived set. During this same screening workflow, we also conducted backward/forward citation checking from eligible full-text papers and performed targeted title/DOI lookups to capture additional central WEN studies that were not retrieved by the query terms or indexing variability; 15 additional studies met the same inclusion criteria. The final coded corpus comprised 71 studies; complete metadata (ID, title, year, journal, DOI) are provided in the open repository [34]. The 2018–2023 window was defined a priori to focus on contemporary WEN literature while keeping full-text screening and coding across nine analytical dimensions feasible and auditable; 2024–2025 publications fall outside this study period. In Web of Science, year-based filtering is applied to database metadata and may return a small number of records later assigned to subsequent issue years; all included studies were retrieved under the stated search settings and met the inclusion criteria.

TI=("water-energy" OR "water energy" OR "energy-water" OR "energy water")

AND (relationship* OR nexus OR link* OR system*)

AND TS=(component* OR subsystem* OR "input-output")

NOT TI=(food)

Analytical framework

A mixed deductive–inductive strategy produced a nine-dimension scaffold (see Table 1): 1) Components, subsystems or sectors; 2) Inputs and outputs; 3) Social actors; 4) Frameworks, paradigms, or research methods; 5) Problems, obstacles, or limitations; 6) Countries; 7) Territorial levels or geographic scales; 8) Definitions of the water–energy nexus; and 9) Type of study.

Stage 1 — Deductive design. Five WEN specialists and the authors defined dimension boundaries and operational definitions.

Stage 2 — Inductive validation. A targeted snowball sample (n = 20) traced from four foundational syntheses and agenda-setting papers [1, 7, 12, 35] confirmed conceptual saturation; only minor terminological adjustments were required. Because our objective was to characterize contemporary structural patterns with a consistent full-text coding protocol, foundational pre-2018 reviews and early syntheses informed framework refinement in this stage but were not systematically included in the coded corpus, which was intentionally bounded to the 2018–2023 evidence base described above.

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Stage 3 — Inter-coder reliability. To assess coding consistency, seven articles (10% of the corpus) were independently double-coded using the full nine-dimension instrument and the 68-category taxonomy. Coding was binary (1 = present; 0 = absent) following the predefined coding rules. Across all binary coding decisions in this subset, overall percent agreement was 80% and Cohen's κ = 0.60. Any discrepancies were resolved through joint full-text review and application of the coding rules, and the consensus coding was entered into the master matrix used for all analyses.

Analytical procedures

1. **Frequency analysis.** Incidence matrices quantified category prevalence and cross-tabulations (e.g., method × country).

2. **Co-occurrence network.** Pairs, triplets, and quadruplets appearing ≥ 10 times (14 % of corpus) formed a 49-node adjacency graph. Community structure was detected with the Louvain algorithm.

3. **Outlier review.** Atypical configurations—such as studies combining system dynamics and civil society engagement—were examined qualitatively to contextualize deviations from dominant patterns.

This protocol provides a transparent and reproducible basis for the Results section.

RESULTS

Corpus-level patterns across the nine analytical dimensions

Table 1 summarizes the full frequency distribution (N = 71). Three corpus-level regularities emerge: (i) 73% of studies focus on production and energy supply sectors, evidencing an engineering orientation; (ii) 41% of empirical cases draw on Chinese provincial data, revealing marked regional concentration; and (iii) government actors dominate (61%), while civil society remains marginal (24%). These corpus-level regularities provide the context for the dimension-specific results presented next.

Table 1. Analytical dimension, categories and frequency of WEN research.
This table defines the 9D coding scaffold (scope + category set) and shows the most frequent category (with examples) used to operationalize each dimension.

Analytical dimension	Focus and scope	Categories	Highest frequency category and examples
(1) Components, subsystems or sectors	Identifies the distinct elements forming the water–energy nexus (e.g., production, supply, governance). Analyzes how each sector/subsystem contributes and interrelates.	Agriculture, Mining, Manufacturing, Production and energy supply, Water supply and treatment, Construction, Transportation and storage, Services, Residential, Governance	**Production and energy supply** (49). [8], [22].

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Analytical dimension	Focus and scope	Categories	Highest frequency category and examples
(2) Inputs and outputs	Examines the flows of resources—particularly water and energy—along with operational processes, transformations, and linkages among different components.	Water consumption and flows, Energy consumption and flows, Embodied resources and transfers, Environmental emissions and pollution, Economic indicators and activities, Resource intensity and efficiency, Virtual water and energy transfers, Infrastructure and technological components, Policy, scenarios, and risk assessment, Indices and analytical tools	**Water consumption and flows** (44).
(3) Social actors	Focuses on stakeholders and their roles and involvement in decision-making.	Government and policymakers, Industry and economic sectors, Academia and research institutions, Communities and civil society, Professionals and technical stakeholders	**Government and policymakers** (43). [10, 5]
(4) Frameworks, paradigms, or research methods	Reviews the theoretical and methodological approaches employed in nexus research, highlighting how studies conceptualize and assess the system.	IO analysis methods, Network analysis methods, Structural path analysis methods, SD modeling, LCA and footprint methods, Optimization and programming methods, Nexus frameworks and approaches, Statistical and data analysis methods, Simulation models and scenario analysis, Literature review and meta-analysis methods	**IO analysis methods** (37). [36, 37]
(5) Problems, obstacles, or limitations	Investigates the challenges that hinder a comprehensive understanding or practical management of the nexus.	Data availability and quality issues, Methodological and modeling challenges, Complex interconnections and system complexity, Policy, regulation, and institutional challenges, Limitations in existing research and knowledge gaps, Environmental and sustainability challenges, Uncertainty and assumptions in modeling, Technological and infrastructure challenges	**Methodological and modeling challenges** (20). [13, 20]
(6) Countries	Explores the global distribution of nexus-related research, showing which regions receive the most attention and where critical gaps persist.	China, Other Asian countries, European countries, North American countries, Latin American countries, Middle East and North Africa, Australia, Global or multiple regions	**China** (41). [16, 15]

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Analytical dimension	Focus and scope	Categories	Highest frequency category and examples
(7) Definition of the water–energy nexus	Compares various conceptualizations, from basic interdependency between water and energy to broader definitions incorporating environmental and social factors.	Interdependency between water and energy, Expanded nexus concepts (including other elements), Importance for sustainability and resource management, Complexity and dynamics of the nexus, Specific contexts or applications, Policy and planning perspectives	**Interdependency between water and energy** (48). [38, 39]
(8) Territorial levels or geographic scales	Considers the spatial dimension of the research to show how scale influences nexus interactions and management strategies.	Local scale, Regional scale, National scale, Global scale, Multiple or combined scales	**Regional scale** (29). [17, 14]
(9) Type of study	Classifies the overarching methodological approaches found in the literature, reflecting the balance between numerical analyses and qualitative insights.	Quantitative studies, Qualitative studies, Mixed methods studies	**Quantitative studies** (59). [11, 40]

Analytical patterns across dimensions

Tables 2A and 2B summarize how the nine analytical dimensions and the six recurrent nexus definitions distribute across the 71-paper corpus. Percentages refer to corpus share; counts are given in brackets. Three regularities stand out. First, methodological concentration: environmentally extended input–output (EE-IO) analysis dominates four definitions [8] whereas system dynamics models appear mainly under "complexity & dynamics" [41]. Second, supply-side bias: Production & energy supply sectors lead every definition, while demand-side sectors such as agriculture rarely place within the top two [10, 11]. Third, actor asymmetry linked to geography: government agencies predominate in studies that rely on Chinese provincial statistics [16, 17], whereas civil society rarely exceeds one quarter of cases, echoing gaps noted by [18]. Taken together, these associations show that the nexus framing is not merely semantic but directional: it channels methodological choice, tilts sectoral emphasis, and conditions actor inclusion—a pattern further examined in the Discussion section.

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Table 2A. Highest frequency categories per analytical dimension (N = 71).
A compact overview of the dominant category choices per dimension, highlighting which sectors, variables, actors, methods and scales most often structure WEN studies.

Dimension	1st category n (%)	2nd category n (%)
Components / sectors	Production & energy supply 49 (69)	Water treatment 25 (35)
Inputs & outputs	Water consumption & flows 44 (62)	Energy consumption & flows 43 (61)
Social actors	Government & policymakers 43 (61)	Academia 28 (39)
Frameworks / methods	EE-IO 37 (52)	Process LCA 16 (23)
Problems / limitations	Modeling challenges 20 (28)	Data gaps 17 (24)
Countries	China 29 (41)	Multi-region 15 (21)
Territorial scales	Regional 29 (41)	National 21 (30)
Nexus definitions	Interdependency 48 (68)	Sustainability 20 (28)
Study type	Quantitative 59 (83)	Mixed-method 8 (11)

Table 2B. Signature of each nexus definition: dominant method, sector, actor and geographic focus (N = 71).
Each row summarizes a "definition signature," showing how conceptual framing aligns with typical methods, sector focus, actor representation, and geography.

Nexus definition	Methods (top 2)	Sectors (top 2)	Actors (top 2)	Geographic focus (top 2)	n (%)
Interdependency	EE-IO 73 % ; Process LCA 19 %	Production & energy 69 % ; Water treatment 42 %	Government 63 % ; Academia 28 %	China 54 % ; Multi-region 21 %	48 (68)
Sustainability	EE-IO 45 % ; Hybrid IO-LCA 30 %	Production & energy 60 % ; Agriculture 35 %	Academia 55 % ; Civil society 25 %	Global 35 % ; Europe 25 %	20 (28)
Extended resources	EE-IO 56 % ; Network 28 %	Production & energy 61 % ; Emissions 39 %	Government 50 % ; Industry 33 %	China 44 % ; N. America 22 %	18 (25)
Complexity & dynamics	System dynamics 57 % ; Agent-based 21 %	Manufacturing 50 % ; Production & energy 43 %	Academia 64 % ; Industry 21 %	China 29 % ; Multi-region 29 %	14 (20)
Policy & planning	EE-IO 55 % ; Scenario 27 %	Production & energy 45 % ; Water treatment 36 %	Government 73 % ; Academia 27 %	China 46 % ; Europe 27 %	11 (15)
Specific contexts*	Qualitative 50 % ; Process LCA 25 %	Urban services 63 % ; Agriculture 38 %	Local authorities 50 % ; Civil society 25 %	N. America 38 % ; Lat. America 25 %	8 (11)

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The framing of the nexus is not merely semantic but predictive. Table 2B indicates that the interdependency frame channels research toward EE-IO footprints, production sectors and state actors, whereas the complexity & dynamics frame selects feedback-oriented models and shifts attention to academic–industry pairs. In contrast, the sustainability frame widens actor participation—civil society appears in 25 % of cases—and broadens geography beyond China. These systematic alignments show that how the nexus is framed helps determine which questions are asked, which data are mobilized, and which policy levers are considered, underscoring the need for an expanded, reflexive definition.

Analysis of variables

Temporal, geographic and category prevalence

Annual WEN publications in our corpus increased from 9 (2018) to 15 (2023), peaking at 16 (2021). Geographically, 58 % of case-oriented studies still rely on Chinese provincial statistics, while Latin America, Africa and the Middle East together account for <10%, confirming the regional concentration and limiting the evidence base available to inform environment–development decisions in data-scarce regions.

Table 3 lists, for each analytical dimension, the five most frequent categories and their shares within the corpus. Two patterns stand out. First, supply-side emphases dominate: Production & energy supply is the leading component (69 %), and volumetric metrics of water and energy flows outnumber externality indicators three-to-one. Second, research is method-driven: environmentally-extended IO (52 %) and process LCA (23 %) together cover three-quarters of methodological choices, whereas dynamic tools such as system dynamics or network models appear in fewer than one-fifth of studies. These distributions provide the empirical baseline for the association analyses developed in the following sub-sections.

Table 3. Top-5 categories per analytical dimension (N = 71).
Baseline prevalence results across the full taxonomy, indicating which categories consistently appear—and which remain comparatively underrepresented—within each dimension.

Dimension	1st category n (%)	2nd	3rd	4th	5th
Components / sectors	Production & energy supply 49 (69)	Water treatment 25 (35)	Agriculture 18 (25)	Manufacturing 15 (21)	Urban services 13 (18)
Inputs & outputs	Water flows 44 (62)	Energy flows 43 (61)	Emissions 16 (23)	Economic value 14 (20)	Carbon footprint 12 (17)
Social actors	Government 43 (61)	Academia 28 (39)	Industry 24 (34)	Civil society 17 (24)	Local authorities 15 (21)
Frameworks / methods	EE-IO 37 (52)	Process LCA 16 (23)	Hybrid IO-LCA 14 (20)	System dynamics 12 (17)	Network analysis 10 (14)
Problems / limitations	Modeling challenges 20 (28)	Data gaps 17 (24)	Scale mismatch 12 (17)	Uncertainty propagation 11 (15)	Institutional barriers 10 (14)
Countries	China 29 (41)	Multi-region 15 (21)	Europe 12 (17)	N. America 10 (14)	L. America 6 (8)

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Dimension	1st category n (%)	2nd	3rd	4th	5th
Territorial scales	Regional 29 (41)	National 21 (30)	City 18 (25)	Province 16 (23)	Basin 12 (17)
Nexus definitions	Interdependency 48 (68)	Sustainability 20 (28)	Extended resources 18 (25)	Complexity 14 (20)	Policy 11 (15)
Study type	Quantitative 59 (83)	Mixed-method 8 (11)	Qualitative 6 (8)	Scenario 5 (7)	Review 3 (4)

Inter-dimensional associations

Eight high-frequency combinations—five pairs and three triplets—account for more than one third of all category co-mentions in the corpus (see Table S1, Online Resource 1). The leading pair, "China × EE-IO" (26 papers, 37 %), confirms that provincial Chinese statistics underpin most economy-wide footprint studies [8, 17]. Two additional pairs—"Production & energy supply × EE-IO" and "Government × China"—underscore the supply-side and state-centric orientation noted above. Among triplets, "EE-IO × Production & energy supply × China" (18 papers, 25 %) dominates, indicating that method, sector and geography co-evolve rather than combine randomly. The next two triplets substitute Government or Interdependency for China, showing that either a governance lens or a conceptual framing can occupy the third slot but rarely both simultaneously. Collectively, these patterns suggest methodological concentration in topic selection and data mobilisation.

Network community structure

We built a weighted co-occurrence graph from the 41 categories that co-appear ≥ 10 times in the corpus (procedures in the Materials and methods section). The Louvain method (Q = 0.42) resolves three stable modules; their composition is shown in Fig. 2a, 2b, 2c and 2d, and the ten most central nodes with community assignment are reported in Table 4.

Community A – methodological core

Anchored by EE-IO methods (degree 38) and Production & energy supply (35), this module links Water flows and the Interdependency framing with the geographic tag China. The dyad China + EE-IO occurs in 24 % of all articles, showing a footprint-driven orientation of Chinese WEN research [8, 17].

Community B – sector-geography.

The Sustainability framing (25) clusters with Hybrid IO–LCA (22), Agriculture (24) and Civil society. Although civil-society participation rises to 25 % within this group, government agencies remain predominant, echoing governance gaps noted by [18].

Community C – government & implementation.

System dynamics (20) and Network models co-locate with the Complexity framing and Manufacturing sectors. These studies emphasise feedbacks and potential tipping points, signalling an emerging WEN line focused on dynamic behaviour [41].

The prominence of certain hubs and the clear modular boundaries in Fig. 2 indicate that conceptual framing steers method selection, sectoral emphasis and actor inclusion. This segmentation constrains knowledge transfer across research traditions—a point we develop in the next section.

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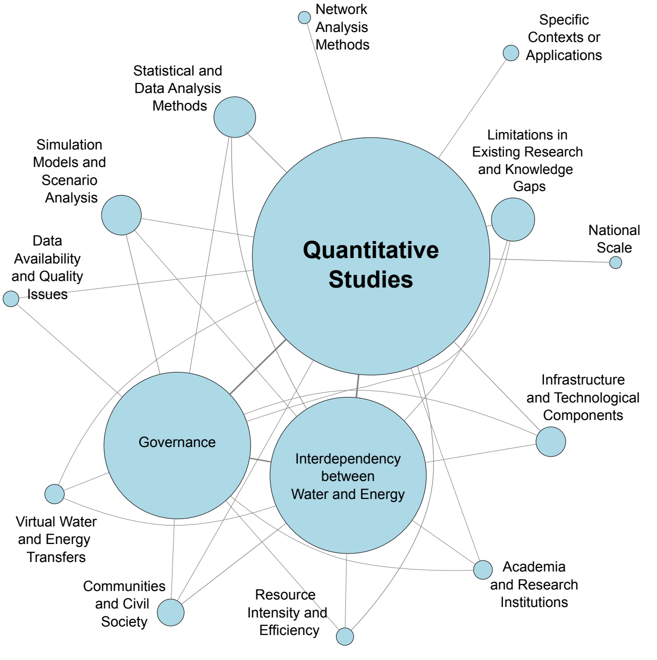
Table 4. Most-central nodes in the inter-dimensional co-occurrence network (N = 41).
Centrality rankings identify the categories that most strongly connect across dimensions and anchor the network's main communities (modules).

Rank	Node (category)	Degree*	Share of all edges	Community
1	EE-IO methods	38	9.3 %	A
2	Production & energy supply	35	8.5 %	A
3	China	32	7.8 %	A
4	Water flows	28	6.9 %	A
5	Sustainability framing	25	6.1 %	B
6	Agriculture sector	24	5.8 %	B
7	Hybrid IO–LCA	22	5.4 %	B
8	System dynamics	20	4.9 %	C
9	Governance & policy	18	4.4 %	C
10	Civil society actors	17	4.2 %	C

*Degree = number of distinct categories co-mentioned with the node.



2A Methodological core

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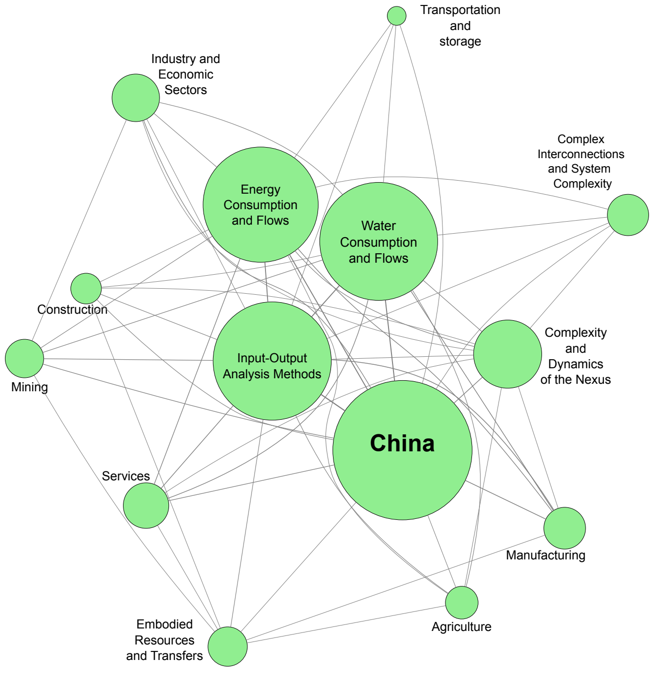
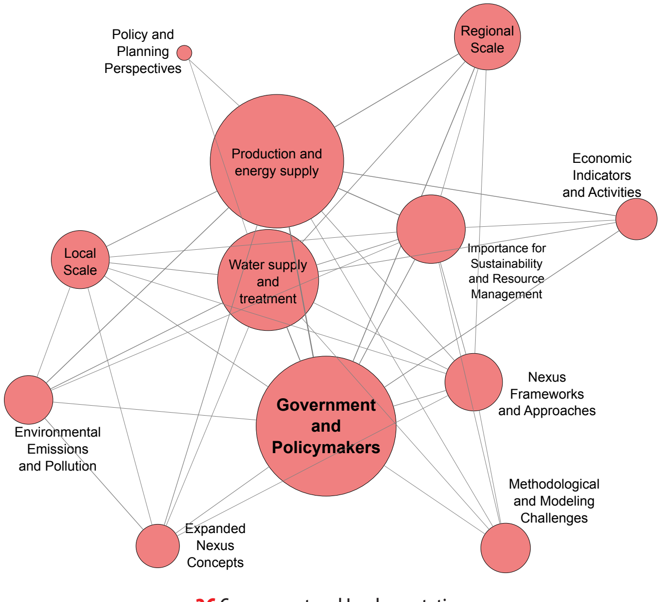


2B Sector-geography nexus



2C Government and Implementation

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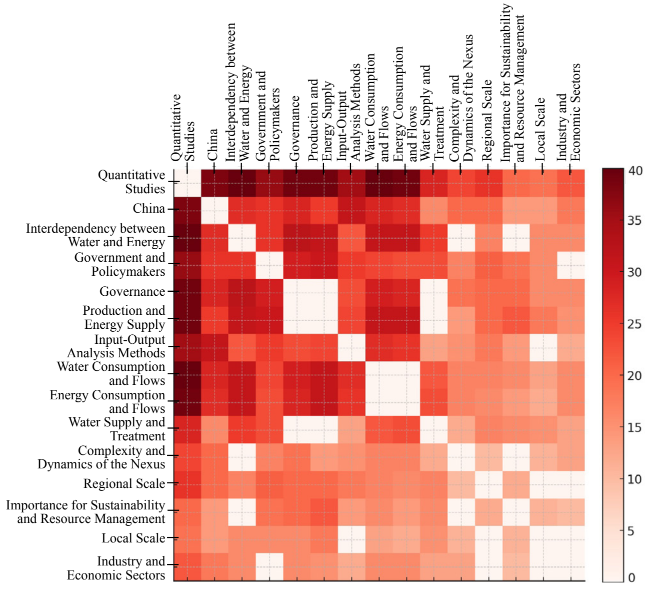
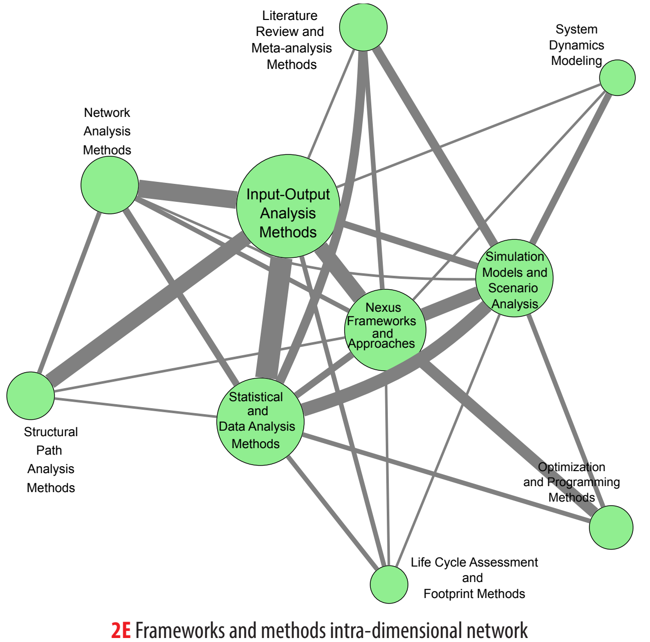


2D Top-15 category co-occurrences



2E Frameworks and methods intra-dimensional network

Figure 2. Network analytics of the 71-article corpus. (**2A**) Community A shows a methodological hub centred on quantitative studies and W–E interdependence. (**2B**) Community B links China-focused flow metrics to IO methods, forming a sector–geography nexus. (**2C**) Community C clusters governance actors and implementation sectors at regional scale. (**2D**) Heatmap of the 15 most frequent inter-category pairings highlights strongly coupled concepts (darker cells). (**2E**) Intra-dimensional network for the Frameworks & Methods dimension: node size is proportional to weighted degree, and edge width to co-occurrence frequency above the 95th-percentile threshold.

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Higher-order combinations and patterns

Of the 12,878 triplets and 52,481 quadruplets detected across all dimensions, only ten exceed the upper-tail thresholds adopted here—triplets cited in ≥ 9 articles and quadruplets in ≥ 4. These sets (reported unchanged in Table 5) capture the multi-dimensional backbone of WEN scholarship.

Flow-accounting backbone. Four of the five most frequent triplets and all five quadruplets couple at least one flow variable (Water or Energy consumption & flows) with input-output (IO) methods and a quantitative design, indicating that volumetric accounting combined with IO modeling dominates empirical work. China–IO axis; the top triplet and every high-frequency quadruplet include the China marker, underscoring how that country's unrivalled data infrastructure drives multi-category studies and reinforces methodological concentration. Peripheral governance; governance appears in higher-order sets only when attached to this technical core (Quadruplet #5: China + Government + IO + Quantitative), indicating that socio-institutional variables remain adjunct rather than integral to prevailing research templates.

These cross-dimensional clusters rest on the internal cohesion of each analytical dimension, examined in the next subsection.

Table 5. Triplets (cited in ≥ 9 articles) and quadruplets (cited in ≥ 4 articles).
Higher-order combinations capture the "backbone" configurations of the literature, revealing which multi-dimensional templates recur most frequently.

Rank	Triplet (categories [dimensions])	n articles (triplet ≥ 9)	Quadruplet (categories [dimensions])	n articles (quadruplet ≥ 4)
1	China [Countries] ; Input-Output Analysis Methods [Frameworks] ; Quantitative Studies [Type]	30	China [Countries] ; Input-Output Analysis Methods [Frameworks] ; Quantitative Studies [Type] ; Water Consumption and Flows [Inputs]	21
2	Energy Consumption and Flows [Inputs] ; Interdependency between Water and Energy [Definition] ; Water Consumption and Flows [Inputs]	29	China [Countries] ; Energy Consumption and Flows [Inputs] ; Input-Output Analysis Methods [Frameworks] ; Quantitative Studies [Type]	20
3	Interdependency between Water and Energy [Definition] ; Input-Output Analysis Methods [Frameworks] ; Quantitative Studies [Type]	29	China [Countries] ; Input-Output Analysis Methods [Frameworks] ; Production & Energy Supply [Components] · Quantitative Studies [Type]	20
4	Energy Consumption and Flows [Inputs] ; Production & Energy Supply [Components] ; Water Consumption and Flows [Inputs]	28	Energy Consumption and Flows [Inputs] ; Interdependency between Water and Energy [Definition] ; Quantitative Studies [Type] ; Water Consumption and Flows [Inputs]	20
5	Production & Energy Supply [Components] ; Quantitative Studies [Type] ; Water Consumption and Flows [Inputs]	28	China [Countries] ; Government and Policymakers [Social actors] ; Input-Output Analysis Methods [Frameworks] ; Quantitative Studies [Type]	20

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Intra-dimensional cohesion and key implications

Table 6 shows, for each analytical dimension, the single most frequent set of three or four categories found in the corpus. Two patterns are found. First, the Frameworks & Methods dimension exhibits the tightest internal linkage: its leading triplet—Input-Output Analysis + Statistical/Data Analysis + Simulation & Scenario Models—occurs in 25 articles, far more than any other dimension. Second, resource-flow blocks also cohere strongly: Components/Sectors and Inputs & Outputs appear as quadruplets in 13 and 15 articles, respectively, reflecting a growing preference for multi-metric accounting that combines physical, virtual and embodied flows. By contrast, Territorial scale integration remains fragmentary: its top triplet appears only three times, confirming that scale hierarchies are still treated piecemeal.

Table 6. Leading intra-dimensional combination by dimension.
Within-dimension co-occurrence highlights internal cohesion (standardized templates) and contrasts tightly coupled dimensions with those that remain fragmented.

Dimension	Combination	Articles (n)
Components, subsystems or sectors	Agriculture ; Construction ; Manufacturing ; Services (quadruplet)	13
Inputs & Outputs	Water Consumption & Flows ; Energy Consumption & Flows ; Virtual Water & Energy Transfers ; Embodied Resources & Transfers (quadruplet)	15
Social actors & governance	Government & Policymakers ; Academia & Research Institutions ; Communities & Civil Society (triplet)	16
Frameworks & Methods	Input–Output Analysis Methods ; Statistical & Data Analysis Methods ; Simulation Models & Scenario Analysis (triplet)	25
Problems & Limitations	Data Availability & Quality Issues ; Methodological & Modeling Challenges ; Uncertainty & Assumptions in Modeling (triplet)	12
Definition & Concepts	Interdependency between Water & Energy · Nexus Frameworks & Approaches ; Expanded Nexus Concepts (triplet)	18
Territorial levels & geographic scales	Local Scale · National Scale ; Multiple/Combined Scales (triplet)	3
Countries & regions	China ; North American Countries ; European Countries (triplet)	22
Type of study	Quantitative Studies ; Network Analysis Methods ; Input–Output Analysis Methods (triplet)	14

Fig. 2e visualises the sub-network for Frameworks & Methods. Input-Output occupies the central hub, while thick links already connect Process-LCA, Hybrid IO-LCA and System dynamics, signalling a gradual toolkits diversification. Thinner edges extend toward Agent-Based Modeling, hinting at future convergence between behavioural and economy-wide approaches.

Taken together, the corpus displays a dual architecture. A compact set of method and flow-centric dimensions furnishes both the inter-dimensional backbone (Fig. 2a, 2b, 2c and 2d) and the strongest intra-dimensional cohesion (Table 6, Fig. 2e), whereas governance-

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oriented or reflexive dimensions remain loosely coupled. This asymmetry underlies the methodological and policy challenges discussed in the Discussion section: without stronger bridges between technical cores and socio-institutional categories, nexus models will continue to excel at accounting while falling short on implementation.

DISCUSSION

The Results section revealed three structural gaps in current WEN research. First, static input–output models dominate and are often paired with limited data transparency. Second, national studies—predominantly on China—eclipse subnational and multiregional analyses. Third, nexus definitions rarely integrate carbon, land, or waste flows. To turn these deficiencies into forward-looking insight, the Discussion section examines five interconnected topics. It begins by probing the methodological landscape (Methodological landscape: assets, blind spots and the method–data gap), highlighting both its assets and the emergent method–data gap. It then examines how evidence loses fidelity when governance levels and spatial equity are ignored (Governance, actors, and scale mismatches). It also analyzes how data geography shapes spatial equity in WEN systems (Spatial equity and data geography). From this foundation, it proposes an extended nexus definition articulated through six interlocking pillars (From linear coupling to adaptive socio-technical systems: an extended definition of the water–energy nexus). It concludes by outlining a roadmap that links an open data spine to multi-level governance solutions (Research and policy agenda: priorities for a dynamic and equitable nexus). Together, these five thematic sections transform empirical patterns into an agenda that is methodologically robust, equity-aware and policy actionable. Fig. 3 provides an integrative summary linking dominant empirical patterns (methods, geography, governance, and conceptual framing) to the six-pillar extended definition.

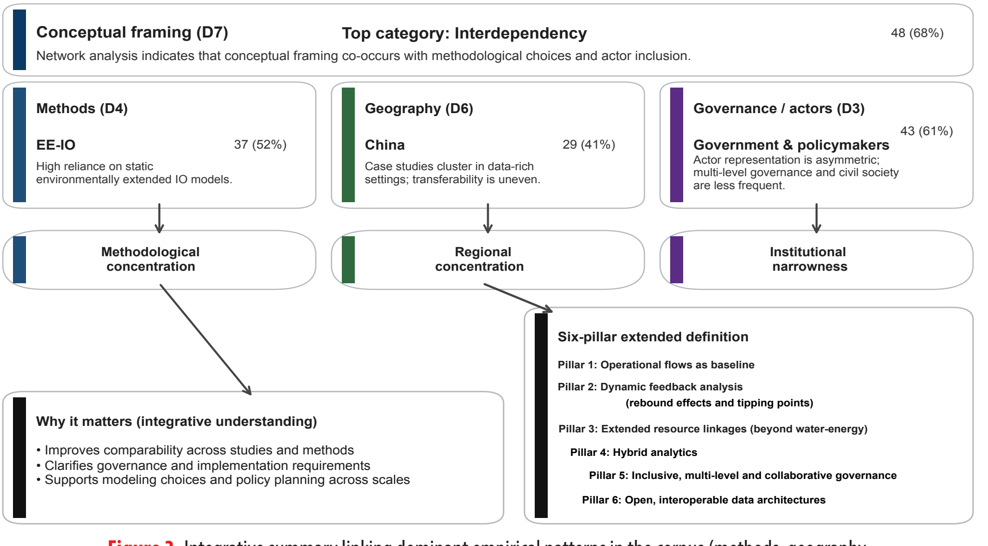

Figure 3. Integrative summary linking dominant empirical patterns in the corpus (methods, geography, governance, and conceptual framing) to the six-pillar extended definition.

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Methodological landscape: assets, blind spots and the method-data gap

The water–energy nexus literature still revolves around environmentally extended input–output models, valued because national supply-use tables provide coefficients that are ready for immediate application [8]. However, their linear structure locks analysis into a single time snapshot, eliminating rebound, delay, and depletion dynamics. Process LCA moves in the opposite direction, revealing plant-level stress points in technologies such as reverse osmosis desalination and hybrid cooling [42, 43, 44]. Yet it shares the same static bias unless coupled to IO extensions, and it invariably loses phenomena outside the system cut-off [45].

Dynamic approaches—system dynamics (SD) loops and agent-based hybrids—remain a minority but reveal feedbacks invisible to static inventories. A Liaoning SD model shows tariff-induced rebounds that erode planned water savings [14]. A multi-scenario SD study for Ningbo captures seasonal shifts that reverse a seemingly favourable electrification pathway [41]. Also agent-based simulations reveal how information diffusion among irrigators accelerates pump adoption while widening income gaps [46]. The drawback is data: hourly or seasonal coefficients these models require seldom exist in public repositories. Table 7 thus evidences a method-data gap: four of the six methodological families we catalogued lack explicit feedback loops, while those that do rely on coefficients that are not yet standardized.

Table 7. Comparative assessment of dominant methodological families in our review.
Side-by-side comparison clarifies what each method family can (and cannot) capture—especially feedback capability and resolution—supporting interpretation of the method–data gap.

Method family	Primary analytical focus	Feedback capability	Spatial / temporal resolution	Main advantages	Key limitations
SR-IO	Sectoral direct & embodied flows within one country	None (linear)	Medium / static	Economy-wide coverage; scenario elasticity	Ignores inter-regional trade; cannot model adaptation or rebound
MRIO	Inter-regional embodied flows	None (linear)	High spatial / static	Tracks global supply-chain spill-overs; policy stress tests	Requires harmonised econ. accounts; still static; high uncertainty for low-income regions
Process LCA	Cradle-to-gate process chains	None (linear)	Facility scale / static	High technological detail; permits hotspot analysis	Truncation error; social variables absent; poor comparability
IO-LCA hybrid	Sector + process	Limited (linear)	Multi-scale / static	Reduces truncation; merges sectoral and process detail	Still static; complex data reconciliation

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Method family	Primary analytical focus	Feedback capability	Spatial / temporal resolution	Main advantages	Key limitations
System Dynamics	Stock-flow feedbacks, policy delays	Full (endogenous)	Flexible / dynamic	Captures non-linear adaptation and rebound	Calibration intensive; scenario dependence; few empirical time series
Network / hybrid ABM	Agents, links, emergent behaviour	Partial / stochastic	Flexible / dynamic	Reveals tipping points, multi-resource interplay	Non-standardised; steep learning curve; data-hungry

Bridging this gap constitutes an infrastructural deficiency rather than a modeling challenge per se. Network-enhanced IO work illustrates what is possible once flow contagion is acknowledged [47], but reviewers remain sceptical unless every coefficient is traceable through a digital chain of custody [48]. Urban energy–water studies reach the same conclusion, calling for minimum data schemas and shared vocabularies [49]. Interoperability guidelines and curated coefficient spines now emerging [11, 50] are not administrative formalities; they are a precondition for any new analytical breakthrough. Without institutional enforcement of interoperability standards, nexus scholarship perpetuates a cycle of epistemologically incompatible approaches: computationally rigid inventories and dynamically unstable.

Governance, actors, and scale mismatches

Based on the patterns reported in the Results section, current nexus modeling exhibits persistent institutional asymmetries: state-level entities dominate analytical frameworks, while municipal agencies, basin councils and community organizations appear only sporadically. This imbalance intersects with subnational IO structures and retrofit-centred scenarios to shrink both the universe of feasible interventions and the empirical basis on which they rest. Three interlocking governance challenges emerge. Challenge 1 — Scale mismatches: when national or provincial models prescribe interventions that cities or districts must execute, policy timelines lengthen and cost projections erode—as experience with river-basin plans shows when financing constraints and enforcement capacity are underestimated [51]. Environmental externalities outpace single-tier regulatory systems, converting well-intentioned mandates into unfunded liabilities that undermine policy credibility.

Challenge 2 — Governance treated as exogenous: Framework reviews highlight that institutional quality is often handled as an exogenous constant rather than a measurable parameter: indicators such as enforcement probability or stakeholder participation rarely enter the coefficient matrix [52]. Where such metadata are absent, models implicitly assume perfect compliance, inflating technical feasibility. Even dynamic approaches struggle to validate feedbacks when budget cycles, subsidy adjustments, and tariff histories remain scattered across non-interoperable databases. This creates a dilemma: decision-makers demand proof of model utility before investing in data, while modellers cannot demonstrate utility without those data.

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Challenge 3 — Legitimacy and inclusion: implementation evidence shows how exclusionary modeling practices undermine intervention legitimacy [53]. These outcomes confirm that actor diversity functions not merely as an ethical safeguard but as an operational prerequisite for durable policy implementation [54].

Emerging institutional innovations attack these bottlenecks from two directions. Multi-tier governance platforms can align incentives across scales. For example, the Water Smart Landscapes rebate, coordinated by the Southern Nevada Water Authority yet delivered through municipal districts, achieved an 18–20 % reduction in household withdrawals at minimal cost because fiscal and informational responsibilities were distributed [55, 56]. In parallel, open-data protocols knit together previously isolated information systems: HydroShare's deployment of WaterML and the OAI-ORE framework publishes hydrologic time series and rasters as FAIR objects, shrinking coefficient uncertainty and enabling block-level targeting [57]. Interoperability boosts legitimacy, and inclusive governance provides the mandate to improve data quality—a mutually reinforcing loop that purely technocratic approaches cannot replicate.

Embedding governance-sensitive parameters—budget-autonomy thresholds, enforcement-probability indices, stakeholder-diversity metrics—directly into nexus models is therefore imperative. Only then can WEN methodologies progress from theoretically optimal blueprints to institutionally actionable roadmaps, a transition operationalised in the tiered agenda detailed after the next section.

Spatial equity and data geography

WEN research exhibits persistent geographical and methodological imbalances. A predominant focus on well-documented regions (e.g., China) has left gaps in understanding across diverse developmental contexts. These disparities arise from structural differences in data infrastructure and analytical capacity, with direct consequences for both research outcomes and policy applications.

A central concern is the routine transfer of standardized parameters across diverse geographical contexts. Bazilian et al. [1] show that frameworks designed for industrialized economies often underestimate local variability in production methods, resource availability, and technology adoption, biasing WEN assessments. Consequently, such transfers can degrade model accuracy and distort policy recommendations, especially in systems with unique biophysical constraints or development pathways that diverge from standardized assumptions.

These challenges are amplified by persistent data limitations in many developing regions. In the absence of comprehensive, regularly updated resource inventories, analyses are often confined to static approaches—a constraint highlighted by [58], who shows how dynamic processes (e.g., climate adaptation and market shocks) remain invisible without reliable longitudinal datasets. The resulting data scarcity creates a self-reinforcing cycle: limited local research output reduces incentives to invest in statistical infrastructure, which in turn deepens analytical disparities. The equity implications are immediate. Regions with robust data systems can articulate nuanced policy positions based on detailed analyses of trade flows and resource dependencies; by contrast, areas without such infrastructure often depend on external assessments that may fail to capture local realities [59]. Addressing these challenges requires coordinated improvements in data-collection frameworks and the adoption of context-sensitive analytical approaches. Two immediate pathways are: (i) minimum data standards for international collaborations, and (ii) adaptive assessment designs that explicitly account for regional variation. Together, these steps would increase the external validity of WEN studies across developmental contexts and support more equitable policy outcomes.

From linear coupling to adaptive socio-technical systems: an extended definition of the water–energy nexus

Early work framed water–energy relations as a bilateral technical interdependence—water withdrawn for energy production and energy required for water services. Our evidence shows that this "linear-coupling" view still dominates. To reconcile concept with observed patterns, we propose an extended definition organized around six interlocking pillars.

The Results section provides evidence across the 71-study corpus through our nine-dimension scaffold (see the Results section; Table 3; Table 2B; Fig. 2). It integrates cross-dimensional frequency patterns and the co-occurrence network structure, complemented by the qualitative synthesis used to interpret recurring gaps and design requirements within the reviewed literature. Together, these results indicate a field with a strong technical backbone in flow accounting and method–framing regularities, but with comparatively weaker integration of dynamic feedbacks, broader coupled-resource boundaries, governance and non-state actors, and transparent data practices. Building on this combined empirical and interpretive basis, we formulate the extended definition as six pillars:

Pillar 1 codifies flow accounting as the common baseline. Pillar 2 makes feedback dynamics and non-linear risks explicit, and Pillar 3 extends system boundaries to capture additional coupled resources. Pillars 4–6 promote hybrid analytics, inclusive multi-level collaboration, and open, interoperable data architectures to address documented governance asymmetries and recurring data constraints.

Extended definition (six-pillar frame)

In this view, the water–energy nexus is a multi-level socio-technical system in which (1) operational water and energy flows are (2) dynamically coupled through non-linear feedbacks and (3) embedded in broader resource linkages—carbon, land, food, and waste. Effective stewardship further requires (4) hybrid quantitative–qualitative analytics, (5) inclusive, multi-level collaborative governance, and (6) transparent, interoperable data architectures that enable adaptive, scale-consistent decision-making. These pillars are sequential and mutually enabling: baseline flow accounting reveals feedback mechanisms; feedback analysis surfaces externalities; managing those externalities motivates integrated methods; and hybrid methods, in turn, depend on standardized data infrastructure and shared governance.

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Pillar 1: Operational flows as baseline

Our systematic analysis indicates that 70% of the literature employ IO or life cycle methodologies to quantify direct and embodied water-energy flows. For example, MR-IO tables trace how industrial provinces in the Yellow River Basin export large volumes of virtual water and energy to downstream regions while importing finished goods [60]. Technology-specific LCA reports water-consumption intensities per kWh and repeatedly identifies thermoelectric cooling as a dominant hotspot—often an order of magnitude above wind or photovoltaic generation [61]. Together, these empirically grounded inventories establish the system's baseline constraints: without them, dynamic models cannot detect rebound risks, and governance extensions cannot evaluate the feasibility of proposed measures.

Pillar 2: Dynamic feedback analysis (rebound effects and tipping points)

Building on Pillar 1's baseline flow accounts, dynamic models—system dynamics (SD) and agent-based approaches (ABM)—make explicit the feedbacks that static inventories cannot represent, including rebound, delays, and tipping behavior. At the basin scale, SD simulations show that irrigation-efficiency measures can reduce conveyance losses yet simultaneously induce higher groundwater pumping, gradually driving aquifers toward unsustainable thresholds [62]. By tracing these feedback mechanisms through time, dynamic approaches convert baseline accounts into forward-looking risk assessments that flag when and under which conditions efficiency gains rebound or cascade into new vulnerabilities. This diagnosis is a prerequisite for Pillar 3's cross-resource accounting and for Pillar 4's hybrid analytics, which operationalize mitigation and monitoring responses.

Pillar 3: Extended resource linkages (beyond water-energy)

Building on Pillars 1 and 2, Pillar 3 extends the nexus beyond water and energy to explicitly couple carbon, land, food, and waste flows. For instance, MR-IO studies show that gaps between production- and consumption-based CO_2 accounts reveal outsourced emissions to trade partners [63]. Global bioenergy assessments indicate that biomass from marginal lands—agricultural residues, manure, and municipal wastes—could supply ~100 EJ yr^{1}, which requires cascade-utilization schemes to avoid shifting burdens to soil, water, or air [64]. By internalizing these cross-resource trade-offs, Pillar 3 converts isolated efficiency gains into joint objectives across carbon, land, waste, and food, reducing burden shifting across sectors and regions and preparing the ground for the hybrid analytics operationalized in Pillar 4.

Pillar 4: Hybrid analytics

Hybrid analytics integrate baseline flow accounts with dynamic system-dynamics (SD) engines and artificial intelligence, while digital twins provide real-time inputs from meters, markets and sensors. This continuously updated replica allows planners to stress-test resource allocation and pricing rules before implementation. For example, the Irbid Camp digital twin simulates alternative water- and energy-use scenarios on the WEFE nexus with live sensor inputs and machine-learning forecasts [65]. Hybrid analytics also expose cross-scale bottlenecks; in the Hanjiang River case, an SD model driven by hydrological and socioeconomic data reveals how water and energy shortages emerge and propagate across sub-basins over time [66]. By translating these complex nexus outputs into actionable dashboards, hybrid analytics convert the insights from Pillars 1–3 into day-to-day decision support.

Pillar 5: Inclusive, multi-level and collaborative governance

The Results section reveals a marked actor asymmetry: state agencies dominate global WEN research, while private-sector, academic, and civil society actors appear far less frequently. This imbalance constrains the legitimacy and implementability of modeling outcomes. The technical coherence developed in Pillars 1-4 becomes actionable only when decision-making is genuinely shared. We therefore define Pillar 5 as inclusive, multi-level and collaborative governance—the vertically and horizontally coordinated formulation, implementation and monitoring of nexus policies by local, regional and national authorities together with industry, academia and community-based organizations. Comparative evidence shows that such arrangements (i) improve cross-scale policy coherence, (ii) institutionalize meaningful participation, and (iii) embed adaptive accountability mechanisms [18, 19].

Two recent Latin-American cases illustrate these benefits. In Brazil, the Piracicaba–Capivari–Jundiaí river-basin committee brought together municipal agencies, firms, and citizens to manage the 2014–2015 drought; this platform shortened decision-making cycles and accelerated emergency responses by ≥ 30% [67]. In the transboundary Upper Lempa basin, a tri-national dashboard co-designed with stakeholders increased users' correct understanding of climate–land-use vulnerabilities by 35%, demonstrating how shared data tools can catalyze collective action [68].

Embedding this multi-level, collaborative governance pillar within the six-pillar frame links the analytical insight of Pillars 1–4 and the data infrastructure of Pillar 6 to decision processes that are both equitable and adaptive across scales.

Pillar 6: Open, interoperable data architectures

The implementation of all preceding pillars ultimately hinges on building FAIR-compliant, interoperable data architectures capable of supporting both analytical rigor and governance legitimacy. These architectures provide the foundational layer upon which hybrid analytics, dynamic modeling, and multi-level coordination can reliably operate.

Functionally, open data frameworks perform two critical and complementary roles. First, as in Pillar 4, they serve as machine-interpretable input streams, enabling hybrid analytics, digital-twin integration, and continuous model updating through real-time hydrological, economic, and infrastructural data [69]. Without harmonized schemas—common identifiers, shared vocabularies, and standardized metadata—digital twins and adaptive models cannot maintain internal consistency, undermining their forecasting and stress-testing capabilities. Second, these same architectures constitute verifiable reference baselines that underpin inclusive, multi-level and collaborative governance (Pillar 5). They enable cross-institutional auditing, transparent coefficient traceability, and joint monitoring—conditions required for coordinated action across agencies, jurisdictions, and sectors. By reducing parametric uncertainty, clarifying data provenance, and exposing knowledge gaps, interoperable infrastructures strengthen the credibility of model outputs and increase the willingness of public and private actors to rely on them for investment and policy decisions [70]. Through these mechanisms, an open, FAIR-aligned data spine operationalizes the entire six-pillar framework: it supplies the structured datasets required by Pillars 1–3, enables hybrid computational tools in Pillar 4, and reinforces the procedural safeguards central to Pillar 5. In doing so, it transforms the conceptual advances of Pillars 1–5 into a continuously improving, adaptive socio-technical management system rather than a one-off analytical exercise.

Integrative insights and global outlook

The architecture proposed in this study reconfigures nexus practice along two empirically grounded dimensions. First, it shifts the analytical baseline from static, inventory-driven assessments to dynamic, feedback-rich modeling, enabling researchers to detect rebound effects, cascading failures, and path-dependent risks that static tools systematically overlook. Second, it moves the field beyond technocratic, top-down prescriptions toward inclusive, multi-level, and collaborative governance, aligning analytical sophistication with decision-making structures capable of implementing adaptive measures.

Together, these shifts produce four system-level gains. They (i) facilitate scale integration by fusing local monitoring streams with national economic accounts; (ii) enhance systemic resilience through early identification of nonlinear adaptation pathways; (iii) strengthen procedural justice by enabling transparent verification of externalities, particularly for under-represented regions; and (iv) accelerate methodological innovation through open, modular, and interoperable data infrastructures. Through this dual transformation—dynamic analytics and collaborative governance—the extended water–energy nexus framework provides a pathway for more adaptive, equitable, and institutionally grounded resource-management strategies at regional and global scales.

Research and policy agenda: priorities for a dynamic and equitable nexus

The transition to a dynamic and equitable water–energy nexus requires a sequenced agenda that strengthens evidentiary foundations, expands analytical capability, and institutionalizes inclusive multi-level governance. We structure this agenda into two mutually reinforcing phases: (i) the Foundation phase, which establishes a flexible data spine and hybrid modeling capacity, and (ii) the Integration phase, which embeds data-driven governance into decision processes at multiple scales. The discussion concludes by clarifying why this sequencing—while adaptable across contexts—still provides essential orientation.

Foundation phase — establishing a flexible data spine and hybrid capability

Sustainable advancement requires establishing a common evidentiary foundation while allowing for context-specific implementation pathways. Statistical agencies, utilities and research networks can progressively release versioned water-energy coefficients [71] and governance metadata in FAIR formats [72], forming an empirical commons that simultaneously supports baseline quantification (Pillars 1–3) and advances interoperability requirements (Pillar 6). As data coverage improves, analysts can incrementally hybridise

MR-IO tables with dynamic engines [73], enabling models to capture non-linearities and feedbacks. Concurrent extensions to carbon, land, and waste boundaries further reveal trade-offs and prevent burden shifting across sectors. To ensure broad accessibility, modular toolkits—designed to operate on continuously updated open datasets—enable basin authorities and planning ministries to implement hybrid modeling frameworks without bespoke programming. At the same time, pilot funding mechanisms that position academic institutions in data-limited regions as core project leaders [74] embed local expertise and enhance institutional legitimacy. Although implementation timelines may vary across jurisdictions, the underlying logic remains stable: transparent data systems and standardized methodological approaches reinforce one another, creating the conditions for robust, equitable, and reproducible nexus governance.

Integration phase — embedding multi-level, data-driven governance

Once real-time analytics are operational—exemplified by the Changi Water Reclamation Plant digital twin, which processes >1,200 live tags to predict hourly water–energy demand [75]— the priority shifts from diagnosis to coordinated action. Multi-level river-basin committees, supported by shared hydro-economic dashboards, can co-design bulk-water tariffs aligned with local scarcity and sectoral demand. In Brazil's Paraíba do Sul basin, the CEIVAP board's negotiated tariff schedule proved politically acceptable and fiscally self-sustaining, with all revenues earmarked for basin reinvestment [76].

At the international scale, a distributed monitoring architecture already exists through global virtual-water accounts, which allow countries to verify embedded blue, green, and grey water in bilateral trade [77]. Development-finance agencies can convert this transparency into a competitive advantage by requiring dynamic, data-backed nexus assessments within their disclosure rules, thereby mainstreaming open-data practices.

As governance experiments proliferate, they feed back into the data spine: tariff performance, drought-protocol audits, and basin-level learning cycles expand the metadata catalogue, while model–data comparisons identify gaps to address in subsequent releases. This interaction keeps the system genuinely adaptive.

Why sequencing still provides orientation

Although real-world contexts may compress, overlap, or partially reorder the steps in a nexus implementation process, maintaining a clear sequence remains essential for both conceptual coherence and institutional coordination. Sequencing provides an orienting structure: it clarifies dependencies, stabilizes expectations across organizations, and ensures that methodological advances remain grounded in credible empirical baselines.

The sequence begins with openly shared data, which enable the construction of credible hybrid models [73, 78]. These hybrid models, by combining static inventories with dynamic engines, surface the cross-scale trade-offs that require and legitimize inclusive, multi-level, collaborative governance [19]. Once such governance arrangements are in place, they strengthen and expand the shared data commons through continuous monitoring, auditing, and accountability mechanisms that feed new information back into the empirical spine. If any component of this chain is bypassed, the system falters: omitting

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shared data leads to models built on unverified inputs, while omitting collaborative governance results in policies that lack actionable intelligence or stakeholder legitimacy. When pursued flexibly—allowing iteration, recalibration, and local adaptation—the agenda moves the nexus community beyond descriptive footprinting toward adaptive stewardship. It embeds equity, resilience, and continuous methodological refinement as core features of water–energy decision-making and environmentally sustainable development, rather than aspirational add-ons.

CONCLUSIONS

This study reconceptualises the water–energy nexus (WEN) as a multi-level socio-technical system whose stewardship depends on integrating high-resolution data, hybrid analytical tools and inclusive, collaborative governance. While the literature excels at quantifying operational flows, models that privilege physical metrics alone overlook feedbacks linked to carbon, land-use change and stakeholder agency. Broadening the analytical lens to encompass these environmental and social variables reveals the trade-offs that arise when one resource is optimized at the expense of another. Although technical infrastructure remains essential, our analysis shows that long-term policy relevance ultimately rests on governance quality and strategic planning. Evidence-based interventions must therefore be co-produced by government, industry, academia, and civil society if model insights are to translate into practice.

To guide this expansion, we propose an extended WEN definition articulated through six interlocking pillars—spanning baseline flow accounting, dynamic feedback modeling, cross-resource coupling, FAIR data architectures and genuinely polycentric governance. These pillars are not a prescriptive template but a flexible scaffold that can be recalibrated to local data availability, institutional maturity and the depth of multi-actor collaboration. This adaptability ensures relevance from data-rich metropolitan basins to data-scarce rural catchments while preserving comparability across studies.

Our empirical mapping across nine analytical dimensions pinpoints where this scaffold can deliver the greatest marginal gains. Static EE-IO models still dominate 52 % of methodological choices, yet dynamic hybrids capture rebound effects that would otherwise double-count savings. Our evidence supports methodological concentration in this corpus; we do not infer structural barriers or lock-in from frequency or network patterns alone. "Production and Energy Supply" co-occurs most with "Water Consumption and Flows," but is rarely paired with "Embodied Emissions," confirming carbon blind spots our second pillar targets. A 41 % reliance on Chinese provincial data and a 4 : 1 dominance of national over subnational governance references validate the need for FAIR data protocols and polycentric architectures (Pillars 4 and 5). Finally, studies adopting an expanded nexus frame are three times more likely to employ open data standards, underscoring how transparent information systems catalyse conceptual breadth and policy uptake. Taken together, these findings convert the six pillars from a purely normative aspiration into an empirically grounded roadmap for dynamic, equitable stewardship.

Delivering on this vision demands methodological pluralism. Merging quantitative footprints with dynamic simulations and participatory inquiry captures non-linear

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feedbacks and equity implications, enabling strategies that reconcile economic growth, social justice and environmental stewardship under climate stress. By advancing an expandable conceptual scaffold grounded in robust diagnostics, this study aims to catalyse cross-regional collaboration, improve data transparency in under-represented regions and anchor water–energy planning in coordinated, stakeholder-driven management. We hope these insights will foster new technical collaborations, focus attention on data-scarce regions, and ultimately drive progress toward integrated water-energy policies. Such policies should be built on an empirical basis, inclusive governance frameworks, and the active engagement of engineers, technologists, and all relevant stakeholders to achieve environmentally sound and technically viable development outcomes.

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AUTHORS' CONTRIBUTIONS

Author 1, E.P.D.: Conceptualization; Methodology; Investigation; Data curation; Formal analysis; Visualization; Writing – original draft. Author 2, D.R.P.S.: Conceptualization; Investigation; Validation; Writing – review & editing.

DECLARATION OF GENERATIVE AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

For this work, the authors used ChatGPT (OpenAI) in order to support language editing and improve clarity and readability of selected passages. Afterwards, the authors reviewed and edited the content as deemed necessary and take full responsibility for the final version and the published content.

DATA AVAILABILITY STATEMENT

Data are available in an open-access repository: Zenodo. Persistent identifier (DOI): https://doi.org/10.5281/zenodo.15832592.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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