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Reflexive Resource Provision: An epistemic diagnostic perspective for assessing resource-provision pathways

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Research Article

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Abstract

Industrial Ecology (IE) provides diverse approaches for analysing resource use, environmental pressures, and socio-metabolic transformations, yet their findings are often related to broader claims about the viability of resource-provision pathways. This paper proposes Reflexive Resource Provision (RRP) as an emerging research field that takes primary resource provision as its object of inquiry and treats it as a socio-ecological decision space in which levels and configurations of provision are continuously reconsidered in relation to geophysical conditions, ecological limits, and societal needs. We develop epistemic reflexivity as a foundational orientation of RRP and examine how heterogeneous forms of IE evidence can and cannot support broader claims about resource-provision viability. To establish an initial epistemic foundation, we conduct a comparative cross-case synthesis of six studies from different resource-provision contexts, methods, spatial scales, and types of evidence. The analysis identifies recurring tensions concerning representation, scale, system and causal scope, temporality, evidence adequacy, and evidential reach. These tensions are synthesised into the RRP Diagnostic Prism, a provisional analytical architecture for examining the relationship between representation, evidence, and claim. The paper establishes this epistemic foundation as a first analytical entry point into RRP and outlines a broader research agenda for developing the field.

1. Introduction

Industrial Ecology (IE) has developed a broad and increasingly differentiated repertoire for studying the material and environmental foundations of human societies. Its analytical approaches range from life cycle assessment (LCA), material and substance flow analysis (MFA), environmental input–output analysis, and footprint methods to dynamic modelling of material stocks and flows, prospective scenario analysis, and more integrative approaches linking resource use to infrastructures, provisioning systems, services, and human needs (Streeck et al. 2023; Krausmann et al. 2017; Wiedenhofer et al. 2024; Graedel 2019; Baars et al. 2022). Approaches based on resource budgets and absolute environmental sustainability further relate resource use to ecological limits, while provisioning-system and stock–flow–service perspectives connect material infrastructures and flows to the services and needs they support (Plank et al. 2021; Desing et al. 2020; Fanning et al. 2020). Rather than representing different versions of the same analysis, these approaches provide complementary forms of knowledge about complex socio-metabolic systems.

This analytical breadth is particularly important for understanding the future of primary resource provision. Despite substantial efforts towards resource efficiency, recycling, substitution, and circularity, primary extraction remains a major component of the global material economy. At the same time, the configuration of resource provision is changing rapidly. Energy-system transformation, electrification, digitalisation, new production technologies, changing patterns of consumption, resource-efficiency strategies, geopolitical restructuring of supply chains, and increasing attention to recycling and secondary materials are altering both the types and quantities of resources required and the geographical and technological pathways through which they are provided. Global resource extraction

has increased substantially over recent decades and, under current trajectories, is projected to continue growing, while the energy transition is generating rapidly increasing demand for several critical minerals and exposing new vulnerabilities related to supply concentration, trade restrictions, and geographically concentrated environmental pressures (United Nations Environment Programme 2024; International Energy Agency 2026). Consequently, questions about resource provision are no longer adequately described as questions of whether sufficient material can be supplied. They increasingly concern which configurations of resource provision can remain viable under changing biophysical, ecological, technological, social, and geopolitical conditions.

Resource provision therefore constitutes a complex and dynamic socio-ecological transformation problem in its own right. It is not simply a response to externally determined demand. The level and configuration of resource provision are actively shaped through choices concerning extraction, processing, infrastructure, trade, substitution, recycling, product design, service provision, and demand reduction, while simultaneously being constrained by geophysical conditions, ecological limits, technological capabilities, institutions, economic structures, and societal needs. What constitutes viable resource provision is consequently neither fixed nor universally optimal. It depends on the conditions under which provision occurs and must be reconsidered as framework conditions change. This shifts the analytical question from how a given resource demand can be supplied towards a broader question: how should resource provision itself be understood, evaluated, and continuously reconsidered as a socio-ecological transformation?

We propose Reflexive Resource Provision (RRP) as an emerging research field addressing this question. Here, resource provision refers to the provision of primary materials, understood as abiotic and biotic materials extracted from nature and entering the technosphere (Schmidt-Bleek 1993; Schmidt-Bleek and Bierter 1998). RRP understands resource provision not simply as the satisfaction of material demand, but as a socio-ecological decision space in which the level and configuration of resource provision are actively determined in relation to geophysical conditions, ecological limits, and social needs. RRP aims at providing a way of thinking about resource provision in which the object of inquiry is not only the material pathway itself, but also the conditions under which different pathways can be considered viable and how these conditions may change. RRP can therefore draw together and extend existing IE approaches. LCA, material flow analysis, dynamic stock modelling, resource-budget approaches, provisioning-system analysis, and prospective modelling can all contribute to RRP while retaining their respective analytical strengths.

A central implication of this perspective is that reflexivity becomes a constitutive dimension of research on resource provision. The differentiated analytical repertoire of IE is precisely what makes the field capable of addressing complex resource-provision problems, but each analytical approach necessarily represents only particular properties, scales, temporal horizons, causal relationships, and forms of evidence. The epistemic challenge arises when heterogeneous forms of evidence are related to broader conclusions about the viability of resource-provision pathways. A quantified result may be highly robust within its defined analytical scope while remaining insufficient to support a conclusion formulated at a

different spatial, temporal, causal, or normative scale. Similarly, different evidence streams may each be valid while describing dimensions of a resource-provision system that cannot simply be reduced to or compensated against one another. Reflexivity in RRP therefore concerns making explicit what a particular form of evidence represents, under which conditions it is informative, how it can be related to other forms of knowledge, and which conclusions are warranted by their combination. This becomes particularly consequential when findings generated within bounded analytical configurations are taken up to inform broader sustainability, policy, or transition claims. Existing IE research already addresses many elements of this epistemic problem, including uncertainty, system boundaries, indicator construction, spatial differentiation, model structure, and interpretation (Lo Piano and Benini 2022a, 2022b; Bromwich et al. 2025). The epistemic dimension is therefore not absent from IE; rather, it is dispersed across methodological traditions. What has received less explicit articulation is its role as a constitutive dimension of a broader research field concerned with the viability of resource provision.

The novelty of this contribution lies in proposing RRP as a distinct research field for sustainable resource management and in identifying epistemic reflexivity as its epistemic orientation. Therefore, we establish an initial epistemic entry point into the proposed field by revisiting six studies that investigate different resource-provision contexts using empirical, modelling, and methodological approaches. These studies are treated as an intentionally bounded analytical corpus from which recurring epistemic tensions can be identified across otherwise heterogeneous forms of research. The purpose is not to test a predefined set of criteria against a representative sample, but to use the diversity of the cases to identify recurring dimensions along which scientific representations of resource provision differ in scope and inferential reach. This synthesis provides the basis for an initial RRP Diagnostic Prism comprising six dimensions: Representation, Scale, System and causal scope, Temporality, Evidence adequacy, and Evidential reach. The Prism constitutes a first analytical entry point for engaging with the epistemic dimension of RRP to make visible conditions under which different forms of resource-provision evidence can be related, where their scopes diverge, and where apparently compatible findings may remain non-compensable.

Against this background, this paper has three objectives. First, it establishes the conceptual foundation of RRP by defining resource provision as a socio-ecological decision space and positioning RRP as an emerging research field within IE. Second, it develops epistemic reflexivity as one foundational dimension of this field and derives an initial Diagnostic Prism from the comparative analysis of six existing studies. Third, it uses this epistemic foundation to outline a broader research agenda for RRP, in which the analysis of resource provision can progressively connect biophysical conditions, ecological limits, technologies, infrastructures, social needs, institutions, and forms of knowledge. The aim is therefore not to close the question of how resource provision should be organised, but to establish a scientific field in which this question can be investigated as a continuously revisable problem of socio-ecological transformation.

2. Materials & Methods

2.1 Conceptual and literature-based approach to defining the analytical object

Throughout this study, primary materials refer to abiotic and biotic materials extracted from nature and entering the technosphere. This definition includes, for example, metallic and non-metallic minerals, fossil resources, and biomass (Schmidt-Bleek 1993; Schmidt-Bleek and Bierter 1998). Our conceptual starting point also builds on several established strands of research. The analysis of material flows and resource use has developed from accounting for material inputs and outputs towards increasingly integrated perspectives on stocks, flows, and the services they support (Graedel 2011, 2019; Haberl et al. 2019). Work in resource economics and material-flow research has long examined the dynamic relationship between resource demand, extraction, production capacity, technological development, prices, and material availability (Lusty and Gunn 2014; Ryter et al. 2024; Vidal et al. 2022). Provisioning-system research extends the analysis by conceptualising the transformation of resources into services in relation to technologies, infrastructures, institutions, practices, social needs, and biophysical constraints (Fanning et al. 2020; Plank et al. 2021). This perspective has increasingly been extended to the political-economic and historical constitution of provisioning systems, including the roles of actors, institutions, capital, material stocks and flows, and processes of lock-in and transformation (Schaffartzik et al. 2021). Research on ecological resource availability and extraction boundaries, in turn, explicitly relates resource provision to environmental constraints and ecological budgets (Desing et al. 2020; Thomassen et al. 2024). Recent global resource assessments likewise frame resource use and provision as central elements of sustainability transformations and emphasize the need to align resource use with environmental limits and societal needs (United Nations Environment Programme 2024).

These approaches provide the conceptual basis for examining primary resource provision as a conditional, dynamic, and socio-ecologically embedded phenomenon. RRP is developed through the subsequent conceptual synthesis of these strands.

2.2 Literature-based epistemological analysis

IE provides a particularly diverse methodological repertoire for investigating resource and environmental systems. Life cycle assessment, material flow analysis, environmentally extended input–output analysis, footprint methods, stock–flow analysis, resource-budget approaches, prospective modelling, and provisioning-system approaches make different properties and relationships of socio-metabolic systems visible. This methodological diversity is a strength because no single analytical representation can capture all relevant properties of complex resource-provision systems. At the same time, each representation is necessarily selective. A life-cycle model represents a defined product or service system; a material-flow analysis emphasises stocks and flows; a spatially explicit footprint represents environmental pressures at a specified geographical resolution; a resource-budget approach relates resource use to a defined ecological boundary; and a provisioning-system analysis places resource use within technological, institutional, and social relations. These representations are therefore not

interchangeable descriptions of a single fully observable object. Rather, they constitute different ways of constructing and investigating an object of inquiry.

Our epistemological foundation is consequently reflexivity, understood here as the systematic examination of the relationship between a scientific representation, the conditions under which it is informative, the conclusions that can legitimately be drawn from it, and the consequences for resource provision pathways. This perspective builds on broader work in the philosophy and sociology of science that emphasises the situated, selective, and theory- and practice-dependent character of scientific knowledge, as well as on research in environmental epistemology concerning the construction and interpretation of environmental knowledge. Within IE and sustainability assessment, these concerns have been addressed more specifically through research on system boundaries, uncertainty, framing, model and data quality, value choices, spatial and temporal differentiation, and interpretation (Cederlöf and Hornborg 2021; Clavreul et al. 2013; Lo Piano and Benini 2022b; Bromwich et al. 2025). Analytical choices are therefore treated as conditions that influence what can become visible and what can subsequently be inferred.

This does not imply that bounded representations are deficient. On the contrary, analytical selectivity is a necessary condition of tractability and often of scientific rigor. The epistemic problem arises when evidence generated for a bounded analytical question is used to support a broader claim than that evidence can warrant. Related concerns arise when environmental results are interpreted against absolute sustainability thresholds. Research on absolute environmental sustainability assessment has shown that such comparisons depend on choices concerning allocation, spatial differentiation, temporal compatibility, and other methodological assumptions (Bjørn et al. 2020; Guinée et al. 2022). These contributions provide an epistemological basis for examining not only whether evidence is sufficiently robust, but also what kind of claim that evidence can support.

In the subsequent cross-case analysis, this epistemological perspective was operationalised through four guiding questions concerning representation, conditions of validity, the relationship between heterogeneous evidence, and evidential reach. The detailed analytical criteria and associated literature base are provided in the Supplementary Methods.

2.3 Comparative cross-case synthesis of six existing studies

The analysis was conducted as a comparative cross-case synthesis of six studies from the author's own work covering different sectors, analytical scales, spatial contexts, and methodological approaches (Table 1). The cases were selected from the authors' own published work because detailed knowledge of the underlying analytical choices, assumptions, data limitations, and interpretive decisions enabled an in-depth examination of their epistemic structures. Their heterogeneity was intentional: each case provides a contrasting setting in which the relationship between bounded evidence and broader sustainability or resource-provision claims can be examined.

The cases were not selected to constitute a representative sample of IE research, nor were they treated as independent observations for statistical inference. The analysis focused on the epistemic structure of the published studies. For each study, the analysis examined how evidence was represented, under which spatial, temporal, systemic, causal, and evidential conditions it was informative, and what scope of conclusions it could support. The comparative synthesis then identified recurring epistemic tensions across the cases. Detailed case descriptions, analytical criteria, and the complete cross-case matrix are provided in the Supplementary Methods.

Table 1

Characteristics and analytical basis of the six empirical case studies. The cases represent different resource-provision contexts and sectors and employ diverse IE methodologies, data sources, analytical approaches, and spatial scales. The table summarises the empirical and methodological basis of the comparative cross-case analysis.

Case study	Technology / sector	Primary IE methodology & main data basis	Analytical & spatial scale
Case 1: CSP Morocco	Concentrated Solar Power (Noor I plant, Ouarzazate)	Process-based LCA, regionalised with operational and supply-chain data (Schomberg et al. 2022)	Micro-level / process coordinates; spatially explicit supply chains
Case 2: Lithium brine	Continental salt flats (salars) in the Lithium Triangle	Spatially explicit Water Scarcity Footprint and hydrogeological dynamics analysis (Schomberg and Bringezu 2023)	Regional level / catchment and basin
Case 3: Cobalt mining	Active cobalt mining and arsenic leakage (Bou Azzer mine)	Water Quality Footprint, field measurements and hydrological discharge data (Schomberg et al. 2025b)	Local level / catchment frontier
Case 4: German bioeconomy	Transnational agricultural biomass trade sectors	Macroeconomic multi-regional input–output analysis (EXIOBASE) and global nutrient models (Schomberg et al. 2023)	Macro level / national economy and global trade
Case 5: Modular smartphone	Consumer communication electronics (SHIFT6m)	High-resolution hotspot LCA, real-world repair data and consumer behaviour surveys (Schomberg et al. 2025a)	Micro-level / product architecture
Case 6: Lithium & cobalt supply chains	Critical mineral supply for net-zero transitions	Spatially explicit LCA with mine-level GIS-based inventories, ecoinvent, and IEA Net-Zero scenarios (Schomberg et al., 2026, preprint)	Global supply chains / mine clusters and country-level production structures; 2024–2050

3. Results

3.1 RRP as an emerging research field

The conceptual synthesis develops RRP as an emerging research field within Industrial Ecology that takes primary resource provision itself as a socio-ecological field of transformation. Rather than treating resource provision primarily as a supply response to demands generated elsewhere, RRP conceptualises provision as a field in which the conditions, configurations, and consequences of resource provision are themselves subject to analysis. RRP is characterised by three conceptual features:

1. **Primary resource provision as a transformation field in its own right.** Resource provision cannot be understood merely as a supply sector responding to demands generated elsewhere. Rather, the provision of resources is itself shaped by tensions between geophysical conditions, ecological limits, and societal needs, which require these conditions and their interactions to be considered as part of the provision decision space (Fanning et al. 2020; Plank et al. 2021; Schaffartzik et al. 2021). Resource provision therefore needs to actively shape the pathways through which societal needs are met.
2. **Resource provision as a socio-ecological decision space.** A specific level and configuration of primary resource provision may include type of material, physical quantities, origin, geological conditions, environmental impacts and social conflicts associated with extraction and processing, temporal dynamics, infrastructure and technologies, trade routes, relationships with demand structures, recycling and substitutability, circular economy, product design, and more. Its viability is therefore not treated as an intrinsic property of a technology or resource pathway, but rather as dependent on the constellation of relevant biophysical and socio-ecological conditions. Resource-budget and extraction-boundary approaches establish that primary resource availability is environmentally conditional (Desing et al. 2020; Thomassen et al. 2024), while provisioning-system research shows how resource use, technologies, institutions, practices, and societal needs co-evolve (Fanning et al. 2020; Plank et al. 2021; Schaffartzik et al. 2021). RRP consequently conceptualises resource provision as a socio-ecological decision space in which different levels and configurations of provision are evaluated and continuously reconfigured as conditions change.
3. **Non-provision as a legitimate outcome.** This perspective also changes the range of outcomes that a resource-provision assessment may legitimately consider. If resource provision is treated as a socio-ecological decision space, an assessment need not result in the identification of an acceptable supply pathway. It may instead indicate the need for modified or reduced provision, relocation, substitution, changes in technology or service provision, or the cessation of primary resource extraction. RRP makes the possibility of non-provision itself explicit within the object of inquiry. Non-provision is therefore considered a legitimate possible outcome rather than a residual societal response after a supply pathway has already been assumed.

Taken together, these three features shift the central question from whether a resource can be supplied under specified conditions toward the broader question of whether, where, when, and under which conditions a particular level and configuration of primary resource provision remains viable.

3.2 Foundational principles and epistemic orientation of RRP

The analysis identifies a set of foundational principles and an epistemic orientation that characterise RRP as a research field. Existing work in environmental epistemology, IE, and sustainability assessment demonstrates that scientific representations are necessarily selective and that their informativeness depends on assumptions concerning framing, system boundaries, scale, temporal conditions, evidence, and interpretation (Cederlöf and Hornborg 2021; Clavreul et al. 2013; Lo Piano and Benini 2022a, 2022b; Bromwich et al. 2025). RRP brings these established epistemic concerns together around the specific inferential problem of resource-provision viability.

The analysis identifies epistemic reflexivity as a central orientation of RRP. The relevant epistemic question is not whether an assessment is comprehensive, but whether the scope of the evidence corresponds to the scope of the claim. A scientifically valid representation may provide robust evidence within a defined analytical domain while remaining insufficient to support a broader claim about the viability of a resource-provision configuration. This distinction is consistent with established work showing that absolute sustainability claims remain conditional on allocation, spatial and temporal compatibility, and other methodological premises (Bjørn et al. 2020; Guinée et al. 2022).

The analysis further shows that epistemic reflexivity concerns not only uncertainty in numerical results but also the conditions under which evidence becomes informative and the limits of its interpretation. Across the analytical corpus, these conditions concerned recurring issues of representation, spatial and temporal scale, system and causal scope, evidence adequacy, and evidential reach. These dimensions determine which properties of a resource-provision system become visible, under which conditions they can be considered informative, and how far the resulting evidence can legitimately be interpreted. The literature reviewed supports these dimensions through established work on representation, spatial differentiation, system boundaries, temporality, uncertainty, and inference.

A further foundational principle is plural validity and non-compensability. Different evidence streams may each provide valid information about different properties of a resource-provision system while remaining non-equivalent for a broader viability claim. Their combination therefore does not necessarily produce a more valid aggregate conclusion. Where representations concern different properties, scales, causal relations, or normative reference conditions, their non-equivalence may itself constitute an epistemically relevant result.

RRP is further grounded in a safe-and-just understanding of sustainability. This understanding relates the satisfaction of societal needs to the maintenance of biophysical conditions within ecological limits, rather than treating environmental protection and societal well-being as separate objectives. The safe-and-just space framework developed by O'Neill et al. (2018) explicitly links human needs with planetary boundaries, while provisioning-system research has applied this perspective to the ways in which resources are transformed into services and needs satisfaction (O'Neill et al. 2018; Fanning et al. 2020).

For RRP, this implies that the viability of a resource-provision configuration cannot be determined solely from its biophysical or environmental performance. It must also be considered in relation to the societal purposes that provision is intended to serve. Sustainability therefore constitutes a boundary condition of the RRP decision space in both directions: resource provision must remain within relevant biophysical limits while contributing to the satisfaction of legitimate societal needs.

Taken together, these principles and the reflexive epistemic orientation define how resource-provision configurations are approached within RRP. Epistemic reflexivity is therefore not merely a quality-control step applied after an assessment has been conducted. It provides the analytical logic through which the foundational principles of RRP can be examined in practice, by making explicit the relationship between representation, evidence, conditions of validity, and the scope of conclusions that can legitimately be drawn.

3.3 Epistemic tensions revealed by the cross-case analysis

The comparative analysis of the six studies revealed recurring epistemic tensions between bounded representations, the conditions under which their evidence is informative, and the broader sustainability or resource-provision claims to which their findings may be related. Although the cases differ substantially in topic, method, scale, and empirical basis, each illustrates how a scientifically valid assessment can support a specific conclusion while remaining insufficient to establish a broader claim about resource-provision viability. The heterogeneity of the cases therefore reveals a common epistemic structure rather than a common methodological limitation.

The cases reveal distinct but related tensions across the analytical dimensions. In the CSP case, the representation of environmental performance becomes conditional on spatial resolution when distributed supply-chain activities cannot be adequately regionalised. The lithium-brine case shows how the definition of a resource category determines which physical and hydrological processes become visible within the assessment. The cobalt case demonstrates that highly precise local evidence may not translate into representative information at aggregated scales. The German bioeconomy case shows how changes in temporal and spatial aggregation can alter the interpretation of environmental pressures. The modular-smartphone case highlights the gap between technical environmental potential and the broader socio-technical conditions required for that potential to materialise. Finally, the prospective lithium-and-cobalt case demonstrates that conclusions about future environmental pressures remain conditional on the supply structures represented in the scenario. Together, the cases therefore expose tensions between representation and scale, representation and system and causal scope, scale and evidence adequacy, temporality and representation, system and causal scope and evidential reach, and temporality and evidential reach (Fig. 2). The comprehensive analysis can be found in the Supplementary Results.

Across these cases, the cross-case synthesis suggests a recurring inferential sequence: bounded representation → bounded evidence → inferential constraint → reflexive conclusion. Different evidence streams may each be valid within their respective domains while remaining non-equivalent for a broader

resource-provision claim. The relevant result is consequently not always a single integrated assessment, but may instead be the identification of conditions, unresolved relations, or non-compensable dimensions that constrain the conclusion. These recurring tensions provide the empirical basis for the six-dimensional RRP Diagnostic Prism developed in the following section.

3.4 The RRP Diagnostic Prism

The RRP Diagnostic Prism was developed inductively from the comparative cross-case synthesis. It provides an analytical architecture for making recurring epistemic tensions in resource-provision research visible and systematically comparable. The literature reviewed in Section 2.2 informed the epistemological rationale of the analysis but did not determine the final architecture a priori. The resulting six dimensions describe complementary conditions that shape what can be represented, under which conditions evidence becomes informative, and how far resulting findings can legitimately be interpreted.

Representation concerns how a resource-provision phenomenon is conceptually and analytically represented, including the categories, indicators, proxies, reference conditions, and value-laden choices through which aspects of the system become visible. Scale concerns the spatial resolution and representativeness of the analysis and its correspondence with the spatial distribution of processes, impacts, and relevant thresholds. System and causal scope concerns which processes, relationships, indirect effects, and causal mechanisms are included or excluded, and which counterfactuals are represented. Temporality concerns the temporal conditions of validity, including time horizons, dynamics, path dependencies, and changes in system relationships over time. Evidence adequacy concerns whether the data, models, and empirical basis are sufficiently appropriate, representative, and robust for the analytical question, including relevant forms of uncertainty. Evidential reach concerns the scope of the conclusions that the available evidence can legitimately support, including the conditions and limitations of generalization and the avoidance of inferential overreach.

These dimensions are analytically distinct but interdependent. Choices concerning representation, scale, system and causal scope, and temporality determine which properties of a resource-provision system become visible and under which conditions they can be considered informative. Evidence adequacy concerns the robustness and fitness of that evidence for the analytical purpose, while evidential reach concerns the relationship between the resulting evidence and the claim made from it. The Prism therefore provides a structured diagnostic for examining the relationship between representation, evidence, and claim and for identifying where epistemic tensions constrain the interpretation of resource-provision viability (Fig. 3). By making these relationships explicit, the Prism provides a common diagnostic architecture through which IE can reflexively assess how its own findings are interpreted and extended beyond the analytical context in which they were generated. Detailed criteria and the derivation of each dimension are provided in the Supplementary Methods.

4. Discussion

4.1 Limitations and scope of the present study

The present study provides a conceptual and analytical foundation for Reflexive Resource Provision (RRP), but several limitations define the scope of its contribution. First, the comparative analysis is based on six previously published studies from the authors' own research. The cases were deliberately selected for their methodological and contextual heterogeneity and for the detailed knowledge available about their analytical choices, assumptions, data, and interpretation. They do not constitute a representative sample of IE research and cannot establish the prevalence of the identified epistemic tensions across the field.

Second, the RRP Diagnostic Prism is derived from this bounded analytical corpus and should therefore be understood as a provisional diagnostic architecture, rather than as a complete or validated epistemic taxonomy. The six dimensions identified in the present analysis are not assumed to exhaust the conditions under which resource-provision claims may be warranted. Other cases, particularly those involving stronger social, political, distributive, or justice-related dimensions, may reveal additional or differently structured epistemic concerns.

Third, the analysis does not propose a procedure for determining whether a particular resource-provision pathway is ultimately desirable. RRP concerns the relationship between evidence and inference; it does not replace normative deliberation or decision-making. Whether a provision pathway should be pursued may depend on values, political priorities, distributional considerations, and societal preferences that cannot be resolved through epistemic diagnosis alone.

These limitations are therefore not only constraints on the present study but also delimit the claim being made. The contribution is to formulate and operationalise a perspective on how claims about resource-provision viability can be examined.

4.2 What RRP can – and cannot – do

The central contribution of RRP is a shift in the object of epistemic scrutiny: from the question of whether an assessment is sufficiently comprehensive to the question of whether the evidence is commensurate with the claim being made. A larger number of indicators, more detailed models, or greater spatial and temporal resolution may improve an assessment without necessarily establishing a stronger viability claim. Evidence integration and claim integration are therefore not equivalent. Different evidence streams may be assembled while retaining differences in meaning, scale, causal structure, uncertainty, and normative reference conditions.

RRP does not oppose methodological integration. Rather, it makes the inferential step accompanying integration explicit. A global supply-chain model and a local contamination measurement can both provide valid evidence while addressing different properties of the same resource-provision system. Similarly, a technical assessment and evidence on user behaviour may each be necessary to understand a transformation without being reducible to a single result. Plural validity and non-compensability are

therefore treated as principles of RRP: evidence does not have to be mutually reducible to be jointly informative. In some cases, retaining distinct findings is epistemically preferable to constructing an aggregate indicator that conceals their differences.

The six dimensions of the Diagnostic Prism provide a structured way of examining this relationship. They ask what is represented, at what scale, within which system and causal scope, for which temporal conditions, with what evidential adequacy, and with what evidential reach. They are not a completeness checklist. Requiring every assessment to address every dimension would reproduce the very logic that RRP seeks to avoid: the assumption that epistemic complexity can ultimately be resolved by adding sufficient categories, indicators, or data. The Prism is instead a structured prompt for examining the conditions and limits of inference.

This also clarifies what is novel about RRP. The individual epistemic concerns identified here – representation, scale, system boundaries, causality, temporality, uncertainty, and interpretation – are well established in IE and adjacent fields. Existing work already provides sophisticated treatments of several of these dimensions, including uncertainty appraisal, system-boundary reflexivity, and absolute sustainability assessment. RRP therefore does not claim to introduce previously unknown epistemic problems. Its contribution is to organise established concerns around the warrant relationship between bounded evidence and resource-provision claims, and to derive this architecture comparatively across heterogeneous resource-provision cases rather than from a single assessment methodology. The resulting architecture is intended to make not only the internal validity of individual assessments, but also the conditions under which their findings are transferred into broader resource-provision claims, an explicit object of scientific scrutiny.

Accordingly, RRP is best understood as an emerging research field and research agenda with epistemic reflexivity as one of its foundational orientations. It complements established IE approaches by addressing a question that arises when their results are related to broader claims about resource-provision viability: What does this finding actually warrant us to claim about resource provision?

4.3 Research agenda

The present study opens several directions for further research. First, the Diagnostic Prism should be applied to a broader and more heterogeneous corpus of resource-provision research to examine whether the proposed dimensions recur across contexts and whether additional dimensions or alternative structures emerge. Such work would provide an empirical basis for assessing the usefulness and transferability of the present architecture rather than seeking conventional validation of the six-case synthesis.

Second, RRP provides a basis for developing approaches to cross-method evidence synthesis that retain epistemic differences between LCA, MFA, spatial assessment, resource-budget approaches, provisioning-system analysis, hydrology, and socio-technical research. A particularly relevant question is

when evidence from different scales, indicators, and causal models can legitimately be combined and when plural validity should instead be retained.

Third, future research could strengthen the treatment of temporality and causality in resource-provision analysis. Resource-provision configurations change through interactions among technologies, infrastructure, markets, institutions, behaviour, and environmental conditions. Prospective modelling, transition research, and explicit causal analysis could therefore help distinguish evidence about current configurations from evidence about transformations and future configurations.

Finally, RRP could be extended from assessment analysis to the systematic study of resource-provision claims themselves. Future work could map claims made in scientific research, policy, corporate strategies, and technology assessments against the evidential scope supporting them. This would allow researchers to investigate where claims remain appropriately conditional, where additional evidence is required, and where apparently conflicting evidence reflects genuinely different representations rather than disagreement about the same empirical object.

Taken together, these directions position RRP as an emerging research field for examining how heterogeneous evidence can, and cannot, support claims about the viability of resource provision.

Declarations

Conflicts of Interest

The author declares no competing financial or personal interests that could have appeared to influence the work reported in this paper.

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Author Contribution

Author Contributions: Anna C. Schomberg: Conceptualization, Methodology, Investigation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing.

Data Availability

No new primary empirical datasets were generated during this study. The synthesis is based on previously published and publicly available studies and a qualitative comparative evaluation of their epistemic tensions.

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Figures

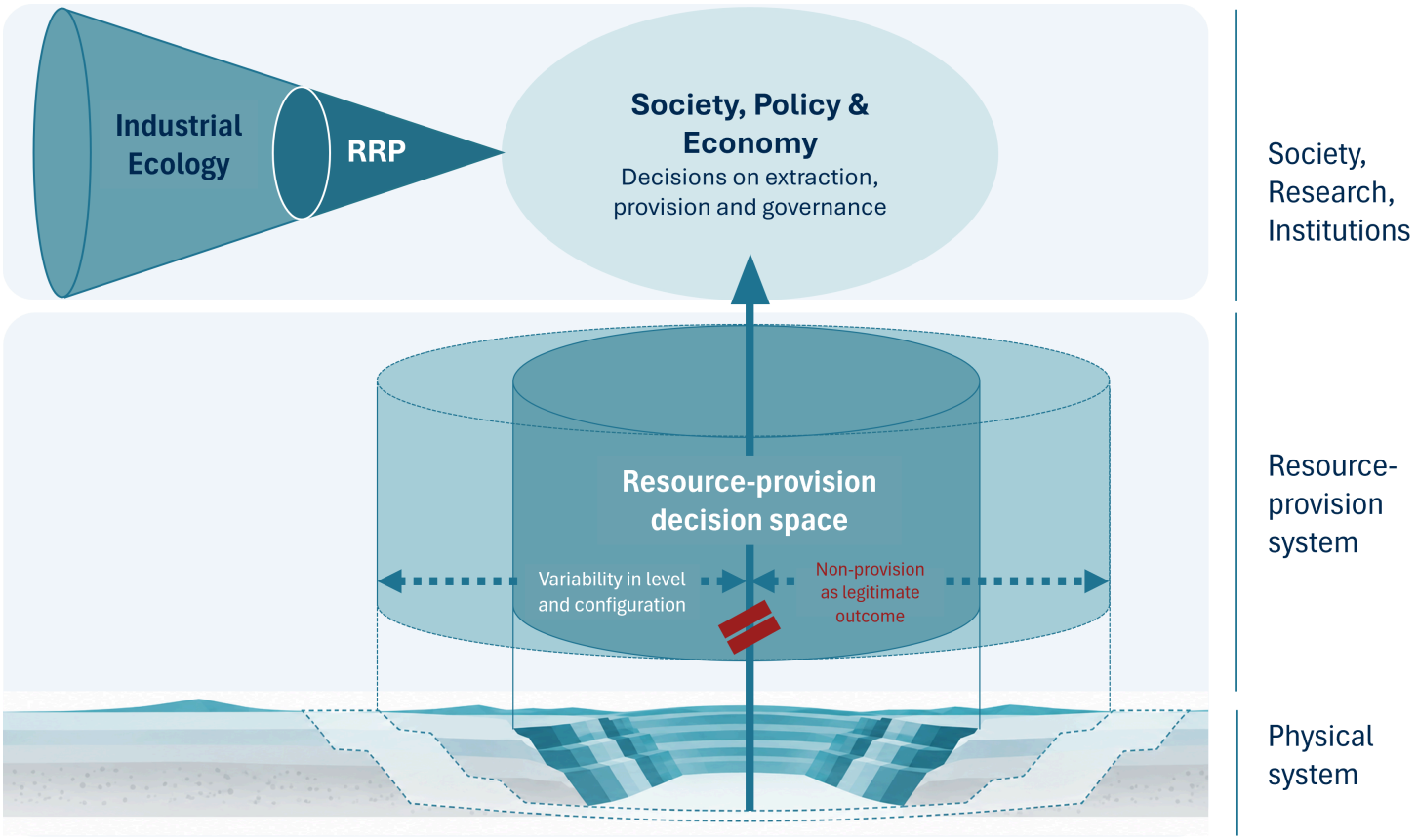


Figure 1

Conceptual positioning of Reflexive Resource Provision (RRP) as an emerging research field. RRP is situated at the interface of Industrial Ecology and society, policy, and economy, taking resource provision

as a socio-ecological decision space connecting societal needs and governance with the physical conditions of resource extraction. The decision space allows for variation in the level and configuration of provision, including non-provision as a legitimate outcome.

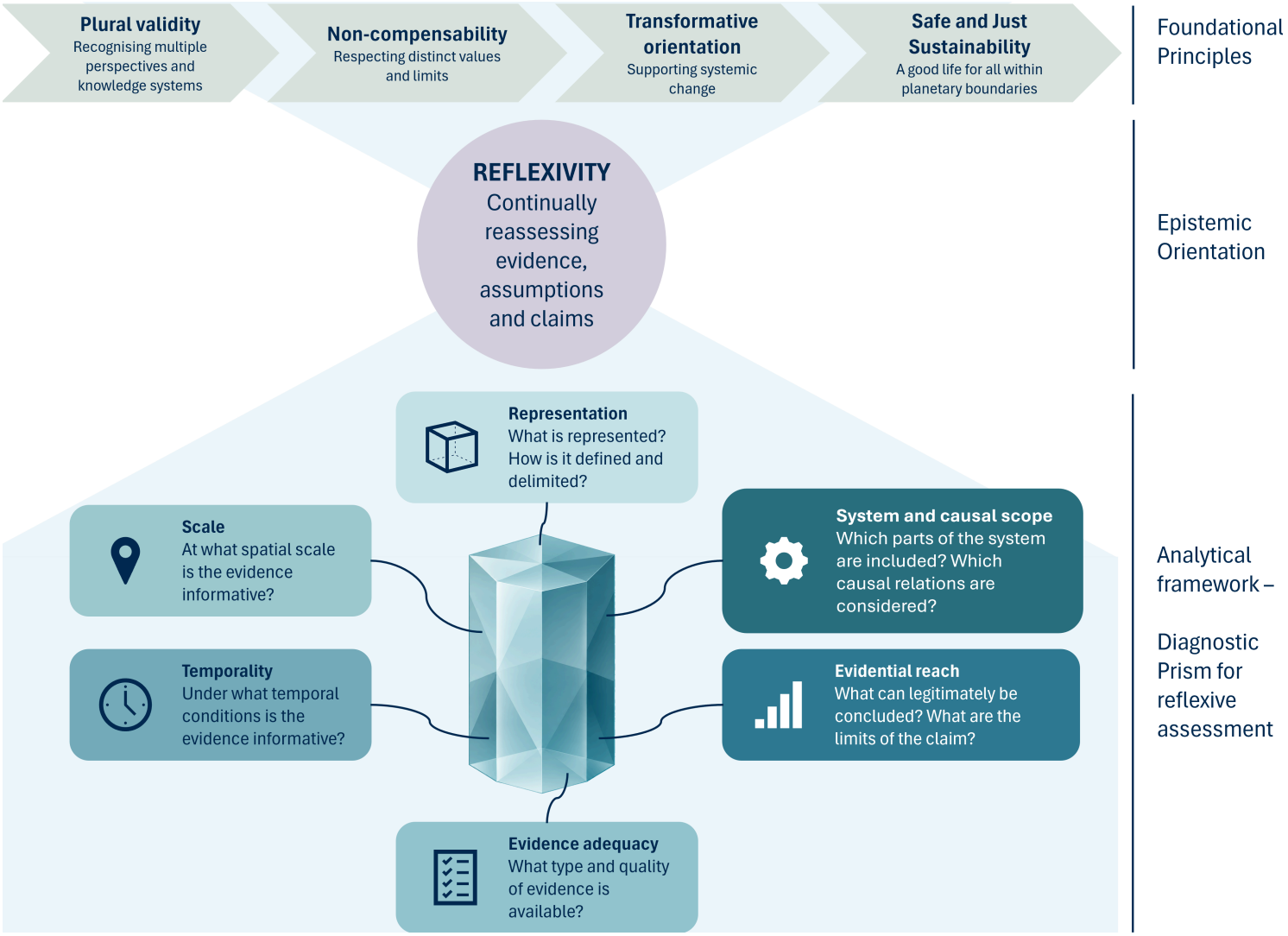


Figure 2

Empirical basis and epistemic tensions of the RRP analysis. The six empirical case studies span different resource-provision contexts, Industrial Ecology methodologies, spatial and analytical scales, and types of evidence. For each case, a representative visualization and selected quantitative results from the underlying study are shown together with the central epistemic tension identified through the comparative analysis. The cases illustrate how heterogeneous forms of scientific evidence can provide robust findings within defined analytical domains while differing in their implications for broader claims about resource-provision viability.

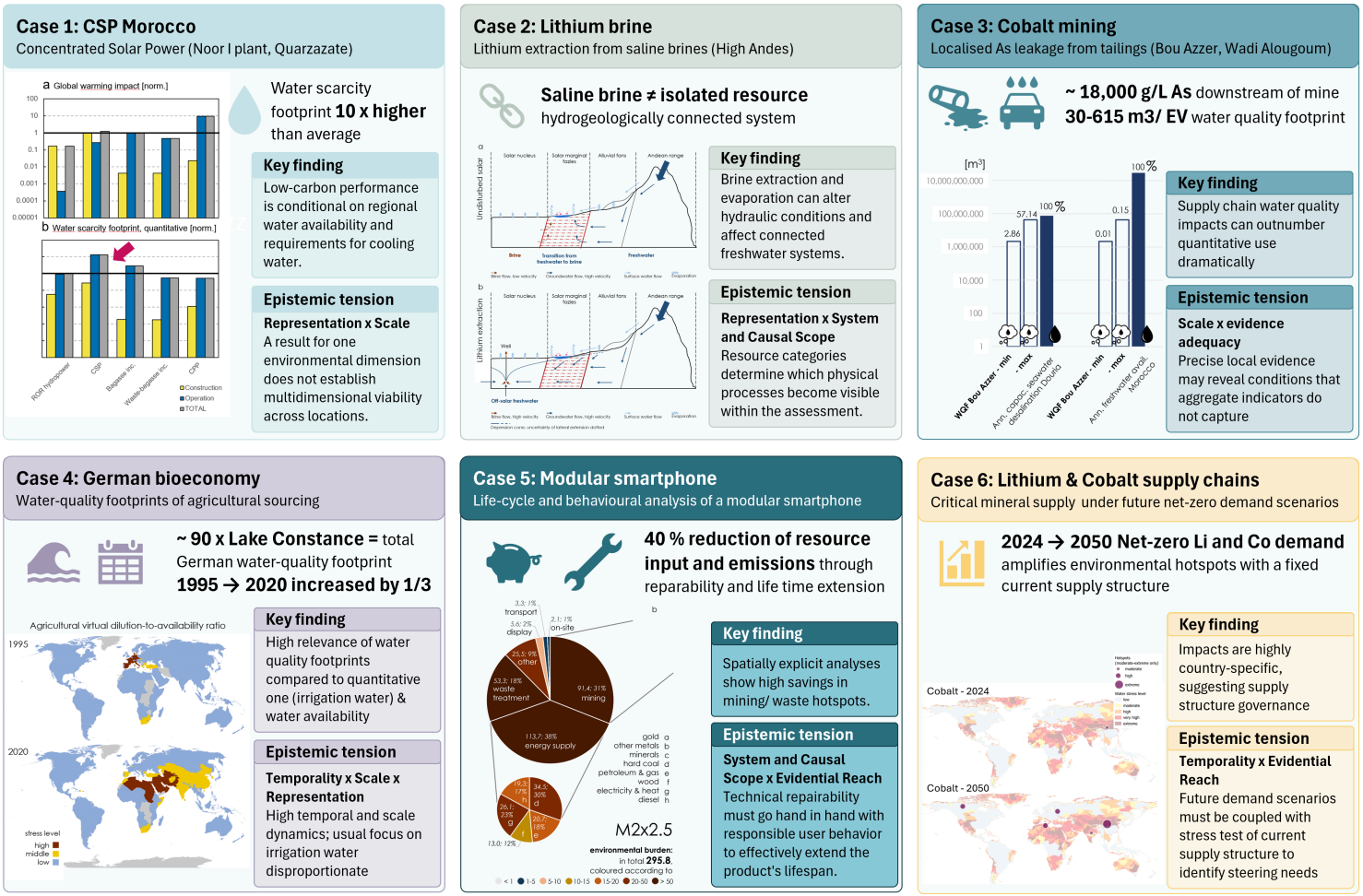


Figure 3

Internal conceptual architecture of Reflexive Resource Provision (RRP). RRP is grounded in foundational principles of plural validity, non-compensability, transformative orientation, and safe-and-just sustainability. Reflexivity provides the epistemic orientation through which representations, evidence, assumptions, and claims are continuously reassessed. The RRP Diagnostic Prism operationalises this orientation through six analytical dimensions: representation, scale, system and causal scope, temporality, evidence adequacy, and evidential reach.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryMaterial18092026.docx