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MOReCriT: Understanding Multi-Objective Optimization Results in Resource Criticality Analysis through Visual Analytics

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Abstract

Energy transition technologies depend on an expanding set of raw materials that are geographically concentrated and often sourced from politically or economically unstable regions, introducing substantial supply risks. To account for these uncertainties, multi-objective optimization models incorporate material-related criticality alongside system costs, enabling the exploration of trade-offs between economic performance and resource risk. Although this trade-off is expressed in two objective dimensions, each Pareto-optimal solution represents a high-dimensional configuration of technological and capacity decisions shaped by numerous criticality assumptions. Existing tools typically rely on isolated visualizations of objective values or tabular inspection of these complex results. Such static plots and fragmented material flow visualizations make cross-cutting reasoning across the trade-off frontier unwieldy and time-consuming. Thus, we present MOReCriT, a visual analytics tool for the interactive exploration of solution spaces derived from multi-objective optimization. The system enables experts in resource and energy modeling to interactively analyze Pareto fronts, trace solutions back to their underlying assumptions, and compare alternative technology pathways through coordinated, interlinked views. We evaluate MOReCriT with four domain experts. The results indicate that integrating established visual representations into coordinated, interlinked views substantially improves the interpretability of high-dimensional Pareto spaces. Compared to existing analysis workflows, our approach enables faster exploration and supports informed refinement of optimization parameters by making the impact of modeling assumptions explicit. This also revealed previously overlooked patterns in which certain technologies did not follow the expected proportional shift along the cost–criticality trade-off, obscured by the complexity of the result space.

CCS Concepts

• ***Human-centered computing*** → ***Visual analytics; Visualization application domains;*** *Information visualization; Empirical studies in visualization;*

1. Introduction

The transition from a fossil-based to a renewable energy system is material-intensive, shifting attention from fuel extraction risks to those associated with sourcing the raw materials required for energy infrastructure. Unlike fossil fuels, which are continuously consumed, renewable systems depend on substantial upfront material investments in technologies such as wind turbines, photovoltaic modules, and batteries. As a result, the transition not only increases the overall demand for mineral resources compared to fossil-based systems, but also expands the range of required materials, introducing additional complexity as a growing number of global supply chains become intertwined [Int25, G*22].

Current geopolitical tensions have brought the power of large suppliers of raw materials and renewable energy equipment, especially China, to the center of international discussions [Int26]. These developments have renewed attention to resource criticality, which seeks to capture the risk associated with supply disruptions and their potential economic and technological consequences across interconnected value chains. Criticality assessments typically combine indicators of geological availability, market concentration, governance quality in producing countries, and demand dynamics [S*20, STE24, Hoo26].

For energy system planning, such assessments are particularly relevant, as material shortages or price shocks can directly affect technology costs and deployment pathways, potentially undermining long-term decarbonization strategies [SN25, BADMP16]. Different approaches have emerged to assess the risks associated with individual technologies [U.S10, MTK*25, BADMP16] or with the system as a whole [TELGu23]. However, these tend to be add-on or ex-post exercises because energy models typically only optimize costs while implicitly assuming immediate and unrestricted availability of the requisite equipment [W*24, KBS*21]. Although this assumption simplifies optimization, it neglects how supply risks and geopolitical constraints may fundamentally reshape technology competitiveness.

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Recent advances have thus brought raw material security concerns directly into energy system modeling [LBNS*26]. By introducing material-related risk dimensions alongside system costs, these approaches generate Pareto fronts that express trade-offs between economic efficiency and resource security. This cost-criticality front exists in a two-dimensional objective space, where each point represents one Pareto-optimal trade-off between aggregated cost and criticality. Yet, each point corresponds to a high-dimensional solution in decision space, comprising detailed technology deployment levels, generation mixes, storage capacities, transmission expansions, and country-specific supply dependencies. Interpreting movement along the trade-off requires more than comparing objective values: experts must understand why particular technology portfolios emerge, how material dependencies shift across solutions, and which assumptions drive structural differences between neighboring configurations. Concretely, a planner might need to decide whether a marginal cost increase would meaningfully reduce dependence on a specific country's supply.

In practice, however, existing workflows rely largely on static Pareto scatterplots, spreadsheet-based tabular inspection, and fragmented visualizations of material flows—making such reasoning cumbersome and time-consuming (see Section 3). Visual Analytics (VA) offers a promising approach to address this gap by coupling interactive visualization with analytical support, enabling experts to navigate trade-offs while simultaneously examining the high-dimensional structures that produce them.

In this work, we present **MOReCriT**, the **M**ulti-**O**bjective **R**esource **Cri**ticality **T**ool, a visual analytics tool designed to support expert exploration of Pareto-optimal energy system solutions derived from a customized REMix [W*24] model. The tool integrates resource-criticality inputs, based on country- and year-specific assessments, with optimization outputs, enabling users to interactively explore cost-risk trade-offs and trace them back to underlying material and geopolitical dependencies. By making complex optimization results transparent and navigable, MOReCriT aims to support informed decision-making in resource-constrained energy system transformation. In particular, it enables experts to identify robust solution regions, understand the role of individual critical materials, and assess how geopolitical risks propagate through energy system design choices. We contribute:

- **MOReCriT**, a visual analytics tool for interactive exploration of Pareto-optimal energy system solutions, providing an integrated overview of cost-risk trade-offs alongside the underlying technology deployments and material flows (OSF).
- A **linked-view design** that makes transitions *between* solutions explicit, enabling structural differences across the trade-off frontier to become directly interpretable.
- **Expert evaluation findings** assessing analytical utility and workflow integration across four domain perspectives.

2. Background & Related Work

Multi-objective optimization (MOO) addresses decision problems with competing objectives, where no single optimal solution exists but rather a Pareto front of Pareto-efficient alternatives representing different trade-offs. Understanding and navigating these trade-offs is central to multi-criteria decision-making and has motivated extensive research on Pareto front visualization.

Pareto Front Visualization and MOO. For bi-objective problems, Pareto fronts are commonly visualized using scatterplots, which provide direct and interpretable representations of trade-offs and dominance relations. As dimensionality increases, projection-based approaches such as those discussed in Visualizing Pareto Sets [LM08] aim to embed high-dimensional solution spaces into lower-dimensional views. Dimensionality reduction combined with clustering techniques has also been employed [KPF13], while radial coordinate systems, such as 3D-RadVis, encode multiple objectives within unified spatial layouts [IRMD16]. Surveys in multi-criteria decision making and evolutionary multi-objective optimization provide methodological foundations for Pareto visualization. Miettinen et al. [Mie14] review techniques such as parallel coordinates, scatterplot matrices, and interactive filtering for analyzing alternatives, while Tušar and Filipič [TF15] evaluate visualization methods on benchmark approximation sets. More recent systems, such as PaletteViz and PaletteStarViz by Talukder et al. [TD20a, TD20b], enhance interactive exploration of neighborhood structures within objective space, with interactive MOO approaches explored across further domains [CMMK20, BMPM12, BPFG11]. A recurring challenge across these approaches is that navigating the objective space provides little intuition for what drives structural differences among solutions. Users can observe that two points on the front differ in cost and risk, but not why the underlying configurations diverge. Thus, they do not support reasoning about the domain-specific factors producing particular trade-offs.

Visual Analytics for Energy and Decision Support. VA research emphasizes the importance of linked views, interaction, and user-centered design for supporting complex reasoning tasks. Goodwin et al. [GDJ*13] demonstrate that dashboard-based designs can support energy-related decision-making through coordinated views and task-driven layouts, while Granacher et al. [GNCM22] propose interactive techniques for exploring multi-objective optimization processes, highlighting how tight coupling between objective-space navigation and solution-space detail is essential for actionable insight. In the energy systems domain, EnergyViz by Alemasoom et al. [ASBL16] combines geo-spatial flow maps, Sankey diagrams, and temporal visualizations to analyze energy systems, illustrating how heterogeneous data types benefit from coordinated multi-view designs. More directly related to resource risk analysis, the dashboard by Hoiten et al. [HMP24] enables interactive exploration of raw-material criticality indicators, recyclability, and supply-chain dependencies, though these indicators are treated independently of system-level optimization results and do not link into technologies affected by it. Conceptual work by Weidner et al. [WGRG22] motivates the inclusion of resource and supply constraints in energy system optimization, but it does not address the interactive exploration of resulting trade-offs. Other large-scale infrastructure representations, such as the European power plant visualization by Wang et al. [WKK24], further demonstrate the value of spatial aggregation without focusing on multi-objective trade-off reasoning. Taken together, existing tools either advance geometric Pareto visualization without domain grounding or provide domain-rich energy and resource dashboards without optimization trade-offs. To our knowledge, no existing system combines Pareto front exploration with linked traceability to underlying material dependencies and geopolitical risks within a single VA workflow.

Figure 1: *Overview of **MOReCriT**. The **Pareto front scatterplot** A1 provides the primary entry point for trade-off exploration, here with a selected solution (pareto12, highlighted in orange) that mediates between the cost- and criticality-extreme ends of the front selected via the LinkGroup feature. This selection propagates to the **stacked bar chart** A2, which reveals the underlying technology build-outs per country across all Pareto solutions, and to the **bar chart overlay** on the map A3, which quantifies energy flows between two countries as selected on the **map visualization** B. The **stacked area chart** C integrates input data by showing lithium refinery volumes broken down by supplying country alongside an aggregated criticality line, which spikes when refining is concentrated among a few countries. Each visualization panel provides dedicated adaptation and fixed interaction options D, including export and data selection options.*

3. System Design

MOReCriT was developed in the context of interdisciplinary research on multi-objective energy system optimization and resource criticality assessment. The underlying project combines large-scale techno-economic optimization modeling, material flow analysis, and geopolitical risk evaluation to study future energy system configurations under cost and supply security considerations. This setting involves the analysis of Pareto-optimal solution sets, where each solution represents a complete energy system configuration characterized by technology deployment levels, material demand projections, and country-specific supply dependencies.

Design requirements emerged during iterative exchanges with researchers working at the intersection of optimization modeling, resource analysis, and scenario interpretation. Through structured discussions and requirement elicitation sessions conducted alongside the development of the tool, we identified recurring analytical challenges in the exploration and communication of multi-objective optimization (MOO) results. Existing workflows relied heavily on static Pareto scatterplots, spreadsheet-based inspection of technology mixes, and fragmented visualizations of material flows and country exposure. From these observations, we derived three central design goals to support structured trade-off exploration, traceability from the objective space to the underlying system configurations, and comparative assessment of geopolitical risk. These goals subsequently informed the expert evaluation conducted for this work, which assessed analytical utility and is described in further detail in Section 4.

G1 **Explore Trade-offs in Pareto Space:** Multi-objective optimization produces sets of Pareto-optimal solutions rather than a single optimal configuration. In objective space, these appear as points on a Pareto front plotting cost against aggregated criticality. Analysts must be able to navigate these solutions, compare neighboring trade-offs, and identify structural differences. To lower the barrier to adoption, we deliberately built upon visualizations already familiar to the target audience rather than introducing novel encodings. Additionally, panel arrangement is kept flexible; linked highlighting and selection serve as the primary coordination mechanism across views, rather than relying on aligned fixed axes.

G2 **Trace Solutions to Underlying Material and Technology Assumptions:** Objective values alone conceal the structural characteristics of the corresponding solutions. Each Pareto-optimal point represents a specific combination of generation technologies, storage capacities, network expansions, and associated material requirements. Experts require mechanisms to trace selected solutions back to their technology mixes, resource demand profiles, and derived criticality indicators in order to assess plausibility, robustness, and policy relevance.

G3 **Compare Country-Specific Risk Exposure:** Material criticality is shaped by the geographic concentration of extraction and refining activities. Different Pareto-optimal configurations can shift dependency patterns across countries and regions. Analysts, therefore, need to be able to compare how alternative solutions redistribute exposure to specific supplier countries and evaluate associated geopolitical and economic risks in a coordinated manner.

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3.1. Visual Analytics Approach

MOReCriT provides two categories of visualization (see Figure 1). The first comprises five *guided visualizations*, each anchored to an explicit analytical question selectable by the user. These include two map-based views showing country-specific results and cross-border energy flows B, a line chart for temporal evolution, a Sankey diagram for detailed inspection of a single Pareto-optimal configuration, and a stacked bar chart for comparison across Pareto front points—for instance, addressing questions such as “What proportion do individual technologies take up under a specific commodity for a specific country in a given year?”, which produced the view shown in A2. The second category consists of three *dimension-based visualizations*, namely a 2D scatterplot A1, a 3D scatterplot, and a Parallel Coordinate Plot, in which users freely assign dimensions for open-ended exploration.

Exploration of multi-objective optimization results is inherently non-linear, with experts iteratively moving between trade-off inspection, material analysis, and geopolitical risk assessment. Interactive brushing in the Pareto scatterplot A1 enables selection of regions of interest, with highlights propagating immediately across all linked views to reveal corresponding changes in technology mixes, country dependencies, and flow structures A2 A3 B, directly supporting G1 and G2. Complementary filtering by technology, material, time horizon, or region enables iterative hypothesis testing and progressive narrowing of differences in the solution spaces across the optimization output. Color encodings follow established conventions from the domain experts, mapping technology categories to widely recognized associations (e.g., blue for hydro, yellow for solar), ensuring consistency with existing workflows.

Underlying this coordination is the concept of *linkgroups*, which allow experts to dynamically define sets of views sharing selection and filtering states, enabling side-by-side comparison without losing contextual reference. As shown in Figure 1, the cost- and criticality-extreme solutions are selected together with a mediating point A1, thereby immediately revealing how the intermediate configuration mixes technology build-outs A2. Linkgroups can be separated or synchronized, giving users control over the degree of coordination between views.

To support G3, MOReCriT integrates the underlying input assumptions directly into the exploration workflow. A *treemap*, accessible via context menu on the stacked bar chart A2, reveals material intensity per technology and geopolitical risk exposure, making visible how minor materials can exert disproportionate influence on aggregated criticality scores. For each material, two further views detail the supply-side dynamics: a *stacked area chart* C showing production and refining volumes per supplying country, and a complementary supply-and-demand pressure view. Both cover historical data and projections through 2050, with an overlaid criticality line on a simplified 1–5 scale capturing trends such as exporter over-reliance or demand outpacing supply.

Finally, the ability to store and restore custom layouts, export individual visualizations D, and annotate Pareto front points supports asynchronous collaboration and communication between analysts at different stages of the exploration process; highlighting aspects of interest given that the high-dimensional Pareto space offers a near-endless combination of dimensional parameters to evaluate.

4. Evaluation

To assess MOReCriT’s applicability in practice, we conducted a semi-structured, summative expert evaluation that examined the analytical utility, interpretability, and potential for workflow integration [KF14]. Rather than evaluating isolated visual encodings, the study examined how the system as a whole supports expert reasoning over multi-objective optimization results—specifically, whether it enables meaningful interpretation of Pareto-optimal trade-offs in objective space while maintaining traceability to the high-dimensional decision space underlying the technology portfolios, material compositions, and country-specific supply dependencies. This directly maps onto our design goals: supporting structured Pareto front exploration (G1), enabling traceability from objective space to solution structure (G2), and facilitating comparative assessment of resource and geopolitical risk exposure (G3).

We interviewed four domain experts (**E1**–**E4**) with complementary expertise in energy system modeling, resource criticality analysis, and visualization of optimization results; none are co-authors of this paper. **E1** (4+ years domain experience, multi-objective energy system optimization) was directly involved in developing the optimization method used to generate the Pareto solution sets examined here. **E2** (8 years domain experience, federal research institution) specializes in extraction, refinement, and geopolitical supply risks of critical materials. **E3** (data scientist) has experience building dashboards for energy system scenario analysis, primarily for individual optimization runs rather than Pareto solution sets. **E4** brings extensive experience in European-scale energy network modeling and optimization, with a background in logistics and applied mathematics. This combination provides coverage across all three of our earlier design goals: **E1** and **E4** anchor the assessment of G1 and G2, **E2** brings domain authority on material criticality central to G3, and **E3** contributes a practitioner’s perspective on usability and analytical expressiveness.

Interviews followed a semi-structured format organized around three themes: participants’ *current analytical practice* with optimization results and material data, their *conceptual understanding* of Pareto optimality and differences in solutions, and their *assessment of MOReCriT* in relation to their own workflows. Participants interacted with the deployed system using a representative dataset, thinking aloud as they explored trade-offs, compared neighboring Pareto solutions, and investigated country-level exposure patterns. The format allowed assessments to be grounded in concrete institutional tasks, yielding qualitative insights into analytical expressiveness, trust in model-derived indicators, and interpretability of the coordinated views.

4.1. Findings

Given the semi-structured and exploratory format, each expert naturally gravitated toward aspects of the tool most relevant to their domain, with **E1** focusing on Pareto front shape and solution clustering, **E2** on the drill-down to resource-level inputs, **E3** on dashboard layout and linking behavior, and **E4** on technology build-out comparisons across front points. Despite this variation, all participants engaged with the core interaction mechanisms, such as brushing, cross-view highlighting, and the treemap drill-down, introduced at the outset as a minimal working example, thereby ensuring a consistent baseline. All four experts agreed that the tool fulfilled its core premise, with responsiveness and interactive linking between visualizations standing out most clearly relative to their existing workflows. **E3** explicitly tested the tool's limits by opening more than seven simultaneous visualizations in one view, while **E4** noted that the web-based interactions felt noticeably faster than generating static plots from individual Python scripts, with linked views enabling quick cross-referencing between the Pareto front and technology distributions.

The linked, multi-view design was particularly valued for supporting different analytical workflows. **E1**, focused on mathematical soundness, appreciated being able to identify clusters of marginally differing solutions on the Pareto front at a glance—anomalies that would be tedious to detect in tabular form. **E2**, coming from a resource analyst background, valued the drill-down capability that allowed tracing back from selected solutions to the underlying input data, helping to explain why counterintuitive technology choices might have been made during optimization. **E4** similarly highlighted the ability to quickly compare technology build-outs and identify the primary contributors to criticalities across Pareto front points.

Several usability issues were consistently raised, like the custom mini-selector embedded within each visualization was found unintuitive by multiple experts, as it initially appeared to offer only a single adaptation option. **E2** and **E3** also flagged the right-click interaction for accessing drill-down information as unexpected in a browser-based context. Additionally, **E4** noted that some labels and aggregation names were cryptic to those without a background in resource analysis, and suggested that default configurations could be made more accessible.

Regarding future development, the experts proposed several extensions reflecting their individual analytical needs. **E4** proposed a 3D Pareto front view that allows users to define a primary projection plane, enabling examination of the front from different objective-space perspectives, a feature of particular relevance when more than two objectives are involved. **E2** expressed interest in a richer integration of input data into the stacked bar charts, enabling direct aggregation of widely used materials such as aluminum to better isolate the contribution of critical resources. **E3** proposed more integrated geographic visualizations, such as maps that combine country-level values with inter-country flow representations and support detail-on-demand interactions.

Overall, the tool was regarded as a meaningful improvement over current workflows across all expert profiles. While some interface elements require refinement, the guided visualization selection, dynamic linking, and responsive performance were considered to provide immediate practical value for both internal analysis and the communication of results to non-technical stakeholders.

5. Discussion

The contribution of this work does not lie in novel visual encodings but in their coordination: linking objective-space representations of Pareto-optimal solutions to the domain-specific decision variables and material inputs that underlie them. The expert evaluation confirmed that viewing the Pareto front in isolation is insufficient G1; traceability to technology portfolios, material compositions, and country-level supply dependencies G2 was essential for experts to reason about solution validity and build analytical trust in optimization outputs. This need was reinforced by the inherently iterative nature of Pareto exploration. Analysts can compare neighboring solutions rather than committing to a single point G1; a pattern well supported by the brushing and linking mechanisms. The geographic views further supported reasoning about how geopolitical supply risks propagate across technology choices G3, though the current single-indicator-per-country representation flattens the heterogeneity of multi-stage supply chains that domain experts were sensitive to. Still, the tool's overall complexity presents a non-trivial learning curve for non-specialist users.

The tool is tightly coupled to our custom REMix [W*24] data schema; adapting it to alternative optimization frameworks would require re-engineering of the data pipeline. The current architecture also does not support comparison across multiple Pareto fronts, which may be required by realistic workflows. Finally, the evaluation was limited to four experts on a single output, reflecting qualitative impressions rather than a controlled usability assessment.

Several directions for future development follow from these findings. Supporting multiple Pareto fronts simultaneously G1 would enable direct comparison across model runs with differing assumptions or scenario parameters. At the level of individual visualizations, extensions that more explicitly surface differences between neighboring Pareto points G2 would reduce cognitive load during iterative exploration. More granular supply chain representations, capturing multi-stage dependencies rather than single country-level indicators, would better reflect the heterogeneity that experts flagged as analytically relevant.

6. Conclusion

We present MOReCriT, a visual analytics tool for expert exploration of Pareto-optimal energy system solutions under material criticality and geopolitical supply risk constraints. By coordinating linked views across objective space, technology portfolios, and country-specific material dependencies, the tool makes the high-dimensional decision structures underlying each trade-off navigable, addressing a gap in existing workflows that rely on isolated plots or manual tabular inspection. The expert evaluation confirmed that this traceability is the tool's central contribution, enabling analysts to reason about why particular technology configurations emerge and to iteratively compare neighboring solutions in a way that current practice does not readily support. We showed that future work could extend the tool to support simultaneous comparison of multiple Pareto fronts and more expressive highlighting of differences between neighboring solutions.

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