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Standardizing Energy Policy Analysis: A Global Ontology of Factors and Research Questions for a Sustainable Transition

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Abstract

Despite the surge in energy policy research, the absence of a standardized vocabulary for analytical factors hinders the comparability of studies and, therefore, the effectiveness of policy design. This study addresses this gap by developing a comprehensive, multidimensional ontology of 190 unique factors extracted from a structured review of 150 high-impact articles published in 2024 and 2025. Factors were organized into 11 functional categories and classified by their analytical roles as inputs, outputs, decisions, or mediating variables. Input and output roles accounted for most factor assignments, representing 44.4% and 36.8%, respectively, while mediating and decision-oriented factors were less frequent. The analysis also identified geographical differences within the reviewed sample. The regional comparison focused on China, Europe, and the Middle East, the three most represented regions in the dataset. Chinese studies more frequently emphasized environmental policy stringency and government intervention, European studies placed greater emphasis on system profitability and capital investment requirements, and Middle Eastern studies highlighted demand flexibility and system profitability. These patterns should be interpreted as descriptive findings within the reviewed sample. Although the short time window limits the ability to infer long-term trends, it allows the ontology to capture recent developments and emerging analytical priorities in energy policy research. This ontology provides a robust, standardized framework that bridges the gap between technical power system modeling and socio-economic policy analysis. By aligning research variables with global sustainability targets, this tool facilitates more transparent decision-making toward sustainable energy systems.

Keywords: energy policy; ontology; decision-making support; research questions; policy factors; energy transition; standardized framework

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1. Introduction

The global energy landscape is undergoing a profound transformation, driven by technological advances and uneven progress toward decarbonization. In recent years, this transition has been further complicated by a volatile geopolitical environment. Events such as the war in Ukraine and tensions in the Middle East have exposed the fragility of global energy supply chains and reinforced the importance of resilience and strategic autonomy. Policy responses, such as the European Union's REPowerEU plan, illustrate how energy policy is evolving beyond decarbonization toward a broader framework that integrates security of supply, affordability, and sustainability [1].

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Despite these efforts, a significant implementation gap persists. Although renewable capacity reached a record 700 GW in 2024, progress remains uneven: emerging economies such as China and India still rely on coal for nearly 60% of their power generation, while regions such as Africa receive only a small share of global clean energy investment [2].

Reflecting on these practical challenges, energy systems research has expanded rapidly, generating a growing body of studies that address diverse aspects of the energy transition. This growth is driven by increasing academic and policy interest in topics such as decarbonization pathways, system flexibility, and investment strategies. However, this expansion has also made it more difficult to systematically assess what is being studied and how research efforts are distributed across topics.

While numerous studies address similar problems, the research questions that guide these analyses are often implicitly defined and lack a standardized structure. As a result, it remains unclear which questions receive the most attention, how they vary across contexts, and what gaps remain. This highlights the need for a structured approach to analyzing and classifying research questions in the field of energy policy.

Recent research has increasingly employed bibliometric, scientometric, and data-driven analytical approaches to examine the evolution of energy-related studies, identifying dominant themes, emerging research fronts, and patterns of scholarly collaboration [3–12]. Harichandan et al. [3], for example, map the evolution of energy transition research and identify future directions in the field, while Ahlborg et al. [4] provide a large-scale landscape analysis of energy and power research over the last thirty-five years. Other studies focus on specific dimensions such as energy governance [5], green energy technologies [6], renewable energy research trends [8], innovation dynamics in renewable energy systems [9], public policy and sustainability transitions [10], and scientific collaboration networks in renewable energy research [11]. Collectively, these studies highlight both the rapid expansion of the field and the growing diversity of research directions, revealing how research priorities have evolved across different thematic and geographic contexts.

A second strand of the literature emphasizes the interaction between energy system analysis, policy support, and socio-technical transitions. Sovacool et al. [13] review future directions in energy and climate research from a socio-technical perspective, emphasizing the importance of integrating institutional and governance dimensions into energy transition analysis. Similarly, Hirt et al. [14] explore how quantitative energy models can be linked with socio-technical transition theories to better support energy and climate solutions. Tavana et al. [15] focus on uncertain decision-making methods in energy management using text mining and data analytics. In parallel, Yu et al. [16] analyze the evolution of energy resilience research through bibliometric techniques. These studies highlight the importance of integrating technical, economic, institutional, governance-related, and resilience factors when analyzing energy and climate solutions, reinforcing the need for analytical frameworks capable of bridging quantitative modeling and policy-oriented decision-making.

A final line of research focuses on energy system analysis and modeling frameworks. Dominković et al. [17] review two decades of energy system analysis using bibliometric methods, highlighting the evolution of modeling practices and analytical structures within the field. Kang et al. [18] provide a systematic review of energy systems for climate change mitigation, emphasizing the methodological diversity of models used to support energy and climate policy analysis. In addition, Entezari et al. [19] analyze the growing integration of artificial intelligence and machine learning techniques into energy systems research, illustrating the emergence of new analytical approaches for energy planning and decision-making. Collectively, this line of research illustrates the increasing methodological sophistication of energy system analysis and the growing diversity of models, methodological approaches, and analytical structures used to support energy and climate policy analysis.

In parallel, initiatives such as the IPCC AR6 Scenario Explorer [20] and related work by Daniel Huppmann have contributed to the harmonization of variables and indicators across large-scale energy system models, improving transparency, comparability, and interoperability. Similarly, Santos Oliveira et al. [21] propose a structured methodology for selecting and combining energy models to support policy decisions, reinforcing the importance of systematic frameworks capable of linking research questions, analytical processes, and model implementation.

Despite these advances, existing approaches do not explicitly link research questions to the factors and analytical roles used in individual studies. As a result, the connection between problem formulation and quantitative analysis remains insufficiently explored.

This study addresses this gap by proposing a structured framework to analyze and classify research questions in energy policy. The framework establishes a systematic link between research questions, the factors they involve, and their role within analytical models. Based on a systematic review of 150 peer-reviewed articles, the study identifies and organizes 190 distinct factors, thereby enabling the systematic comparison and classification of research questions in the energy policy context across the literature.

By connecting problem formulation with analytical structure, the framework clarifies how energy policy research is conducted and highlights both dominant lines of inquiry and underexplored areas. The framework is further applied across the geographical contexts represented in the reviewed sample to examine how research priorities vary by region. The detailed comparative analysis focuses on the three regions with the largest number of articles: China, Europe, and the Middle East. Overall, this work offers a unified analytical perspective that enhances the transparency, comparability, and policy relevance of energy research.

2. Materials and Methods

To address policy fragmentation and inconsistent terminology, this study adopts a structured modeling framework that formalizes the links between different energy models and their policy drivers. The methodology builds upon the approach developed by Santos Oliveira et al., which presents the modeling process as a sequence of interconnected stages, linking problem formulation to model implementation (Figure 1) [21].

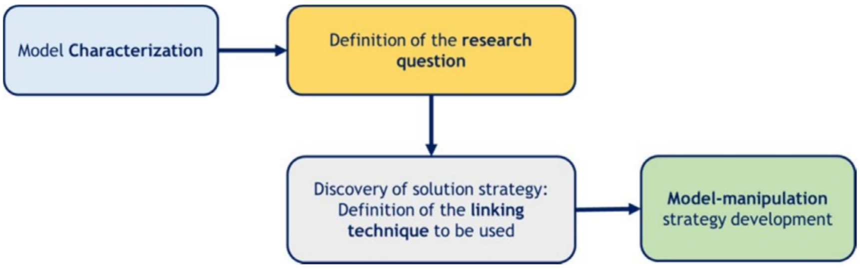


Figure 1. Proposed framework stages from Santos Oliveira et al. [21].

Within this framework, the research question is central. It determines the selection of modeling strategies and shapes the analytical structure. The framework identifies four main stages: model characterization, research question definition, identification of solution strategies, and model-manipulation development. Together, these stages systematically connect policy questions with modeling techniques.

This study focuses on the second stage, which emphasizes defining the research question as a prerequisite for selecting appropriate model-linking strategies. To support this stage, we develop a systematic process that transforms the fragmented literature into a standardized ontological framework. The methodology consists of five operational steps, shown in Figure 2.

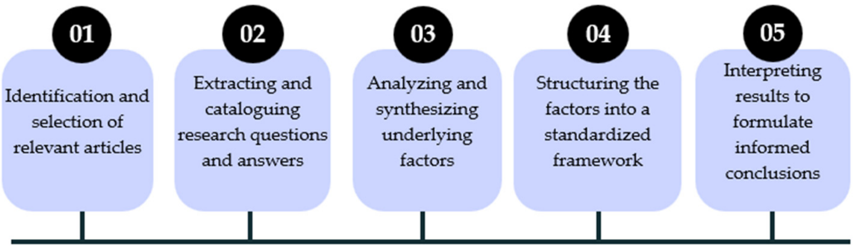


Figure 2. Process flow for the development of the energy policy ontology.

The process begins with the identification and selection of relevant articles, followed by the extraction and standardization of research questions and their corresponding answers. Next, it identifies and synthesizes the factors underlying each research question. These factors are then organized into a structured framework based on their functional role. Finally, the results are interpreted to derive insights into the structure and evolution of energy policy research.

2.1. Literature Selection and Scope Definition

The literature-selection process was designed to identify recent quantitative studies suitable for constructing an ontology linking energy-policy research questions, analytical factors, and factor roles. The review was conducted through ScienceDirect and focused on articles published in the journal *Energy* between December 2024 and June 2025, corresponding to Volumes 313–324.

Energy was selected because of its broad interdisciplinary coverage of energy-system analysis, modeling, planning, management, efficiency, renewable energy, environmental performance, and policy-related issues. Its combination of technical, economic, and environmental perspectives provided an appropriate basis for identifying the heterogeneous variables employed in quantitative energy-policy research.

The selected publication window was deliberately restricted to capture recent terminology, emerging analytical priorities, and the latest developments in a rapidly evolving field, rather than providing a longitudinal overview of energy-policy research. A shorter and more recent period was examined in greater depth, allowing the records within the selected volumes to be screened systematically and each included article to undergo detailed manual extraction and classification. Extending the review to a longer period would have required sampling from a substantially larger body of the literature, potentially reducing the consistency and depth of the ontology-development process.

No topic-specific keyword restriction was applied. All records published in the selected volumes were initially considered and underwent a preliminary assessment based on publication type and scope. Potentially relevant articles were then screened by title and abstract, followed by full-text retrieval and eligibility assessment. The complete numerical breakdown of the identification, screening, retrieval, and inclusion stages is presented in Figure 3.

Studies were eligible for inclusion when they met the following criteria: (i) publication in English as a peer-reviewed research article; (ii) publication within the defined period; (iii) use of a quantitative empirical, econometric, optimization, simulation, spillover, or comparable analytical approach; (iv) availability of sufficient methodological and empirical information for the extraction of research questions, findings, and factors; and (v) explicit relevance to energy-policy decision-making or actionable policy implications.

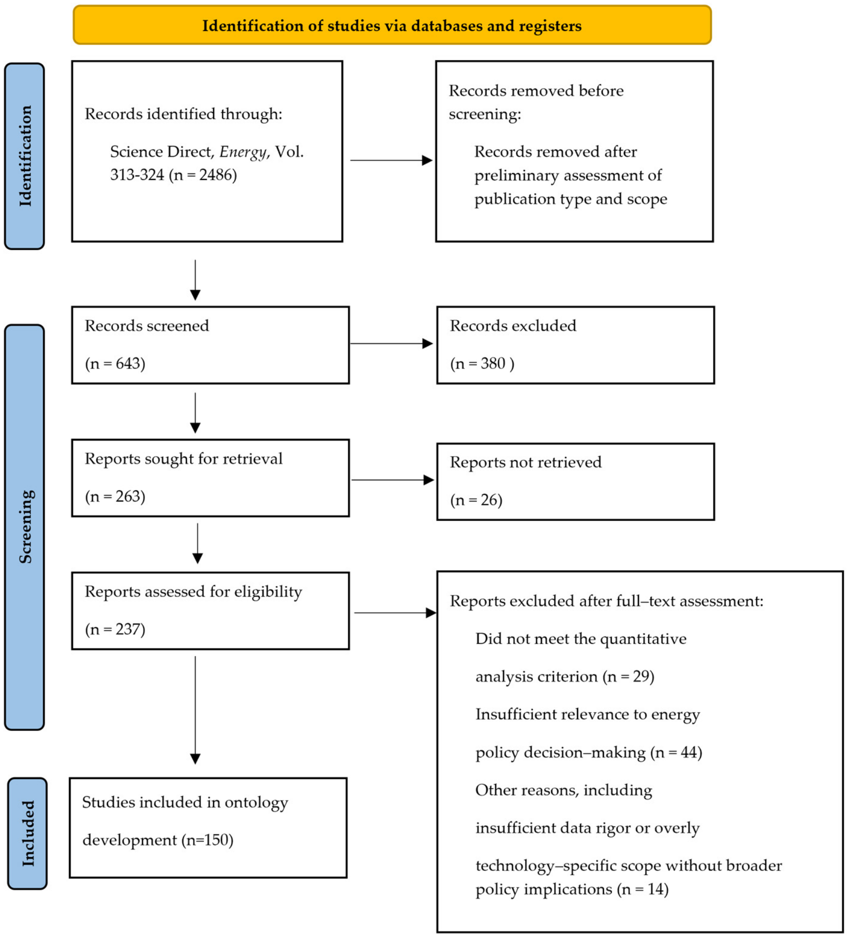


Figure 3. PRISMA−style flow diagram of the study selection process.

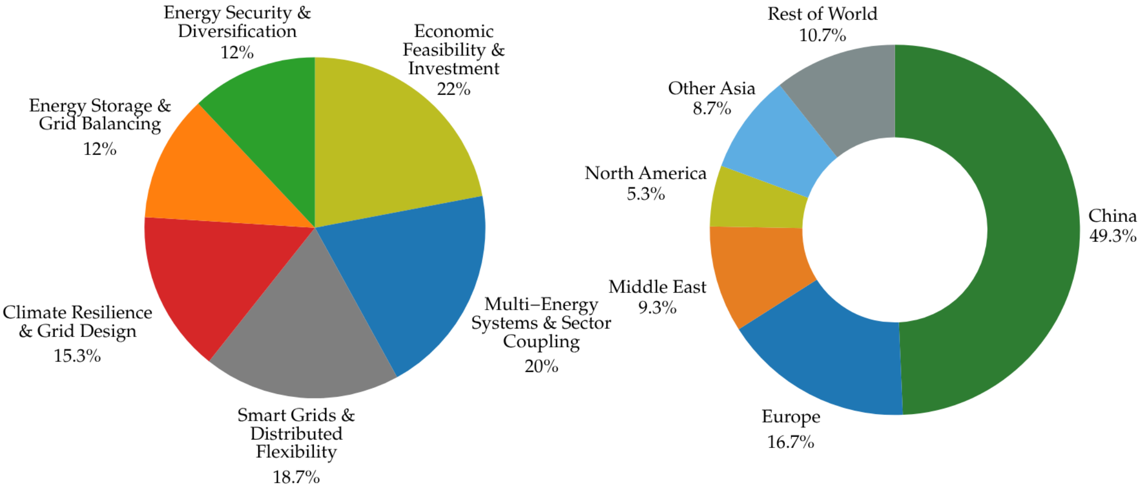
Studies were excluded at the full-text stage when they did not meet the quantitative-analysis criterion, lacked sufficient relevance to energy-policy decision-making, presented insufficient methodological or data rigor, or focused on highly specific technologies without broader policy implications. The detailed breakdown of exclusions is provided in Figure 3.

Each included article was subsequently reviewed manually to identify its central research question and corresponding answer, extract the analytical factors involved, standardize these factors across studies, and classify their analytical roles.

To ensure comprehensive coverage of the main research domains, the selected articles were further organized into six thematic categories: (i) Energy Storage and Grid Balancing; (ii) Smart Grids and Distributed Flexibility; (iii) Multi-Energy Systems and Sector Coupling; (iv) Economic Feasibility and Investment; (v) Climate Resilience and Grid Design; and (vi) Energy Security and Diversification.

As shown in Figure 4a, the distribution of articles across thematic categories reveals a strong concentration in economic feasibility and multi-energy systems integration, which together account for more than 40% of the dataset. This pattern indicates a dominant research focus on financial viability and system-level integration.

In addition to the thematic classification, the dataset was analyzed from a geographical perspective. Each article was assigned to a geographical category according to the principal country or geographical context examined in the study. For presentation purposes, the articles were grouped into six categories: China, Europe, the Middle East, North America, Other Asia, and Rest of World. The Rest of World category comprises studies focused on India, Turkey, Africa, Australia and New Zealand, and Latin America, which were grouped because of their comparatively limited individual representation in the dataset.



(**a**) (**b**)

Figure 4. Distribution of selected articles across (**a**) thematic categories and (**b**) geographical regions (North America comprises the United States and Canada; Other Asia comprises the Republic of Korea, Vietnam, Malaysia, and Hong Kong; and Rest of World comprises India, Turkey, Africa, Australia and New Zealand, and Latin America).

Figure 4b shows the regional distribution of articles, revealing a significant concentration of research in China, which represents nearly half of the sample (49.3%). Europe and the Middle East follow, while other regions contribute a comparatively smaller share. This distribution reveals an imbalance within the reviewed sample. The observed pattern may reflect differences in the geographical focus of the selected studies. All geographical categories were retained in the dataset and contributed to the construction of the ontology. However, the detailed regional comparison presented in Section 3.3 focuses on China, Europe, and the Middle East because these were the three categories with the largest representation in the reviewed sample. Consequently, the geographical results should be interpreted as descriptive patterns within the selected literature rather than as representative estimates of global energy policy research.

2.2. *Extraction of Research Questions*

The next stage of the ontology development involves the extraction of research questions and corresponding answers from the selected articles, which constitutes one of the primary objectives of this study. Identifying these elements clarifies what each study investigates and how the authors address those inquiries. This process improves interpretability and helps identify research gaps.

A structured manual review was conducted for each article to extract both research questions and the key analytical factors. Research questions were defined as the central problem explicitly addressed in each study, or, when not directly stated, inferred from the problem formulation, modeling approach, and conclusions.

In parallel, research answers were derived from each article's main findings and conclusions, capturing how the analysis responds to the initial research problem. This two-step interpretation ensures that the extracted factors are directly linked to both the research objective and its analytical resolution.

To illustrate the process, Table 1 provides some examples of how research questions and corresponding answers were identified from the selected articles. These examples show how the central research problem and its resolution are captured, forming the conceptual basis for the subsequent identification and classification of policy factors.

Table 1. Example of research question and answer extraction from selected articles.

Article	Research Question	Research Answer
2	How do subsidy policies impact the reliability of renewable electricity supply?	Without government intervention, renewable energy producers may lack incentives to enhance supply reliability, especially when improvement costs are high, and consumer green consciousness is low.
71	Does the implementation of new energy policies significantly improve the total factor energy efficiency of firms in energy-intensive sectors?	The New Energy Demonstration City policy significantly improves corporate total factor energy efficiency, with the effect becoming stronger after a three-year lag. The study also finds that R&D investment acts as a transmission channel and that the effect is stronger among financially robust firms.
117	How does demand flexibility from electric vehicles and hydrogen electrolysers impact renewable energy integration in the Portuguese power system?	Demand flexibility through smart EV charging and dynamic hydrogen electrolyser operation significantly improves renewable energy integration. In the full flexibility scenario, renewable curtailment was reduced by 97%, backup generation was eliminated, storage use decreased, gas-fired generation fell, and CO_2 emissions were reduced.

In many cases, research questions are not explicitly stated and must be inferred from the study's structure, reinforcing the need for a consistent interpretation framework.

The initial extraction of research questions, corresponding answers, and analytical factors was conducted by the second author. All extracted items and coding decisions were subsequently reviewed by the first author. When ambiguities or disagreements arose regarding the formulation of a research question or the interpretation of the corresponding answer, both authors discussed the case and reached a consensus.

2.3. Ontology Construction and Classification Framework

Following the extraction of research questions and corresponding answers, the next stage identifies and defines the underlying policy factors. At this stage, the objective is not to assign analytical roles, but to establish a consistent, standardized representation of the variables used across the literature.

Each factor is defined as a distinct variable, parameter, or condition used in energy systems or policy analysis. These factors form the fundamental building blocks of the ontology. To ensure consistency and comparability, a standardized framework was developed to describe each factor. For every factor, the following elements were specified:

- Name: A concise label capturing the core concept.
- Unit of measurement: The metric or scale used to quantify the factor, when applicable.
- Definition: A clear description of the factor and its scope.
- Commentary (optional): Additional context where further clarification is needed.

The consolidation process was conducted by comparing the original terms according to their definitions, units, analytical meaning, and use within the corresponding research question. Terms were merged when they represented the same underlying concept despite differences in wording, abbreviation, or level of detail. Synonymous or conceptually equivalent expressions were assigned to a single standardized factor. As a general naming rule, the term with the highest frequency of occurrence within each group was retained as the standardized label, provided that it adequately represented the shared meaning of the grouped expressions.

Terms were not merged solely because they appeared linguistically similar. They were retained as separate factors when they differed in analytical meaning, measurement basis, system boundary, temporal scale, or policy interpretation. Units were harmonized only when they were directly compatible or convertible without altering the underlying concept. For example, Article 124 uses the expression "electricity price uncertainty" in the context of multi-area dynamic economic dispatch, whereas Article 48 refers to "electricity price volatility" as the variable to be forecast. After reviewing the meaning and analytical use of both expressions, they were consolidated under the standardized factor *Electricity Price Volatility*, as both referred to fluctuations and uncertainty in electricity prices within the corresponding models. The label *Electricity Price Volatility* was retained because it was the most frequently occurring term in the reviewed sample.

The initial consolidation was conducted by the second author and subsequently reviewed by the first author. The same review-and-consensus procedure was applied to factor consolidation and analytical-role assignment whenever classification decisions were ambiguous. The resulting set of factors was subsequently cross-checked against the variables included in the IPCC AR6 Scenario Explorer to assess consistency with established energy-system modeling terminology. Final consolidation decisions were based on the authors' expert judgment.

Importantly, factors are defined independently of their analytical role. The same factor may act as an input, output, decision variable, or mediating element depending on the context of the research question and the modeling framework used in each study. The assignment of analytical roles is therefore addressed in Section 3.

To enhance clarity and facilitate interpretation, the identified factors were organized into eleven thematic categories representing the main dimensions of energy policy analysis (Table 2).

Table 2. Thematic categories used to organize policy factors within the ontology.

Category	Description
Energy Supply and Generation	Captures installed capacity, power output, fuel-specific generation, and technological diversity.
Energy Storage and Flexibility	Includes storage technologies, operational modulation, and load balancing.
Energy Demand, Consumption, and Electrification	Covers end-use profiles, total consumption, and sector-specific loads.
Financial Costs and Investment Instruments	Expenses and monetary measures related to the acquisition, operation, and support of energy systems and technologies.
Macro-Economic and Market Indicators	Captures broad economic and market metrics that reflect the overall performance of energy and related financial sectors.
Policy, Regulation, and Governance	Addresses policy reliability, regulatory frameworks, taxes, and decentralization.
Social Development and Equity	Describes human and societal factors: equity, awareness, education, employment, and development.
Technology, R&D, and Innovation Uptake	Covers technological advancement, R&D intensity, and smart systems deployment.
Power System Performance and Reliability	Evaluates grid efficiency, resilience, service restoration, and quality metrics.
Climatic, Resource, and Land Constraints	Focuses on environmental and physical factors influencing system design or feasibility.
Environmental Impact and Emissions	Captures emissions, pollution, and environmental performance metrics.

The eleven-category classification was developed through an inductive coding process based on the 190 standardized factors identified in the reviewed literature, rather than being adopted directly from a single pre-existing energy policy theory. Factors were initially grouped according to similarities in their definitions, analytical meaning, and function within energy policy and energy-system studies. The preliminary groupings were subsequently reviewed and refined through expert judgment to ensure conceptual coherence, appropriate coverage, and consistency with commonly used technical, economic, environmental, regulatory, and social dimensions of energy policy analysis.

For coding purposes, each factor was assigned to one primary category, making the categories mutually exclusive at the factor-classification level. Nevertheless, the categories are conceptually interrelated, as many energy policy variables connect technical, economic, social, and regulatory dimensions. The assigned category, therefore, reflects the factor's predominant analytical meaning within the ontology.

This categorization captures the multidimensional nature of energy policy systems, integrating technical, economic, regulatory, and social perspectives within a unified analytical structure.

2.4. Validation with IPCC AR6 Scenario Explorer

As an additional validation step, the study compares the proposed framework with the IPCC AR6 Scenario Explorer to assess its alignment with established energy and climate indicators. This comparison examines how closely the factors identified here match the variables used in large-scale energy system models, including techno-economic indicators, policy variables, and emerging technological metrics.

For transparency and reproducibility, the complete article-level extraction, standardized factor ontology, factor-role assignments, and geographical and thematic analyses are provided in Dataset S1 in the Supplementary Materials.

3. Results

3.1. Ontology Overview

The ontology developed in this study provides a structured representation of the variables in energy policy research. Based on the analysis of 150 selected articles, a total of 190 policy factors were identified and defined.

The analytical framework operates across two complementary dimensions introduced in the previous section. At the article level, studies are categorized into six thematic domains reflecting their primary research focus. At the factor level, variables are organized into eleven functional categories capturing the main dimensions of energy policy systems. Table 3 summarizes the main characteristics of the dataset and the resulting ontology structure.

Table 3. Summary of the dataset and ontology structure.

Metric	Value
Number of articles selected	150
Number of article categories	6
Number of factors identified	190
Number of factor categories	11

The resulting structure enables consistent representation of heterogeneous studies and provides a unified framework for interpreting variables across modeling approaches and policy contexts.

3.2. Factor Distribution Across Article Categories

To examine how research domains prioritize policy variables, we analyzed the most frequently occurring factors within each thematic category of articles. Across all categories, a set of core factors consistently emerges, including carbon emissions, capital investment requirements, system profitability, and energy investment incentives. Their presence across domains highlights their central role in linking technical, economic, and policy dimensions of energy systems. Distinct patterns, however, emerge by thematic focus.

In Energy Storage and Grid Balancing (i), the most prominent factors relate to system stability and economic feasibility, particularly energy investment incentives, grid resilience, and operational and maintenance costs. These factors reflect the importance of financial mechanisms and reliability targets in the deployment and operation of storage technologies. The relevance of battery storage capacity, capital investment, and demand flexibility further underscores the role of asset sizing and operational adaptability. Lower-frequency factors, such as electricity demand, price volatility, and carbon emissions, indicate a growing interest in the interaction between market conditions, load behavior, and environmental performance.

Smart Grids and Distributed Flexibility (ii) emphasize regulatory and market dynamics, with government intervention and electricity price volatility as dominant factors. This underscores the role of policy frameworks and price signals in enabling distributed energy coordination, particularly in contexts such as virtual power plants and electric vehicle integration. The presence of grid connectivity and demand flexibility reflects a balanced focus on both technological deployment and consumer behavior.

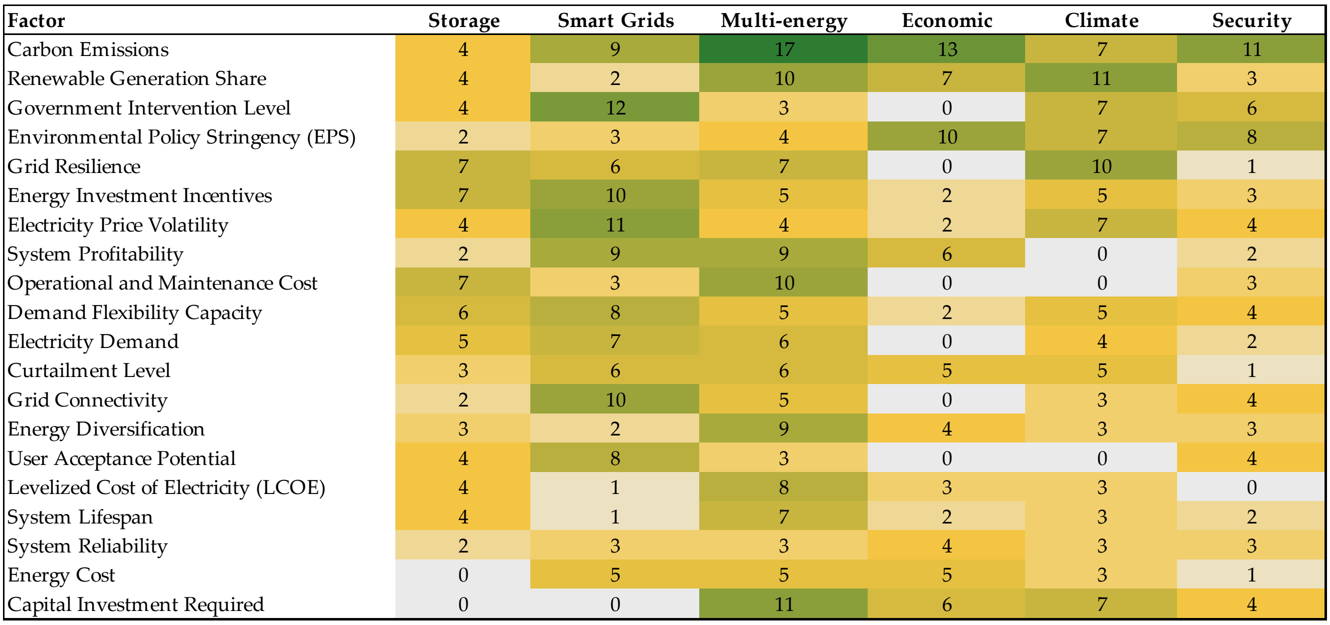
In Multi-Energy Systems and Sector Coupling (iii), carbon emissions stand out as the most frequently analyzed factor, far exceeding others. This highlights the central role of decarbonization in integrated system design. Capital investment and operational costs capture the techno-economic dimension, while renewable generation share and resource availability reflect the need to optimize diverse energy inputs. The combination of economic, environmental, and system performance factors illustrates the complexity of multi-vector systems.

The Economic Feasibility and Investment (iv) category reinforces the importance of policy and environmental constraints. Carbon emissions and environmental policy stringency play key roles alongside cost indicators such as investment requirements, profitability, and energy costs. The lower prominence of subsidy-related variables suggests a focus on structural economic parameters over specific policy incentives.

Climate Resilience and Grid Design (v) emphasizes renewable integration and system robustness, as reflected in the prominence of renewable generation share and grid resilience. A broad set of factors—including climate risk, policy stringency, and capital investment—indicates a holistic approach that integrates environmental conditions, governance, and infrastructure planning. These studies adopt a multidimensional perspective to address system vulnerability.

Finally, in Energy Security and Diversification (vi), carbon emissions again dominate, suggesting that decarbonization is increasingly viewed as integral to long-term energy security. Policy-related variables, including environmental stringency and government intervention, highlight the strategic role of governance in shaping diversified systems. Factors related to flexibility, investment, and user acceptance reflect the need to balance technical, economic, and social dimensions.

Figure 5 presents a heatmap of the most frequently occurring factors across categories, providing a structured view of their distribution. This visualization complements the analysis by highlighting both the relative importance of key variables and their patterns across research areas.



Factor	**Storage**	**Smart Grids**	**Multi-energy**	**Economic**	**Climate**	**Security**
Carbon Emissions	4	9	17	13	7	11
Renewable Generation Share	4	2	10	7	11	3
Government Intervention Level	4	12	3	0	7	6
Environmental Policy Stringency (EPS)	2	3	4	10	7	8
Grid Resilience	7	6	7	0	10	1
Energy Investment Incentives	7	10	5	2	5	3
Electricity Price Volatility	4	11	4	2	7	4
System Profitability	2	9	9	6	0	2
Operational and Maintenance Cost	7	3	10	0	0	3
Demand Flexibility Capacity	6	8	5	2	5	4
Electricity Demand	5	7	6	0	4	2
Curtailment Level	3	6	6	5	5	1
Grid Connectivity	2	10	5	0	3	4
Energy Diversification	3	2	9	4	3	3
User Acceptance Potential	4	8	3	0	0	4
Levelized Cost of Electricity (LCOE)	4	1	8	3	3	0
System Lifespan	4	1	7	2	3	2
System Reliability	2	3	3	4	3	3
Energy Cost	0	5	5	5	3	1
Capital Investment Required	0	0	11	6	7	4

Figure 5. Heatmap of the most frequently occurring policy factors across article categories. Color intensity represents the frequency of occurrence of each factor within each domain.

Overall, these results reveal that a core set of factors underpins most studies, with each thematic domain emphasizing different dimensions depending on its research objectives, reflecting the heterogeneous yet interconnected nature of energy policy research.

3.3. Regional Variability

To examine the geographical variability of energy policy research, the analysis focuses on the three regions with the largest representation in the dataset: China (74 articles), Europe (25 articles), and the Middle East (14 articles). The remaining categories were retained in the full dataset and contributed to the construction of the ontology. However, they were not included in the detailed regional comparison because their smaller sample sizes, or their aggregation of heterogeneous geographical contexts in the case of the Rest of World, provided a more limited basis for comparing factor frequencies. The analysis should therefore be interpreted as a descriptive comparison of the three most represented geographical categories.

Table 4 summarizes the most frequently occurring factors within each region, highlighting how research priorities differ across geographical contexts.

Table 4. Most frequently occurring policy factors by geographic region.

China			**Europe**			**Middle East**		
Factor	***N*** [1]	**%** [2]	***Factor***	***N***	**%**	***Factor***	***N***	**%**
Carbon Emissions	33	45%	Carbon Emissions	14	56%	Carbon Emissions	5	36%
Environmental Policy Stringency	23	31%	System Profitability	9	36%	Demand Flexibility Capacity	5	36%
Government Intervention Level	23	31%	Capital Investment Required	8	32%	System Profitability	5	36%

[1] N = number of articles in which each factor appears; [2] Percentages are calculated relative to the total number of articles within each regional subsample.

As shown in Table 4, carbon emissions emerge as the most prominent factor across the three regional subsamples, indicating a shared emphasis on decarbonization within the articles reviewed. However, beyond this common pattern, notable regional differences can be observed in the selection of secondary factors, reflecting the influence of local policy frameworks, market structures, and system priorities.

Within the Chinese sample, environmental policy stringency and government intervention level are among the most frequently occurring secondary factors. This pattern suggests that the selected studies focused comparatively more on regulatory and government-related dimensions of energy policy. In the European sample, system profitability and capital investment requirements are more prominent, indicating greater attention to the financial and investment-related dimensions of energy-system development. In the Middle Eastern sample, demand flexibility capacity and system profitability appear among the leading secondary factors, reflecting a comparatively stronger focus on operational flexibility and economic performance within the selected studies.

Overall, these regional patterns indicate that, while certain factors recur across the three regional subsamples, the importance given to other factors varies between regions. Such differences may reflect variations in research objectives, policy contexts, market structures, and energy-system characteristics. While these patterns provide useful insights into the geographical distribution of factors within the reviewed literature, they should be interpreted as descriptive observations rather than definitive characterizations of regional energy policy research.

3.4. Factor Roles in Energy Policy Analysis

Understanding the role of each factor within the analytical framework is essential for linking research questions to their corresponding outcomes. While previous sections identified and categorized policy factors, this section examines how these factors function within the context of each study.

To achieve this, each factor was assigned a specific analytical role based on its position within the research question and the corresponding answer. This role-based classification enables a deeper understanding of how different variables contribute to the structure of energy policy models, distinguishing between drivers, outcomes, decision levers, and intermediary mechanisms.

To analyze factor behavior systematically, four distinct roles were defined. These roles capture the functional position of each variable within the analytical structure of the study (Table 5).

Table 5. Definition of factor roles within the analytical framework.

Type	Definition	Role
Input	A factor that feeds into the system or model from the outside, typically not controlled within the study context, and influences the resulting outcomes.	Sets the starting point for analysis or simulation.
Output	A factor that represents the outcome of a policy, model, or system behavior; what you are trying to explain, predict, or optimize.	Used to evaluate the success or impact of interventions.
Decision Factor	A factor that represents a choice or lever that policymakers, planners, or system operators can directly control or optimize to improve outcomes.	Central in optimization models or scenario planning. Can be adjusted to achieve policy or system objectives.
Mediating Factor	A factor that explains how or why an input affects an output, forming part of the causal pathway linking an intervention to its result.	Often included in regression or structural equation models to uncover indirect effects.

By distinguishing among inputs, outputs, decision variables, and mediating factors, it becomes possible to trace how research questions translate into measurable outcomes. This classification provides a structured way to uncover the causal pathways linking system drivers, policy interventions, and observed results.

The analytical role assigned to a factor depends on its position within the research question and the causal or decision structure of the study, rather than on the factor's intrinsic meaning. The same standardized factor may therefore receive different role assignments across studies. Table 6 provides illustrative examples of these context-dependent transitions.

Table 6. Illustrative examples of context-dependent factor-role assignments.

Factor	Article and Research Question	Role	Role Assignment Logic
Electricity Price Volatility	*Article 124:* What is the motivation for incorporating demand response and electricity price uncertainty in multi-area dynamic economic dispatch?	Input	Electricity price volatility is introduced as an external source of uncertainty affecting dispatch decisions and operating costs. It therefore enters the model as a condition that influences other outcomes.
	Article 48: Do climate factors significantly improve the forecasting accuracy of electricity price volatility?	Output	Electricity price volatility is the variable the model seeks to explain and predict; it is therefore classified as an output.
Government Intervention Level	*Article 2:* What level of government intervention is optimal in balancing energy security, environmental benefits, and economic viability?	Decision Factor	Government intervention is treated as a controllable policy lever whose level can be adjusted to balance competing objectives.
	Article 3: What factors can mitigate the negative effects of climate policy uncertainty on energy transition?	Mediating Factor	Government intervention explains how the negative effect of policy uncertainty on energy-transition outcomes can be reduced, so it operates as a mediating mechanism.

These examples show that analytical roles are assigned at the factor–study level. Electricity price volatility functions as an input when it is introduced as an external condition influencing model decisions, but as an output when it is the variable to be explained or predicted. Similarly, government intervention functions as a decision variable when its level can be directly adjusted by policymakers, but as a mediating factor when it explains how

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another condition affects the final outcome. This context-dependent assignment provides the basis for the broader role-distribution analysis presented below.

Each factor was assigned a single role within each individual study, based on the context provided by the research question and its corresponding answer. After classifying all factor–study pairings, two complementary metrics were derived: (i) the total number of occurrences of each factor in each role, and (ii) the proportion of occurrences of each factor assigned to a given role relative to its total appearances.

Figure 6 presents the overall distribution of analytical role assignments across the reviewed studies.

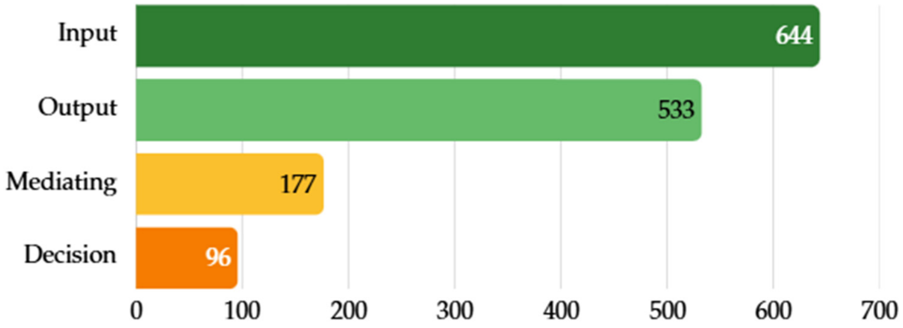

Figure 6. Distribution of analytical role assignments across the reviewed studies (Values represent the total number of factor–study occurrences classified under each analytical role).

As shown in Figure 6, input factors account for the largest number of role assignments (644, 44.4%), followed by output factors (533, 36.8%). In contrast, mediating (177, 12.2%) and decision factors (96, 6.6%) appear significantly less frequently. Within the reviewed sample, this distribution indicates that the selected studies more frequently represent system conditions and measurable outcomes than mediating mechanisms or directly controllable policy variables.

However, the lower frequency of mediating and decision factors should not be interpreted as lower importance or deficiency in the broader energy policy literature. The observed distribution may partly reflect the composition of the reviewed sample, which focuses on quantitative empirical, econometric, optimization, and simulation-based studies. These methodological approaches commonly define model inputs and outputs explicitly, while causal mechanisms and policy levers may be represented less directly or described outside the formal model structure. Accordingly, the results should be understood as descriptive patterns within the selected literature rather than as a comprehensive assessment of the relative attention given to each analytical role across the field.

To explore these patterns further, Table 7 presents the factors most frequently associated with each analytical role, ranked by the share of studies where they are assigned that function. While the previous analysis identifies the most frequently assigned roles, this section examines whether these roles remain stable across different studies. Figure 7 visually summarizes these patterns by highlighting the most frequently occurring factors associated with each analytical role and the context-dependent assignment of some factors across studies.

The results reveal a clear differentiation between structural, performance, and policy-related variables. Core technical and economic factors—such as capital investment requirements, storage capacity, and operational costs—are predominantly modeled as inputs, reflecting their role in defining initial system conditions. Conversely, output roles are largely dominated by performance indicators, particularly carbon emissions, system profitability, and grid resilience, which are commonly used to evaluate the impact of policies and system configurations. Mediating factors are primarily associated with regulatory and behavioral variables, such as government intervention and environmental policy stringency, highlighting their role in shaping the relationship between inputs and outcomes. Decision factors, while less frequent, are mainly represented by investment incentives and subsidy mechanisms, reflecting their function as direct policy levers.

Table 7. Frequency of role assignments for key factors across studies.

Input		**Output**	
Factor	%	Factor	%
Capital Investment Required	23.33%	Carbon Emissions	40.00%
BESS Capacity	21.33%	System Profitability	20.67%
Operational and Maintenance Cost	15.33%	Grid Resilience	20.67%
Mediating		**Decision**	
Factor	%	Factor	%
Government Intervention Level	13.33%	Energy Investment Incentives	16.00%
Environmental Policy Stringency	12.67%	Investment Subsidy Level	5.33%
User Acceptance Potential	11.33%	Government Intervention Level	4.67%

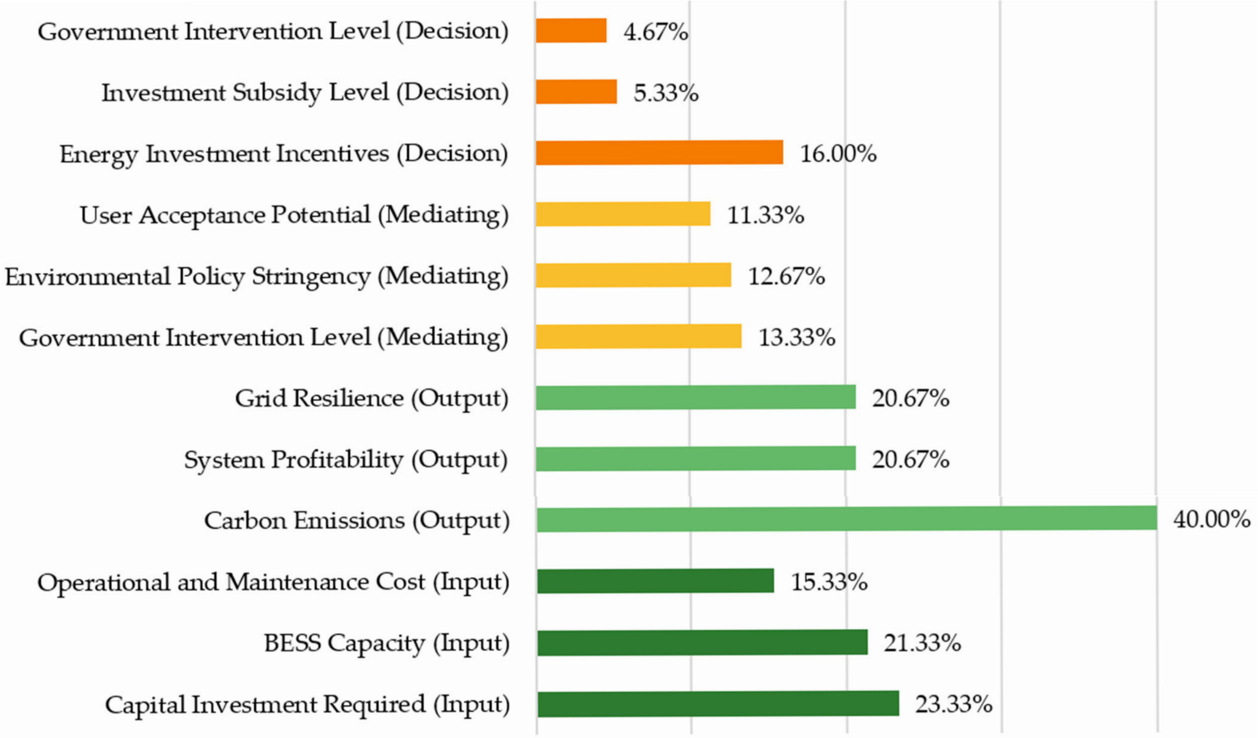

Figure 7. Most frequently occurring factors by analytical role (Values represent the percentage of studies in which each factor is assigned to the corresponding role. Colors indicate the analytical role (input, output, mediating, and decision factors). Some factors appear in multiple roles, reflecting their context-dependent function across different studies.

An additional dimension of the analysis concerns the consistency of factor roles across studies. Table 8 summarizes the variables that most consistently occupy a single role, measured as the proportion of their occurrences assigned to that function.

The results also reveal a clear distinction between structurally stable and context-dependent variables. Core technical inputs and performance outputs show high consistency, indicating a strong consensus regarding their essential role within energy system models.

In contrast, policy and economic variables display greater variability, shifting between roles depending on the analytical framework and research objective.

Table 8. Factors with the highest role consistency across studies.

Input			**Output**		
Factor	*N*	%	*Factor*	*N*	%
Capital Investment Required	35	100%	System Reliability	18	100%
Solar Radiation	14	100%	Load Capacity Factor	12	100%
Wind Installed Capacity	13	100%	Carbon Emission Intensity	9	100%
State of Charge	11	100%	Operational Cost Savings	8	100%
Hydrogen Storage Capacity	9	100%	Voltage Deviation	8	100%
Mediating			**Decision**		
Factor	*N*	%	*Factor*	*N*	%
Coal Cost	1	100%	Investment Subsidy Level	8	100%
Critical Mineral Dependency	1	100%	Operational Subsidy Level	6	100%
Short-Circuit Current	1	100%	Low-Income Household Energy Subsidy	6	100%
Climate Policy Uncertainty	5	83%	Government Support Ratio	2	100%
Energy Policy Uncertainty	4	80%	Energy Investment Incentives	24	75%

This variability reflects the flexible nature of policy-related factors, which may act either as external conditions, mediating mechanisms, or decision levers depending on the study context. These findings underscore the need for a structured framework that captures both stable and context-dependent relationships.

Overall, the role-based analysis reinforces the value of the proposed ontology, which provides a systematic representation of how variables contribute to energy policy modeling and bridges the gap between conceptual research questions and empirical implementation. These results also offer a consistent basis for comparison with existing frameworks and datasets.

4. Conclusions and Discussion

4.1. Conclusions

This study develops a multidimensional ontology that links policy-oriented research questions with standardized analytical factors and the roles these factors perform within quantitative energy models. By structuring these three elements within a common framework, the study addresses the fragmentation of terminology and analytical practices that currently limit comparison across energy policy studies.

Our findings indicate that recent quantitative energy policy research is built around a recognizable analytical core, while retaining substantial flexibility across topics, models, and geographical contexts. Factors such as carbon emissions, capital investment requirements, and system profitability recur across the reviewed literature, but their relative importance and analytical function vary according to the research question and modeling context. Input and output roles predominate, whereas mediating mechanisms and directly controllable policy variables are represented less frequently. Rather than indicating a deficiency in the literature, these patterns illustrate how the reviewed studies primarily organize analysis around system conditions and measurable outcomes.

The main contribution of the ontology lies in its capacity to preserve this contextual flexibility while providing a standardized analytical language. For researchers, it supports a more transparent comparison of how variables are defined and used across studies. For policymakers and model users, it clarifies whether a factor operates as an external condition, an outcome, an explanatory mechanism, or an intervention lever. The framework, therefore, provides a structured connection between policy problem formulation and quantitative model implementation.

The geographical analysis further shows that analytical priorities vary within the reviewed sample, although these differences should be interpreted cautiously because of the uneven regional distribution of the articles. In parallel, the comparison with the IPCC AR6 Scenario Explorer indicates that the ontology is broadly consistent with established techno-economic modeling terminology, while also highlighting opportunities to improve the representation of socio-political and emerging technological dimensions.

Overall, the proposed ontology provides a transparent and adaptable basis for organizing recent energy policy research and supporting more systematic model-based policy analysis.

4.2. Limitations

Several limitations should be acknowledged. First, the analysis is restricted to a dataset of 150 articles published between December 2024 and June 2025. Although this time window was deliberately selected to capture the latest trends and emerging analytical developments in energy policy research, it limits the representativeness of the findings across the broader literature and does not allow long-term trends to be inferred.

Second, restricting the review to English-language, peer-reviewed, and quantitative studies may have excluded relevant evidence published in other languages or developed through qualitative and mixed-method approaches, particularly research addressing institutional, social, and context-specific dimensions of energy policy.

Third, the geographical distribution of the reviewed articles is uneven, with a substantial concentration of studies focused on China and smaller numbers of articles representing the remaining geographical categories. Consequently, the detailed regional comparison was limited to China, Europe, and the Middle East, the three most represented categories in the dataset. In addition, the Rest of World category aggregates heterogeneous geographical contexts, which limits its suitability for direct regional comparison.

Fourth, the observed distribution of analytical roles may also be influenced by the composition of the reviewed literature, which primarily comprises quantitative empirical, econometric, optimization, and simulation-based studies. These methodological approaches tend to define system inputs and measurable outputs explicitly, which may partly explain their higher frequency relative to mediating and decision factors.

Finally, although the extraction and classification process followed a structured methodology, the identification of research questions, consolidation of factors, and assignment of analytical roles inevitably involved a degree of interpretative judgment. To improve consistency, factor consolidation was based on definitions and analytical meaning, and the resulting ontology was cross-checked against the variables included in the IPCC AR6 Scenario Explorer.

These limitations define the scope within which the findings should be interpreted. The regional results and the distribution of analytical roles provide meaningful insights into the structure of the reviewed literature, while further research using broader temporal, geographical, and methodological coverage would be valuable to assess the extent to which these patterns apply across the wider energy policy field.

4.3. Future Research

Future research could extend the proposed framework through the integration of artificial intelligence and natural-language processing techniques aimed at automating the interpretation and operationalization of policy-oriented research questions.

In particular, the development of Natural-Language (NL) interfaces for energy models could enable the direct translation of policy-oriented research questions into model configurations. For example, a query such as: “What level of investment subsidy (€/MW) is required to achieve a 10% reduction in annual CO_2 emissions for a 100 GW solar portfolio?” could be automatically parsed to identify the relevant factors—such as investment subsidy level, CO_2 emissions, and solar capacity—and translated into appropriate model inputs.

Such an NL-to-model translator would facilitate a more direct connection between policy analysis and quantitative modeling, improving accessibility and decision-support capabilities. Further extensions could involve the use of machine-learning techniques to enhance natural-language parsing and mapping accuracy, enabling the system to handle diverse question formulations and model structures.

Additionally, machine-learning approaches could be applied to automatically identify and classify factor roles based on textual and metadata cues, reducing ambiguity and improving consistency in the analytical process. Beyond AI integration, future work could also expand the dataset to include a broader range of journals and geographic contexts, as well as incorporate underrepresented socio-political and technological variables.

Together, these developments would strengthen the robustness and applicability of the proposed framework, contributing to more advanced and scalable approaches to energy policy analysis.

Overall, our results demonstrate that a structured ontology linking research questions, analytical factors, and model roles can significantly enhance the clarity, consistency, and policy relevance of energy policy analysis. By providing a common analytical language across heterogeneous modeling approaches, the proposed framework contributes to a more transparent, interoperable, and actionable understanding of the global energy transition.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su18136648/s1, Dataset S1: Global Energy Policy Ontology and Factor Analysis Dataset.

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References

1. European Commission. *REPowerEU Plan*; European Commission: Brussels, Belgium, 2022. Available online: https://ec.europa.eu/commission/presscorner/detail/en/IP_22_3131 (accessed on 23 April 2026).
2. International Energy Agency. *World Energy Outlook 2024*; IEA: Paris, France, 2024. Available online: https://www.iea.org/reports/world-energy-outlook-2024 (accessed on 23 April 2026).
3. Harichandan, S.; Kar, S.; Bansal, R.; Mishra, S.; Balathanigaimani, M.S.; Dash, M. Energy transition research: A bibliometric mapping of current findings and direction for future research. *Clean. Prod. Lett.* **2022**, *3*, 100026. [CrossRef]

4. Ahlborg, H.; Michael, K.; Unsworth, S.; Hategekimana, S.; Osunmuyiwa, O.; Åberg, A.; Hultman, M. Thirty-five years of research on energy and power: A landscape analysis. *Renew. Sustain. Energy Rev.* **2024**, *199*, 114542. [CrossRef]
5. Tabrizian, H.; Amiri, B.; Abdolhamid, M. Navigating the landscape of energy governance: A bibliometric analysis of research trends and future directions. *Energy Rep.* **2024**, *12*, 6–18. [CrossRef]
6. Tan, H.; Li, J.; He, M.; Li, J.; Zhi, D.; Qin, F.; Zhang, C. Global evolution of research on green energy and environmental technologies: A bibliometric study. *J. Environ. Manag.* **2021**, *297*, 113382. [CrossRef] [PubMed]
7. Okulich-Kazarin, V.; Artyukhov, A.; Artyukhova, N.; Wołowiec, T.; Skrzypek-Ahmed, S. Charting the Global Energy Economy Research: Trends, Gaps, and Paradigm Shifts. *Energies* **2025**, *18*, 3438. [CrossRef]
8. Ghazinoori, S.; Roshani, S.; Hafezi, R.; Wood, D.A. Bursting into the Public Eye: Analyzing the Development of Renewable Energy Research Interests. *Renew. Energy Focus* **2023**, *47*, 100496. [CrossRef]
9. Mentel, G.; Lewandowska, A.; Berniak-Woźny, J.; Tarczyński, W. Green and Renewable Energy Innovations: A Comprehensive Bibliometric Analysis. *Energies* **2023**, *16*, 3142. [CrossRef]
10. Androniceanu, A.; Veith, C.; Ionescu, Ș.; Marinescu, P.; Sima, A.; Paru, A. Shaping Sustainable Futures: Public Policies and Renewable Energy Insights Based on Global Bibliometric Analysis. *Sustainability* **2024**, *16*, 4957. [CrossRef]
11. Alcayde, A.; Montoya, F.G.; Baños, R.; Perea-Moreno, A.-J.; Manzano-Agugliaro, F. Analysis of Research Topics and Scientific Collaborations in Renewable Energy Using Community Detection. *Sustainability* **2018**, *10*, 4510. [CrossRef]
12. Novas, N.; Alcayde, A.; Robalo, I.; Manzano-Agugliaro, F.; Montoya, F.G. Energies and Its Worldwide Research. *Energies* **2020**, *13*, 6700. [CrossRef]
13. Sovacool, B.; Hess, D.; Amir, S.; Geels, F.; Hirsh, R.; Medina, L.; Miller, C.A.; Palavicino, C.A.; Phadke, R.; Ryghaug, M.; et al. Sociotechnical agendas: Reviewing future directions for energy and climate research. *Energy Res. Soc. Sci.* **2020**, *70*, 101617. [CrossRef]
14. Hirt, L.F.; Schell, G.; Sahakian, M.; Trutnevyte, E. A review of linking models and socio-technical transitions theories for energy and climate solutions. *Environ. Innov. Soc. Transit.* **2020**, *35*, 162–179. [CrossRef]
15. Tavana, M.; Shaabani, A.; Santos-Arteaga, F.J.; Raeesi Vanani, I. A Review of Uncertain Decision-Making Methods in Energy Management Using Text Mining and Data Analytics. *Energies* **2020**, *13*, 3947. [CrossRef]
16. Yu, Y.; Chen, K.; Liao, J.; Zhu, W. Detecting the research trends and evolution of energy resilience: A bibliometric analysis. *Environ. Sci. Pollut. Res.* **2022**, *30*, 23768–23785. [CrossRef] [PubMed]
17. Dominković, D.F.; Weinand, J.M.; Scheller, F.; D'Andrea, M.; McKenna, R. Reviewing two decades of energy system analysis with bibliometrics. *Renew. Sustain. Energy Rev.* **2022**, *153*, 111749. [CrossRef]
18. Kang, J.-N.; Wei, Y.-M.; Liu, L.-C.; Han, R.; Yu, B.; Wang, J.-W. Energy systems for climate change mitigation: A systematic review. *Appl. Energy* **2020**, *263*, 114602. [CrossRef]
19. Entezari, A.; Aslani, A.; Zahedi, R.; Noorollahi, Y. Artificial intelligence and machine learning in energy systems: A bibliographic perspective. *Energy Strategy Rev.* **2023**, *45*, 101017. [CrossRef]
20. Byers, E.; Krey, V.; Kriegler, E.; Riahi, K.; Schaeffer, R.; Kikstra, J.; Lamboll, R.; Nicholls, Z.; Sanstad, M.; Smith, C.; et al. *AR6 Scenarios Database Hosted by IIASA*; International Institute for Applied Systems Analysis: Laxenburg, Austria, 2022. [CrossRef]
21. Santos Oliveira, D.; Lumbreras, S.; Alvarez, E.F.; Ramos, A.; Olmos, L. Model-based energy planning: A methodology to choose and combine models to support policy decisions. *Int. J. Electr. Power Energy Syst.* **2024**, *159*, 110048. [CrossRef]