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D.1.1 - SYSTEMATIC LITERATURE REVIEW OF STUDIES AT THE NEXUS OF GENDER EQUALITY AND SUSTAINABLE ENERGY SYSTEMS AND ONTOLOGY OF ENERGY SYSTEMS

WP1 – Gendered analysis of knowledge creation landscape for energy transition

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1. INTRODUCTION

The gEneSys' project deliverable 1.1. (D1.1 thereafter) entitled "Systematic literature review of studies at the nexus of gender equality and sustainable energy systems and ontology of energy systems" brings together the work performed by Task 1.1 (Systematic literature review to design analytical framework for review of EU and national energy transition-related policy frameworks) and Task 1.2. (Defining the mission, agendas, and identifying the change actors in the evolution to sustainable energy systems) in the first eight months since the project's onset. This makes D1.1 deliverable particularly long and rich in insights. Indeed, the afore-mentioned tasks had the overarching goal of setting the groundwork for the tasks and deliverables coming later in the project's lifecycle. However, it is worth noting that the two tasks focused on different aspects and dimensions.

The ontology task was intended to deliver a comprehensive picture of objects and relationships in the energy transition domain and try to delimitate the area of action of the gEneSys project in transforming gendered power relations in energy transition pathways. In other words, the ontology probes what are the key concepts emerging in the extant literature on energy transition and how these concepts are interrelated. The ontology can also unveil missing or overlooked concepts that can be brought to the forefront in future research. Another scope of the ontology is also the establishment of a "common language" for the project, with a set of terms and related definitions. Although not focusing specifically on the gender dimensions, the energy transition ontology can be considered as a guidance to navigate the energy transition knowledge domain. However, it should not be assumed as an immutable output; rather it can be expanded and enriched with new analyses or conceptualizations.

On the other hand, the literature review task has looked specifically into the state of knowledge at the nexus between gender and energy transition, by examining how this nexus has been disentangled in scientific publications as well as in the grey literature. As shown in the sections below, scientific publications were sifted through using a systematic literature review (SLR) methodology (Mengist et al. 2020) which allows answers to formulated research questions by defining search strings and identifying specific eligibility and quality assessment criteria for inclusion/exclusion of search results. SLRs can be accompanied by meta-analyses that generate qualitative and quantitative data on the topic under examination. This results in a mix of qualitative and quantitative findings that deliver a more complete overview. The preliminary analysis of the available knowledge on the nexus between gender and energy transition made evident the relevance of grey literature (e.g., reports by international organizations such as IRENA) that have often tackled this topic from a specific perspective. For this reason, the Task's team has deemed it critical to expand the task to include an analysis of these resources. Taken together, the SLR and the grey literature review shed light on (i) how the nexus between gender and energy transition is framed (e.g., which subsystems are more frequently represented when addressing the interplay between the two dimensions?); (ii) what are the findings of the current analyses; (iii) what are the recommendations put forward in terms of future research or policies to be implemented, and (iv) what are the research gaps that still need to be investigated or anyway need more research to be assessed?

This deliverable is organized as follows. Section 2 will describe the results of the energy system ontology (ESO). Section 3 and section 4 will delve into the relationship between gender and energy transition as framed in the extant knowledge, both in terms of systematic review of scientific publications and of review of grey literature. Finally, section 5 concludes with general considerations.

2. ONTOLOGY OF ENERGY SYSTEM

The ontology of energy system is the main outcome of Task *1.2 "Defining the mission, agendas, and identifying the change actors in the evolution to sustainable energy systems"* included in the *Work Package 1 - Gendered analysis of knowledge creation landscape for energy transition*. According to Gruber (Gruber, 1993) and Borst (Borst, 1997), an ontology is an explicit, formal specification of a shared conceptualization. Indeed, it is a conceptual model of a fragment of an observed reality gathering interlinked concepts pertaining to a given application domain (De Nicola & Missikoff, 2016). In general, the goal of an ontology in a research project is to facilitate effective exchange of knowledge between scholars with different disciplinary backgrounds. In this way, the construction of an ad-hoc ontology will support a common conceptual background for the analysis of the challenges to be faced by the project' partners in the identification of possible, inclusive and sustainable energy transition pathways.

In gEneSys, an ontology of energy system is mainly needed **to set the scope of the domain to be analysed in the subsequent tasks and in the work packages of the project**. In particular, the Energy System Ontology (ESO) is essential **to pave the way for identifying, at a later stage, the energy transition Change Agents, both within the knowledge community and in the society at large**. Indeed, the ESO will enable gender-specific assessments of the energy-systems-knowledge-community through advanced semantic social network analysis (task **T1.3**) and of the stakeholder organisations operating in sustainable energy systems through a survey (task **T1.5**).

There is no agreement at present on the definition of energy transition since the meaning of this process has changed over time along with the progressive transformations in the energy sources used and of the technologies to store and distribute them. The Glossary of the Intergovernmental Panel on Climate Change (IPCC) defines transition as "*The process of changing from one state or condition to another in a given period of time*", adding however an important character of change, i.e., "*Transition can occur in individuals, firms, cities, regions and nations, and can be based on incremental or transformative change.*" (IPCC, 2023). Certainly, the current focus in the definition of energy transition pertains to the shift from a system dominated by finite (mainly fossil-based) energy toward a system that mostly uses renewable energy sources. For example, the Urban Innovative Action (UIA) (European Regional Development Fund, 2023), an EU initiative that aims to test solutions in urban areas, underlines the scope of maximising the opportunities available from increased energy efficiency and better management of energy demand. Moreover, the inclusion of components related to changes in technology and/or economy can be found in the definition of energy transition by Araújo (2014) as "*a shift in the nature or* *pattern of how energy is utilised within a system*", which "*recognizes the change associated with fuel type, access, sourcing, delivery, reliability or end use as well as with the overall orientation of the system. Change can occur at any level – from local systems to the global one – and is relevant for societal practices and preferences, infrastructure, as well as oversight*". Worth noting is, in this case, the addition of the definition of energy system seen as "*a constellation of energy inputs and outputs, involving suppliers, distributors, and end users along with institutions of regulation, conversion and trade*" fra

This brief overview of the different components related to the apparently simple definition of energy transition shed a light on the mixed and interconnected factors that need to be taken into consideration when it comes to modelling the energy domain. This is also well described in Pfenniger et al. (2014) and in Booshehri et al. (2021) who provide an overview of the gradual additions of the different perspectives needed to model the complexity of this domain.

Even if, according to perspectivism (Nehamas, 2000), the understanding of a subject is inherently partial and constrained by the individual perspective through which it is observed, the objective of ESO is to put together these different views and build a comprehensive and coherent ontological model of the energy system subject, with a specific focus on energy transition pathways.

In the first section of this chapter, we present a brief state-of-the-art account on energy ontologies to present the existing ontologies built to-date to motivate the need of a new ontology for this specific sector. Then, in the second section, we present the conceptual model of energy transition that we have developed to highlight the inherent multidisciplinary nature of the energy domain. In the third section, we present the stepwise ontology engineering methodology that we followed to build the ESO. The corresponding steps are aimed to construct, respectively: the lexicon, the glossary, the taxonomy, the semantic network, and, finally, the ontology. All these steps are described in the fourth section. Finally, in the fifth section, we provide some conclusions and some possible research directions.

2.1 State of the Art on Energy Ontologies

There is a consistent number of ontologies which provide a knowledge representation of energy systems at different levels of detail. Some of them link the energy domain with other domains such as environment, health, economy and market, while others focus on specific aspects such as household or smart cities, where energy systems play an intersectional role.

Moreover, these ontologies have been developed for different aims, such as facilitating the interoperability of different data sources (Brutti, Frascella, & Gessa, 2020), supporting applications for decision making (De Nicola & Villani, 2021b), or facilitating the communication among the different stakeholders by providing a common glossary of concepts and their relationships (Booshehri, et al., 2021).

In the case of the gEneSys project, the analysis of existing ontologies has a twofold purpose. On the one hand, it intends to highlight possible gaps in the existing knowledge representations that need to be covered by the gEneSys Energy System

Ontology. On the other hand, it intends to explore possible interconnections with existing ontologies that might be integrated in the gEneSys ontology.

Point of reference for the extractions of the links and information on existing ontology were the literature reviews conducted by De Nicola and Villani (2021a) and by Pritoni et al. (2021) which, even if sometimes specifically focused on specific aspects of the energy domain, do provide an important overview of the state of the art of research in this field.

In the following paragraphs, we provide the results of our analysis reporting the selected ontologies together with a brief description. We also distinguish between the ontologies that make their content publicly available on the web and those described in scientific papers. We excluded the scientific articles that described early efforts or proposed an ontological model at the first stage of development.

Open access ontologies

- Open Energy Ontology (OEO)

Open Energy Ontology (OEO) (Booshehri et al., 2021) is a domain ontology in OWL (W3C, 2012), which supports research in energy system modeling. It is part of the Open Energy Family (Open Energy Family, 2023), i.e., an Open Source toolbox and database for open data in the field of energy and climate. The main module of this tool box is the Open Energy Platform (Open Energy Platform, 2023), a web interface, which allows access to the modules: a) oeo-model that comprises entities related to data and models, b) oeo-social that describes social, economic and political entities involved in energy systems; c) oeo-physical that includes the physical world of energy system. The ontology provides a controlled vocabulary with clear definitions of terms and relationships between those terms. Data annotation adds the possibility of enhanced searching functions and logical querying across data sets. The OEO development was initiated in the project "SzenarienDB" and is augmented in the projects "LOD_GEOSS" and "SIROP".

Currently, OEO is a collaborative community effort that takes place on GitHub (https://github.com/OpenEnergyPlatform/).

- Environment Ontology (ENVO)

Environment Ontology (ENVO) (ENVO, 2016) (Buttigieg PL, 2016) is a community ontology that enables the understanding of different environmental entities. It enables interoperability for everything related to the environment, offering representations of habitats, anthropogenic environments and environmental health in relation to the Global Agenda for Sustainable Development for 2030. Since 2016, ENVO is using OWL and the Basic Formal Ontology (BFO) to connect its 2159 classes.

- ETS-Related European ONtology (EREON)

EREON (De Nicola & Villani, 2021b) (Camporeale, De Nicola, & Villani, 2015) is an ontology to represent the trading of allowances by enterprises within the EU Emissions Trading System (EU ETS). This is a first effort aimed at putting together concepts related to energy and low-carbon technologies, air quality and policies relating to climate change.

- Sustainable Development and Climate (SDC)

Sustainable Development and Climate (SDC) (SDC, 2023) is an ontology that semantically models the interactions of climate change on food, water, and energy systems, which could affect people, resources and the environment, and assess their impacts. It works to ensure interoperability among them, by extending higher-level entities and reusing resources from Common Core Ontologies (Rudnicki, 2019).

- ThinkHome

ThinkHome (Technische Universitat Wien, 2023) is an ontology, consisting of seven subdomains: (i) weather and exterior influences; (ii) resource, facilities and appliances; (iii) architecture and building physics; (iv) building processes; (v) energy consumption and energy production; (vi) user behavior; and (vii) user preferences. It provides a knowledge model on energy consumption and production related to buildings under the perspective of energy efficiency and control mechanisms for homes.

- **PowerOnt**

PowerOnt is an ontology, integrated with DogOnt, that addresses the issue of energy consumption in smart homes (smart houses) and smart environments (PowerOnt, 2008) (Bonino & Corno, 2008) (Bonino, Corno, & De Russis, 2015). DogOnt is able to face interoperation issues allowing to describe: where a smart device is located; the set of capabilities of a smart device; the technology-specific features needed to interface the device; the possible configurations that the device can assume; how the surrounding environment is composed; what kind of architectural elements and furniture are placed inside the home, if the environment considered is a home.

- SAREF4ENER

SAREF4ENER (SAREF4ENER, 2023) (Daniele, 2020) is an ontology developed as an extension of Smart Appliance REFerence (SAREF) (Daniele, 2015) (SAREF, 2023). With the aim of increasing interoperability, it provides concepts related to smart appliances to optimize energy consumption and production and, hence, dealing with energy, environment, building and smart cities domains.

Other ontologies described in scientific articles

- The **Energy Knowledge Graph (EKG)** is an integrated conceptual model, based on an ontological model, proposed in (Chun, Jung, Jin, Seo, & Lee, 2020) to modulate a classification of services in microgrids, through different entities, such as resource, service, smart grid, and so on, with their respective relationships. The integrated conceptual model includes the following 8 concepts: smart grid entity, resource, service, process, event, smart grid participant, community, and devices.

- **DEHEMS** (Shah, Chao, Matei, & Zlamaniec, 2011) is an ontology, funded by the European Union (EU), that addresses the issue of data deduced from energy consumption and energy efficiency of devices.

- **Smart City Ontology (SCO)** (SCO, 2015) is an ontology that provides a knowledge representation of Smart City and identifies the components and processes used to integrate the different dimensions - physical, social and digital - of the smart city. Its origin dates back to 2015 with SCO 1.0, which aimed to evaluate the electronic applications and services of the smart cities. Currently, SCO 2.0 identifies areas where smart solutions enable the improvement of the digital infrastructure and innovative electronic services.

Key insights into the state of the art of energy ontologies

Our analysis of the energy ontologies landscape has yielded the following key insights. Most of the existing ontologies mainly refer to the technological aspects of the energy domain and are used for technical issues, such as systems interoperability. There are only a few partial attempts to address the domain by means of a multi-disciplinary perspective. Hence, the above-mentioned considerations led us to better focus our work. In detail, **considering that the modelling of technological aspects is a prerequisite of the ontology, the aim of ESO is to represent the energy system by incorporating a multi-disciplinary perspective and by highlighting the interconnections and interdependencies between the various sub-systems that compose it.** Indeed, for the overall purpose of the gEneSys project, the interconnection with gender mainstreaming related to social equity and just energy transition makes it necessary to emphasise the socio-technical and eco-political aspects of the energy system along with their interdependences with the related domains that influence the dynamic of this ecosystem.

2.2. A Conceptual Framework for building the Energy System Ontology

As mentioned in the introduction of this Chapter, a milestone towards the construction of the Energy System Ontology was the definition of the conceptual framework of energy transition consisting of layers (or subsystems). Indeed, the aim of this conceptual framework is to highlight the inherent multidisciplinary nature of the energy domain. This was developed by the ENEA team for the gEneSys project following a literature review, with the aim of striking a balance between the specificity of the identified layers and the generality (i.e., high level representation) of the overall framework.

The conceptual framework (see Figure 1) identifies five layers that expose the complexity of this research area: the environmental, the strategy, the policy, the behavior and the operational layers. This five layer are based on the subsystems identified in the gEneSys proposal adapted to the onthology design needs. The environmental layer covers the area of environmental concerns, ranging from climate change and pollution. The energy strategy layer deals with the concepts related to different broad plans or approaches designed to achieve specific energy-related objectives, such as energy transition or energy security. The policy layer covers the measures adopted at national and international level to support the energy strategy goal. In case of energy transition, this layer includes concepts such as incentives and penalties. The behaviour layer deals with the conduct and attitude of the market as well as of groups and individuals in response to the demand and use of energy, the enforcement of regulations related to energy transition. The operational layer deals with the concepts related to the technological and organizational aspects of the energy value chain.

These layers are all interlinked (see Figure 1) and, in most of the cases (such as between the environmental and the operational layers), there exists a mutual relationship (represented by the bidirectional arrows**Errore. L'origine riferimento non è stata trovata.**). Indeed, the energy operations influence the environmental conditions and vice versa the environmental conditions affect energy operations. For instance, the use of coal for power generation has an impact on CO_2 pollution, whereas extreme weather conditions, such as heat waves, can lead to increased energy production to power air conditioners (see links 1(a) and 1(b) in Figure 1).

The energy strategy layer depends on the energy operational layer. Indeed, energy operations could also affect energy strategy definition. For instance, if fusion power generation were to become a viable and widely adopted technology, it could lead some countries to reconsider and potentially change their energy strategies. Hence, this technological advancement could involve reducing their reliance on specific energy sources (see link 2 in Figure 1).

There is also a mutual interdependency between the energy operational layer and the policy layer. For instance, the availability of new eco-friendly appliances may prompt a government to introduce new incentives for their purchase. On the other hand, policies aimed at encouraging the adoption of certain technologies, such as electric cars, can stimulate additional innovation within the sector (see links 3(a) and 3(b) in Figure 1).

The energy operational layer also affects the energy behavior one. For example, the absence of energy services resulting from blackouts or outages can impact citizens' energy consumption levels. Conversely, an increase in energy demand due to misuse can lead to a higher production of energy in power plants (see links 4(a) and 4(b) in Figure 1).

The energy behavior layer can influence the environmental layer, e.g., the subsidized oil market, or energy waste can cause higher levels of pollution and contribute to climate change. At the same time, environmental and climate issues can influence the energy behavior layer by transforming citizens' behaviors with respect to energy consumption both in the sense of increased sustainability (preferring more efficient and less contaminating appliances and means of transportation), but also in the sense of increased consumption (increased use of air conditioning due to high temperature) (see links 5(a) and 5(b) in Figure 1).

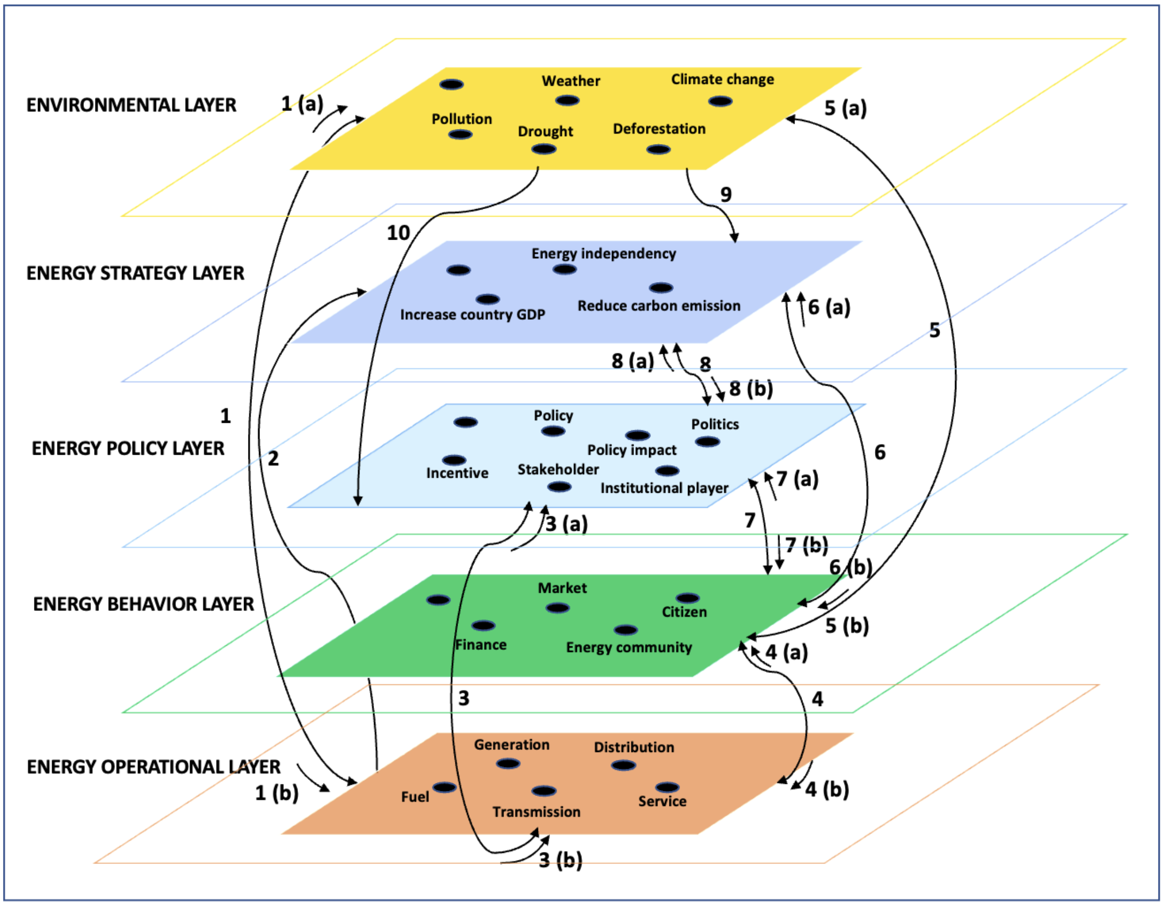
A mutual interdependency can also be found between the energy strategy layer and the energy behavior layer. For example, increases in energy sales prices on the market have an impact on a country's DGP targets, while, in turn, energy independence strategies, such as the interruption of energy trading between certain countries, can affect the behavior of finances in the energy sector (see links 6(a) and 6(b) in Figure 1).

There is also interdependence between the energy behavior layer and the energy policy layer. An example is the creation of energy communities as a response to the measures adopted by institutional bodies (national and local authorities), such as incentives, tax deductions and promulgation of laws to encourage the production and consumption of renewable energy. In turn, energy communities are active subjects who are putting pressure on institutions to fill legal gaps and improve energy transition policies (see links 7(a) and 7(b) in Figure 1).

In the same way, the energy strategy layer influences the energy policy layer, for example an energy independence strategy can lead a country to implement local energy production policies based on the energy resources available on the national territory (solar, wind). The energy policy layer in turn influences the energy strategic layer because national governments establish the terms and timing for achieving emissions reduction objectives, such as Net Zero (see links 8(a) and 8(b) in Figure 1).

The energy strategy layer depends on environmental layer to the extent that certain environmental concerns, such as the demonstrated increase in global temperatures, lead to a shift in energy strategies from those linked exclusively to access and availability of energy (energy security) to strategies that also include the sustainability of energy systems among their objectives (energy transition) (see link 9 in Figure 1).

The environmental layer influences the energy policy layer. For example, the high concentration of pollution due to emissions produced by fossil fuels can lead to the creation of a system of penalties and incentives for companies that favor the transition towards so-called clean energies (see link 10 in Figure 1).



1 (a)	Energy operations have an impact on environmental conditions.
1 (b)	Environmental conditions affect energy operations.
2	Energy operations affect energy strategy definition.
3 (a)	Energy operations affect energy policy definition.
3 (b)	Energy policies affect energy operations.
4 (a)	Energy operations affect energy behavior.
4 (b)	Energy behavior affects energy operations.
5(a)	Energy behavior has an impact on environmental conditions.
5(b)	Environmental conditions influence energy behavior.
6 (a)	Energy behavior influences energy strategy definition.
6 (b)	Energy strategy affects energy behavior.
7 (a)	Energy behavior influences energy policy definition.
7 (b)	Energy policies affect energy behavior.
8 (a)	The impact of energy policies affects energy strategy definition.
8 (b)	Energy strategy drives energy policy definition.
9	Environmental conditions affect energy strategy definition.
10	Environmental conditions affect energy policy implementation.

Row affects column	Environmental layer	Energy strategy layer	Energy policy layer	Energy behavior layer	Energy operation layer
Environmental layer		9	10	5b	1b
Energy strategy layer	-		8b	6b	-
Energy policy layer	-	8a		7b	3b
Energy behavior layer	5a	6a	7a		4b
Energy operation layer	1a	2	3a	4a	

Figure 1. Conceptual framework for building the Energy System Ontology

2.3. The Ontology Engineering Methodology adopted to build the Energy System Ontology

According to (De Nicola & Missikoff, 2016), an ontology is a (fragment of) an observed reality gathering interlinking concepts pertaining to a given application domain. To build the Energy System Ontology (ESO), we adopted an ontology engineering methodology, which is a systematic approach for designing, developing, and maintaining an ontology. This methodology ensures both the reproducibility and the quality of the achieved result (i.e., the built ontology). In the existing literature, there are several methodologies available for building ontologies. Among them, we can identify: Methontology (Fernández-López, Gómez-Pérez, & Juristo, 1997), OntoKnowledge (Sure, Staab, & and Studer, 2004), UPON (De Nicola, Missikoff & Navigli, 2009) NoOn (Suárez-Figueroa, Gómez-Pérez, & and Fernández-López, 2012), GOSPL (Debruyne, Tran, & and Meersman, 2013), Diligent (Tempich, Simperl, Luczak, Studer, & Pinto, 2007), and UPON lite (De Nicola & Missikoff, 2016). However, most of them are quite complex, time consuming and conceived more for skilled ontology engineers rather than for domain experts. Hence, we began with UPON Lite, a lightweight methodology designed for swift ontology engineering, and tailored it to accommodate the unique aspects of the energy system domain, the team of individuals participating in the development, and the availability of automated tools that guarantee rapid and dependable outcomes.

Indeed, similarly to UPON Lite, the adopted methodology requires both the competences of a mixed team of knowledge engineers and domain experts (De Nicola, Missikoff, & Navigli, 2009; De Nicola & Missikoff, 2016). It consists of five steps that are described as follows:

1. **Lexicon construction**. In this step, the aim is to extract some of the most relevant keywords characterizing the domain of energy systems and categorize them into the five subsystems of energy transition (i.e., environment, strategy, policy, behavior, and operations) by means of a voting procedure involving 6 domain experts. This step is partially automated since keywords can be retrieved from large scientific repository, such as SCOPUS (Scopus, 2023) or Web of Science (Clarivate, 2023).
2. **Glossary construction**. Here, the aim is to give a definition to the keywords collected in the previous step. Leveraging the classification into subsystems, each keyword is assigned to a domain expert, in charge of defining the concept. To this purpose, existing vocabularies and thesauri (e.g., WordNet (WordNet, 2023)) and ontologies (Open Energy Ontology (Booshehri, et al., 2021)) have been taken into the account, as well as automatic tools such as ChatGPT (OpenAI, 2023).
3. **Taxonomy construction**. In this step, concepts are organized in a generalization/ specialization (IsA) hierarchy. To guarantee semantic correctness, a foundational ontology, i.e., Basic Formal Ontology (BFO) was also adopted.
4. **Semantic network**. Here, the purpose is to enrich the semantic expressivity of the ontology with domain specific relationships. For this purpose, we identified 18 ontology design patterns tailored for the energy transition domain. An ontology design pattern is a reusable and structured modeling solution,

designed to capture common relationships and concepts, facilitating the development of ontologies (De Nicola & Missikoff, 2016). These patterns will be the backbone of ESO.

5. **Ontology**. The last step is devoted to implementing the ontology in a formal language, such as RDF or OWL. To facilitate this activity, we used the Protégé Ontology Management System (Stanford University, 2023).

The adopted ontology engineering methodology is sketchily depicted in Figure 2. In the next section, the implementation of each step is described in detail.

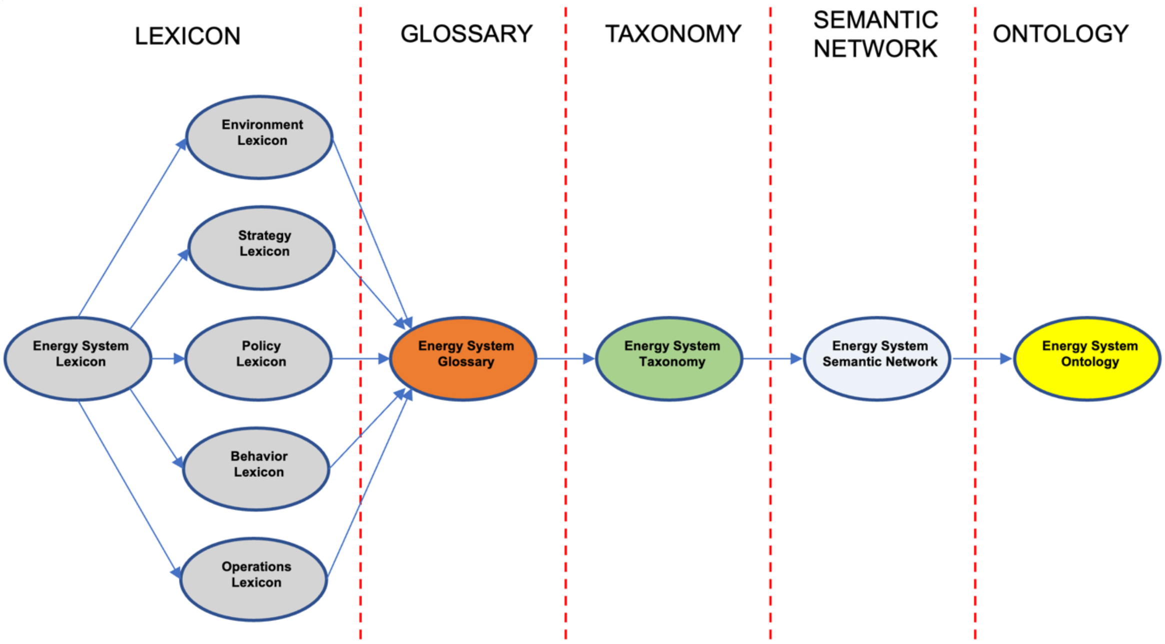


Figure 2. Ontology engineering methodology used for building the Energy Systems Ontology

2.4. Building the Energy System Ontology

In this Section, the implementation of the five above-mentioned ontology engineering steps is described in detail.

2.4.1 Construction of the Energy Systems Lexicon

To define the scope of the energy transition domain we used a bottom-up approach. To this purpose, we run a query on Scopus to retrieve the bibliometric information related to all the papers that contain the terms: “energy transition” OR “energy transformation”. The query was run on 17th March 2023. We retrieved information related to 17591 papers (see Figure 3). Among them, only 15367 are indexed by Scopus with keywords. 12872 papers were published in journals, 2097 in conferences, and 215 in books. Overall, the number of conferences is 909, the number of journals is 3023, and that of books is 215. Figure 4 shows the distribution of journal papers and the most frequent journals where papers on the “energy transition/transformation” appear. Among the most frequent journals for these topics, we found: Energies (685 papers), Energy research and social science (610 papers), Energy policy (516 papers), Sustainability (373 papers), and Renewable and sustainable energy reviews (253 papers). Figure 5 shows the distribution of the papers by year, indicating a significant surge in the number of papers on energy transition in the most recent years.

The overall number of keywords associated with these 15367 papers are 58226. Hence, we decided to consider only those keywords occurring more than 6 times. These are 4582. Most of the keywords are not frequent. The most frequent keywords (i.e., "*energy transition*") occur 5805 times.

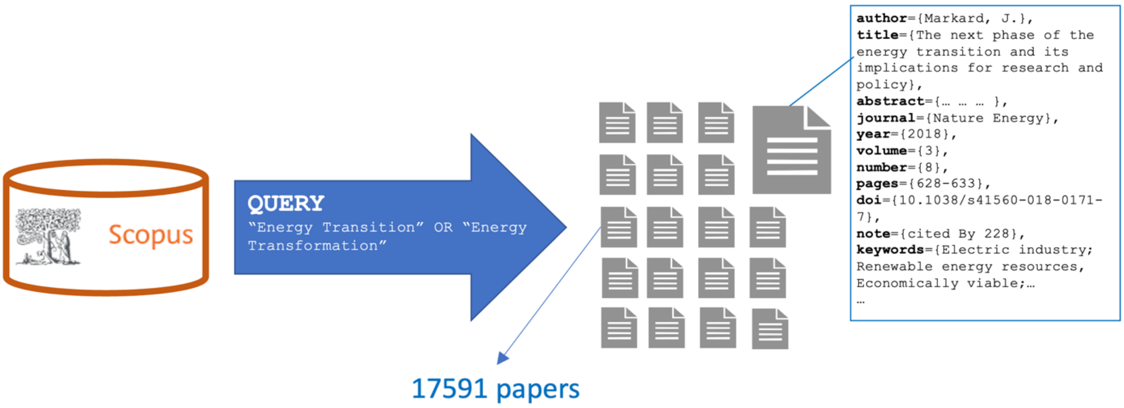
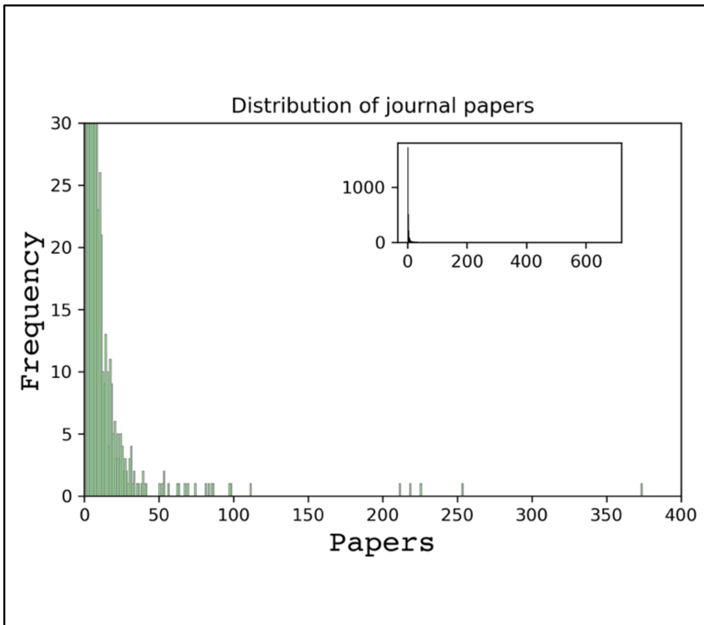


Figure 3. Collection of papers on energy transition/transformation from SCOPUS



MOST FREQUENT JOURNALS FOR THE ENERGY TRANSITION TOPIC	
energies	685
energy research and social science	610
energy policy	516
sustainability (switzerland)	373
renewable and sustainable energy reviews	253
journal of cleaner production	225
energy	218
applied energy	211
renewable energy	111
environmental innovation and societal transitions	98
energy economics	97
frontiers in energy research	86
environmental science and pollution research	85
energy strategy reviews	83
energy reports	81
international journal of hydrogen energy	74
energy, sustainability and society	69
journal of the american chemical society	67
journal of physical chemistry a	63
energy conversion and management	62
technological forecasting and social change	56
lecture notes in energy	53
gaia - ecological perspectives for science and society	53
energy for sustainable development	52
environmental research letters	50
journal of applied physics	41
ecological economics	40
energy and buildings	39
applied sciences (switzerland)	39
journal of physical chemistry c	38
journal of energy storage	36
journal of chemical physics	35
nature energy	33
dianli xitong zidonghua/automation of electric power systems	33

Figure 4. Distribution of journal papers and most frequent journals for the energy transition/transformation topic

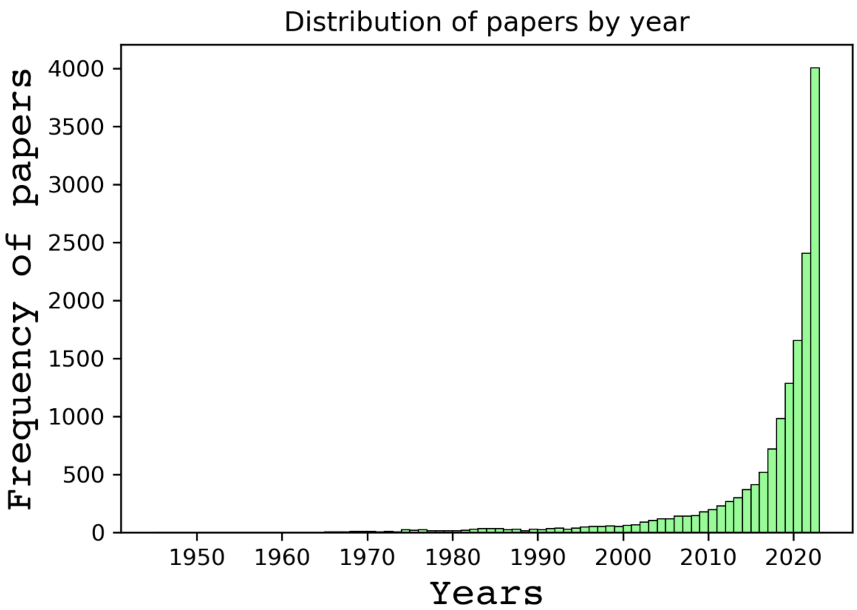


Figure 5. Distribution of papers by year

From the collected papers, we built a network of Scopus keywords (see Figure 6) by exploiting the co-occurrences of the keywords. The resulting network (Figure 7) shows both the complexity of the domain and the need for building a semantic structure to further organize it. The largest nodes represent the most frequently occurring terms (e.g., energy transition, energy transformation, renewable energies, energy policies). The smallest nodes, representing concepts such as seismic data and military operations, are more likely to be excluded from the final lexicon as they are less commonly used by researchers and, therefore, may have less relevance to the field of energy transition.

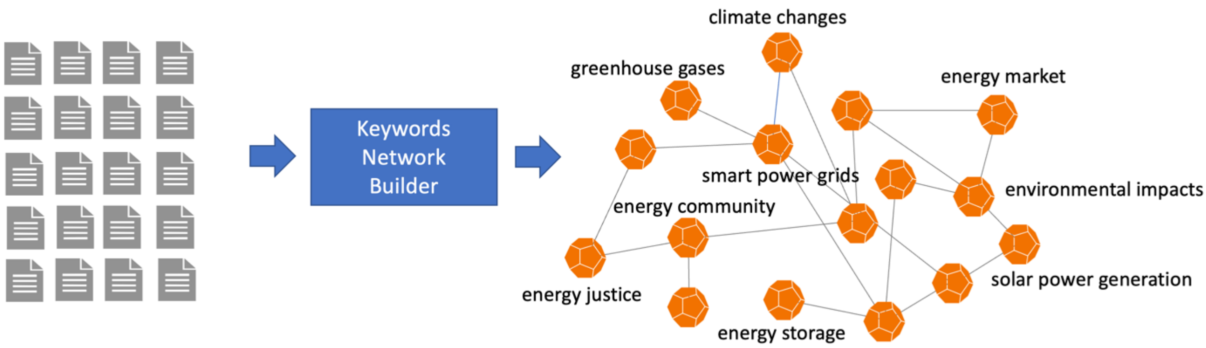


Figure 6. Construction of the SCOPUS keywords network

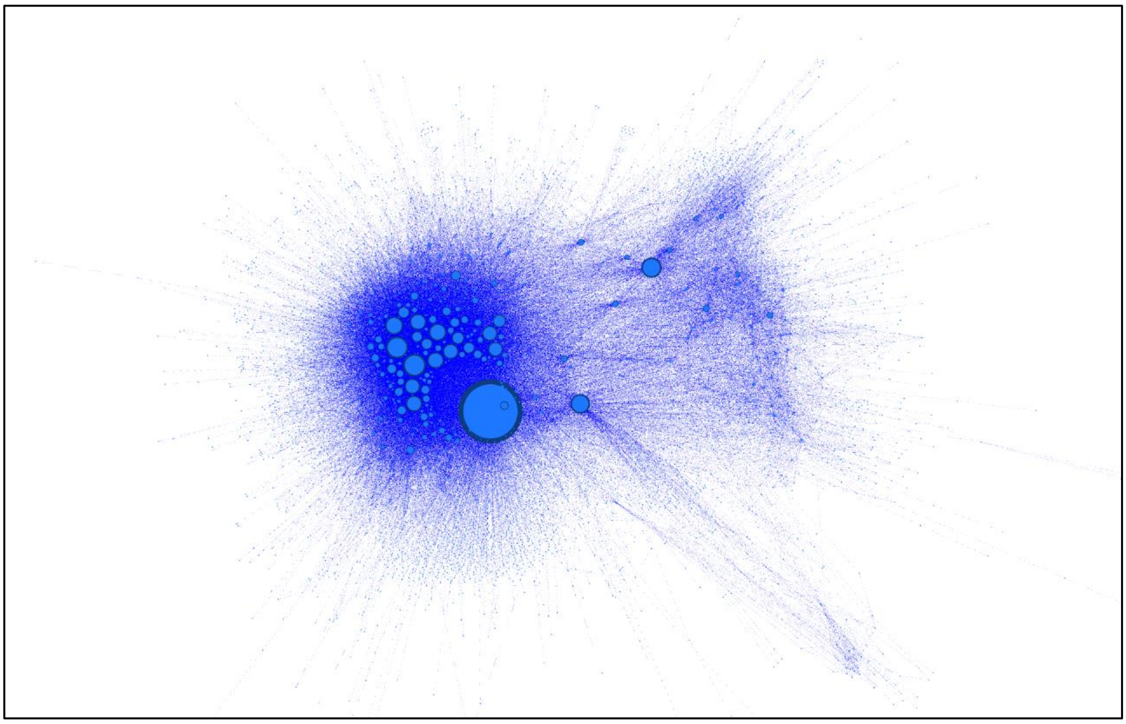


Figure 7. Network of Scopus keywords co-occurrences

To the purpose of further pruning the list of 4582 keywords and to classify them according to the 5 subsystems presented**Errore. L'origine riferimento non è stata trovata.**, we asked six experts in the field of energy transition to vote on the pertinence of each keyword to a subsystem (see Figure 8). It is worth noting that each expert could associate a keyword to more than one subsystem.

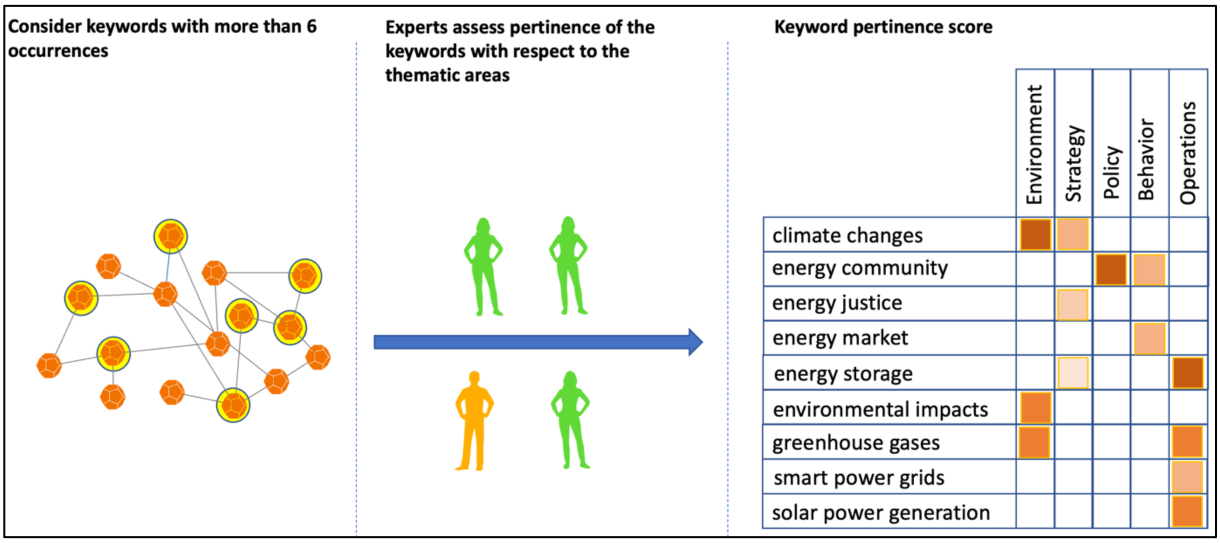


Figure 8. Voting on keywords

After this voting activity, the objective was to reach a consensus on the keywords to be considered among the experts. Three cases were possible (see Figure 9):

Case 1. All the experts either agreed on keeping the keyword or on removing it from the list of keywords associated to a subsystem.

Case 2. The experts failed to reach a consensus regarding the inclusion of some keywords following the voting procedure, leading them to convene a consensus meeting where they ultimately settled on the final decision of "keyword-in" versus "keyword-out."

Case 3. The experts failed to reach a consensus regarding the inclusion of some keywords following the voting procedure and the consensus meeting was not successful. Hence, a weight was assigned to each uncertain keyword and the experts agreed on a threshold for inclusion in the subsystem list. If the weight is higher than the threshold, the keyword is included and, conversely, if the weight is lower, this is removed from the list.

Finally, each of the included keywords is associated to one or more subsystem.

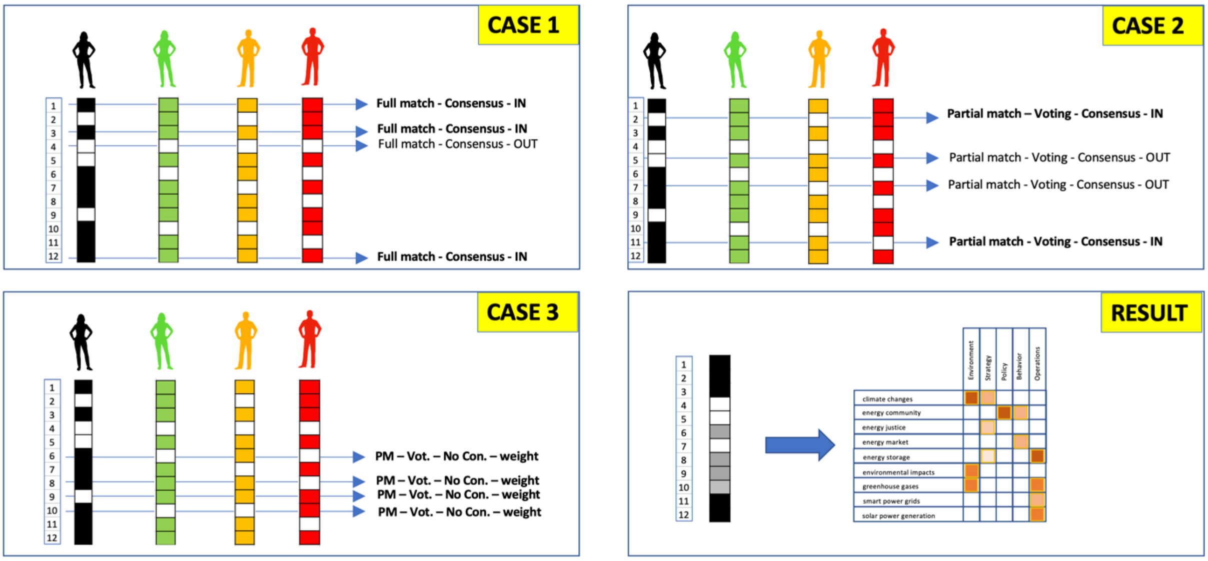


Figure 9. Consensus building among experts

At the end of this activity, we identified 5 lexicons, one for each subsystem. It is worth noting that keywords could belong to more subsystems. The distribution of keywords by subsystem is reported in Figure 10.

At this stage, the lexicons contain some synonyms. Hence, we manually inspected them to uncover some synsets which are defined, according to WordNet (WordNet, 2023), *as sets of one or more synonyms that are interchangeable in some context without changing the truth value of the proposition in which they are embedded*. The overall number of synsets selected by the gEneSys project until this step for all the subsystems is 1980. Hence, to further check the relevance of our work, we compared the gEneSys synsets with the Open Energy Ontology, which is, probably, the most relevant ontology related to energy. Only 121 synsets out of 1980 are already included in the Open Energy Ontology. Indeed, Open Energy Ontology focuses mainly on the energy operation layer and less on the other four also addressed by the gEneSys project. This corroborated the relevance and pertinence of the ontology produced by the gEneSys project.

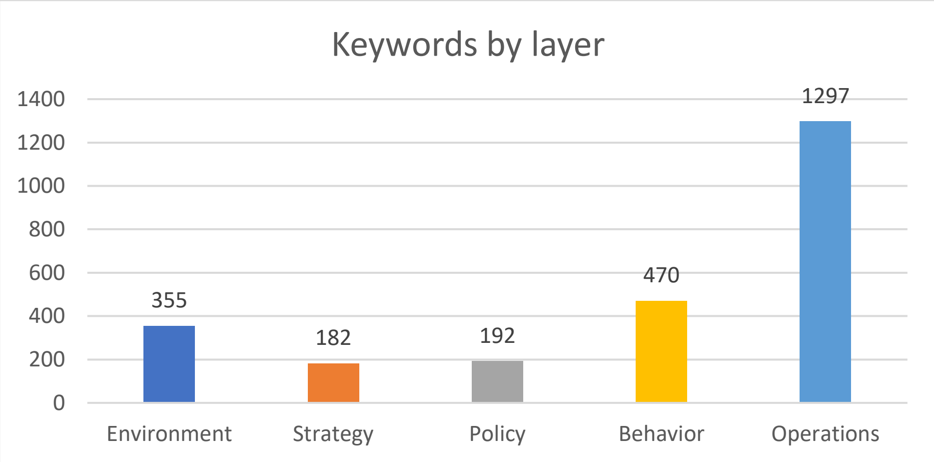


Figure 10. Number of keywords by layer

2.4.2 Glossary

The second step of the ontology engineering methodology consists in providing a definition of the identified terms. To this purpose, we divided the list of synsets among the gEneSys project partners and we asked them to describe each synset by putting the corresponding bibliographic reference. This process was partially automated since we automatically imported the definitions of the terms from WordNet and from the Open Energy Ontology. Furthermore, we advised our colleagues involved in this activity to utilize ChatGPT, even though we recommended that they verify definitions to mitigate potential AI hallucination issues (Bang, et al., 2023). Figure 11, Figure 12, and Figure 13 show, respectively, the definition of the *Energy* concept imported from the *Open Energy Ontology*, the definition of the *Atmosphere* concept imported from WordNet, and the definition of the *Environmental protection* concept retrieved from ChatGPT and checked by the Imperial College.

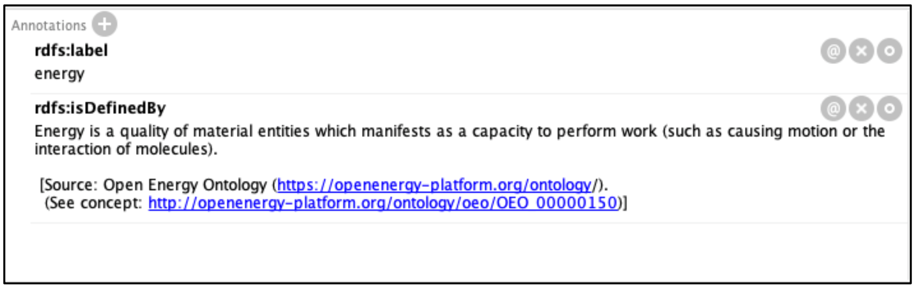


Figure 11. Definition of the Energy concept

Figure 12. Definition of the Atmosphere concept

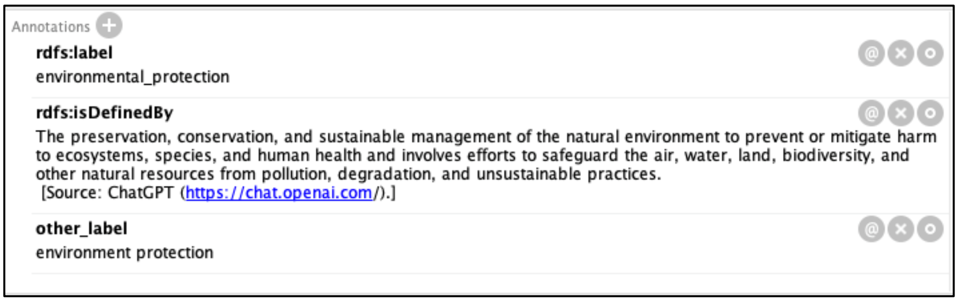


Figure 13. Definition of the Environmental Protection concept

2.4.3 Taxonomy

This step concerns the construction of a taxonomy of concepts. A taxonomy is a hierarchy used for classifying concepts based on their shared characteristics and relationships. Each layer of the taxonomy represents a level of abstraction or specificity within the hierarchy. To the purpose of building it, we extended the Basic Formal Ontology (BFO) (Arp, Smith, & Spear, 2015), which, similarly to DOLCE (Gangemi & Schneider, 2002), SUMO (Niles & Pease, 2001), and UFO (Guizzardi et al., 2015) is one of the most used foundational ontologies. These are aimed at supporting modelling in various domains by providing a conceptual framework gathering high level-abstraction concepts and relationships. BFO has been used to build ontology in different fields, such as industry, biology, and medicine. It facilitates interoperability between different ontologies and information systems.

The most general concept in BFO is the *entity*. Entities are divided into two categories: continuants and occurrents. The former are those entities that continue or persist through time. They include independent continuants (for example, objects such as the fuel); dependent continuants, including qualities (such as your energy and power), functions (such as policies and strategies), and roles (such as consumer and producer); together with the spatial regions these entities occupy at any given time. The latter (occurrents) are the entities that occur or happen, such as “events” or “processes” or “happenings,” which include the processes that unfold in phases, the boundaries at the beginnings or ends of such processes, and) the temporal and spatiotemporal regions in which these processes occur.

At present, all the elements of the glossary have been categorized into BFO foundational concepts. Figure 14 shows an excerpt of the IS-A taxonomy[1] depicted via the OntoGraf tab in Protégé.

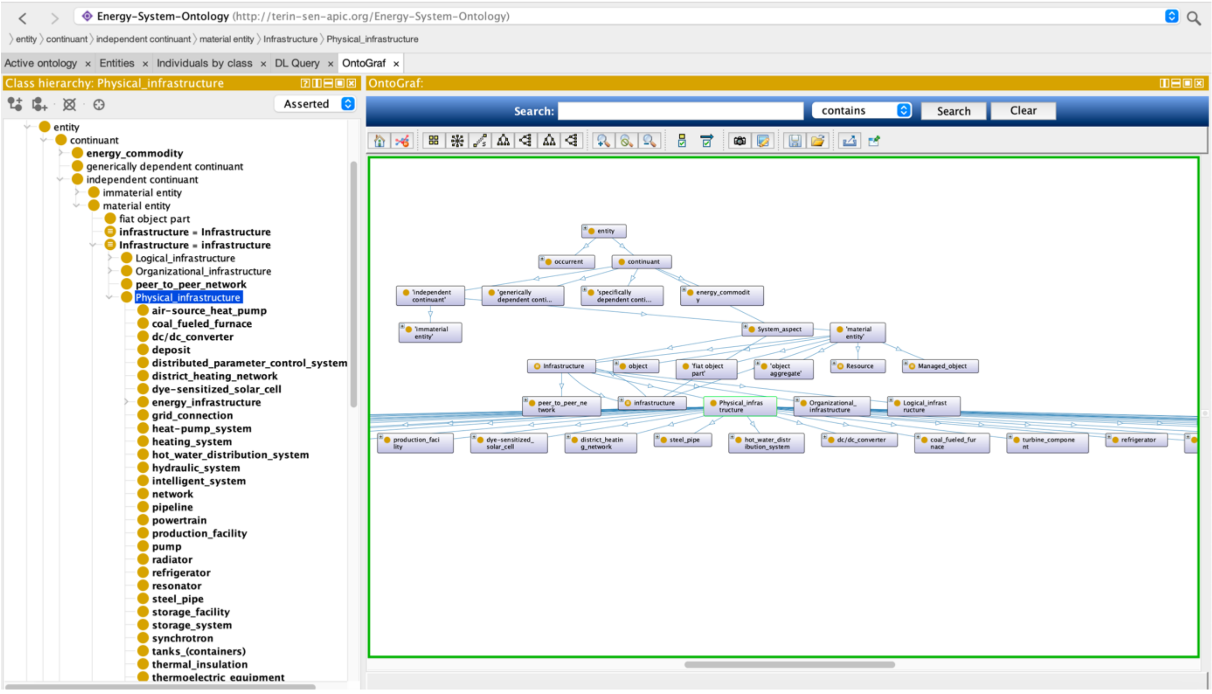


Figure 14. Excerpt of IS-A taxonomy depicted via the OntoGraf tab in Protégé

Advancing towards a more comprehensive ontological representation of the domain involves organizing the hierarchy into additional levels of specialization. To the end of facilitating the identification of actors driving change in the energy transition, our primary emphasis was on constructing a sub-hierarchy within the BFO role concept. Specifically, the concept of "role" is further specialized into not-mutually exclusive classes based on the relevant perspective. This means that a role can belong to more than one of these classes simultaneously. Among the most relevant types of roles are occupational role, organizational role, societal role, and energy market participant. This classification will be further refined in the project as part of the activities in tasks T1.3 and T1.4. An excerpt of it, visualized through the Gephi visualization tool (Bastian, Heymann, & Jacomy, 2009), is presented in Figure 15. In this figure, the size of the spheres is proportional to the number of specialized concepts.

In detail, an occupational role refers to a specific position, function, or job that an individual holds within a particular occupation, profession, or field of work. Examples of such roles are operator, policy maker, and researcher. An organizational role, on the other hand, refers to the type of role within an organizational entity. A societal role is associated with civil society, which can be either structured, as seen in charity

[1] An IS-A taxonomy is a hierarchy of concepts organized by means of the SubClassOf property.

organizations or NGOs, or unstructured, such as minority or vulnerable groups. An energy market role signifies the role played by an individual or organization in the energy market, with examples including provider, market regulator, and shareholder.

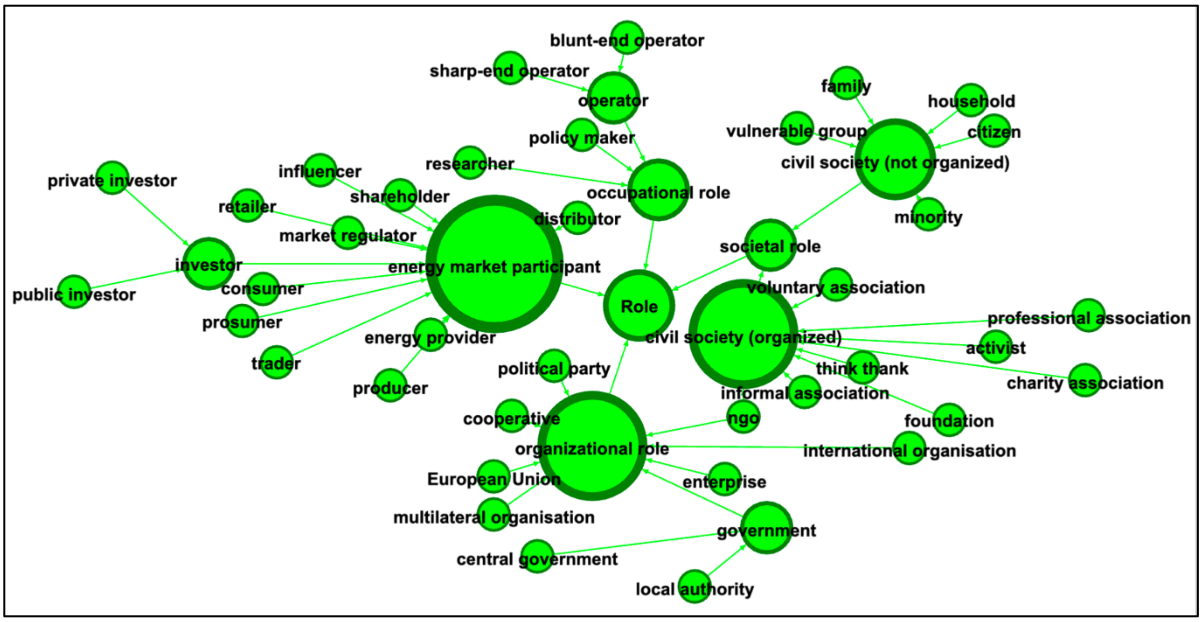


Figure 15. An excerpt of the sub-hierarchy of the BFO concept "role"

2.4.4 Semantic Network

This step was devoted to the design of the semantic relationships between concepts. To this aim, we built 18 Ontology Design Patterns (ODP)s that could also facilitate the extension of the ontology for future development. Indeed, an ODP is a reusable and generalizable conceptual model fragment or template used to represent and model knowledge in an ontology. ODPs aim at modelling complex relationships, attributes, and entities within an ontology to make the ontology modular, interoperable, and easier to understand (Gangemi, 2005). The 18 ODPs are listed in Figure 16. Each ODP addresses one or more subsystems, as they were defined based on inspiration from the conceptual framework for energy transition and the connections that highlight the interdependencies between the layers.

The list of ODPs operates under the open-world assumption (Genesereth & Nilsson, 1987). Consequently, the absence of a particular connection between concepts within a pattern or even a pattern itself (i.e., the absence of an axiom) means, in principle, that the axiom has not been explicitly stated yet. This is irrespective of whether it is true or not, and regardless of whether we believe it to be true or not. Essentially, the mere absence of an axiom does not allow a deductive reasoner to conclude that the axiom is false. In practical terms, it is important to note that the list of ontology design patterns should not be regarded as exhaustive.

CODE	Ontology Design Pattern Name	Environmental layer	Energy strategy layer	Energy policy layer	Energy behavior layer	Energy operation layer
ESO-ODP-001	Energy Demand	■	■	■	■	■
ESO-ODP-002	Energy Form					■
ESO-ODP-003	Energy Infrastructure Development	■	■	■		■
ESO-ODP-004	Energy Market		■		■	■
ESO-ODP-005	Energy Policy			■		■
ESO-ODP-006	Energy Research	■	■	■	■	■
ESO-ODP-007	Energy Saving	■		■	■	■
ESO-ODP-008	Energy Security		■			■
ESO-ODP-009	Energy Sources Exploitation			■		■
ESO-ODP-010	Energy Strategy Definition	■	■	■		■
ESO-ODP-011	Energy Value Chain					■
ESO-ODP-012	Energy Waste	■		■	■	■
ESO-ODP-013	International Cooperation		■		■	
ESO-ODP-014	Mitigation	■	■		■	■
ESO-ODP-015	Policy Acceptance	■		■	■	
ESO-ODP-016	Pollution	■				■
ESO-ODP-017	Risk	■				■
ESO-ODP-018	System Aspect					■

Figure 16. List of ontology design patterns for modeling the energy systems

In the next subsections, we present all the identified ODPs. Each of them is presented together with a natural language description, an UML class diagram showing the ontological relationships between concepts, an ontology path[2] showing the chain of the IS-A relationships until the more specific BFO foundational concept (e.g., entity,

[2] In the ontology path, BFO concepts are reported in bold. For instance, for the *energy demand* concept, the path is **entity**>System_aspect>Service_request>energy_demand where **entity** is the more specific BFO concept for the chain of the IS-A relationships.

continuants, occurrents), and a description of the composing concepts. A legenda for facilitating understanding of the UML class diagrams is presented in Figure 17.

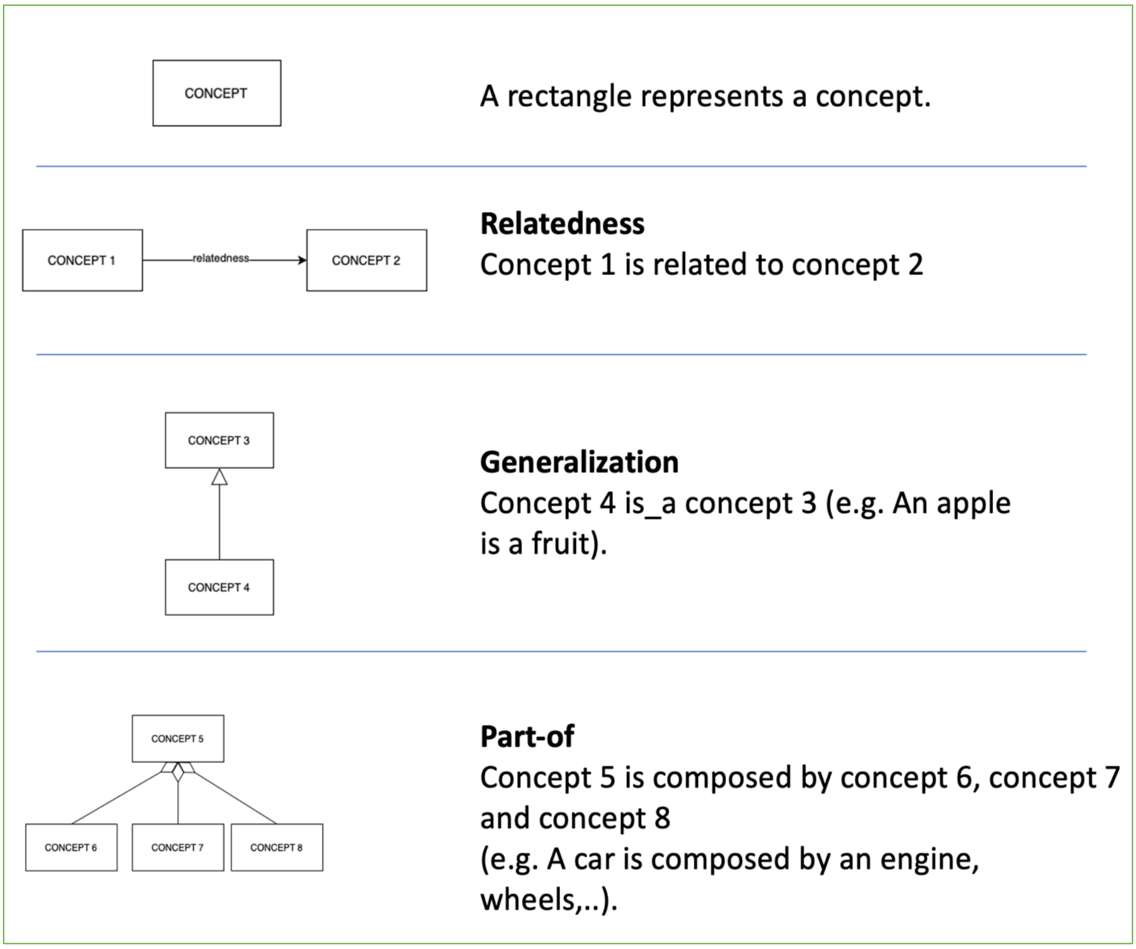


Figure 17. Legenda for UML class diagram

2.4.4.1 Energy demand ontology design pattern (ESO-ODP-001)

The energy demand ODP refers to the amount of energy required by individuals, households, industries, and societies to meet their various needs and activities. It represents the total amount of energy that is consumed over a given period, typically measured in units such as kilowatt-hours (kWh) or joules. It depends on several factors, such as: population, available technology, energy efficiency policy, weather, behavior, and economic conditions. Among the stakeholders interested in energy demand, there are energy providers, policy makers, and researchers.

Figure 18 shows the UML representation of the energy demand ontology design pattern. The edges labelled as "*isInterestedIn*" are used to indicate the actors who may have a potential interest in energy demand. For example, an energy provider might be interested in determining the amount of power to generate, policymakers could use this information to create new incentives, and researchers could develop new models or algorithms to optimize energy consumption. Conversely, the edges labelled as "*dependsOn*" are used to indicate the factors that could influence energy demand. These factors may include population size, the availability of energy efficiency technology (such as a new generation of appliances), weather conditions (e.g., colder weather leading to higher heating energy demand), sustainable energy practices by individuals and businesses, and the economic conditions of the population (e.g., affluent areas leading to increased demand for electric vehicles and electrical energy).

Finally,

Table 1 includes the ontology paths and connections with BFO foundational concepts for the concepts within the energy demand ODP, while Table 2 provides the description of these concepts.

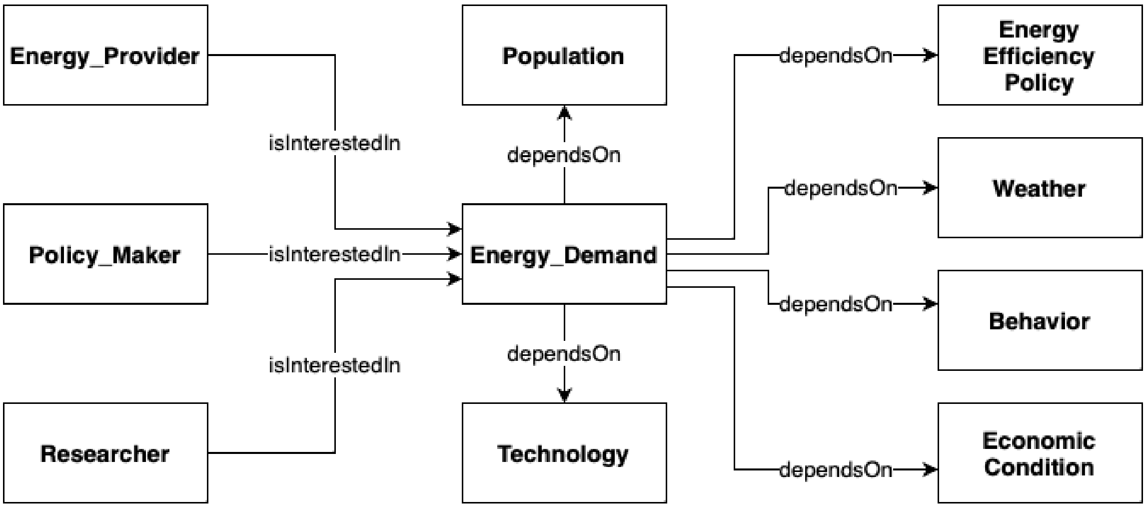


Figure 18. UML representation of the energy demand ontology design pattern

Table 1. Ontology paths and connection with BFO foundational concepts for the concepts within the energy demand ODP

ESO concept	Ontology path
Behavior	**entity>occurrent>process**>behavior
Economic condition	**entity>continuant>specifically_dependent_continuant> quality>**economic_condition
Energy demand	**entity**>System_aspect>Service_request>energy_demand
Energy efficiency policy	**entity>continuant>specifically_dependent_continuant> realizable_entity>disposition>function**>policy>energy_policy> energy_efficiency_policy
Energy provider	**entity>continuant>specifically_dependent_continuant> realizable_entity>role**>actor>market_participant> energy_market_participant>energy_provider
Policy maker	**entity>continuant>specifically_dependent_continuant>**

	realizable_entity>role>actor>policy-maker
Population	**entity>continuant>independent_continuant>material_entity>object_aggregate**>population
Researcher	**entity>continuant>specifically_dependent_continuant>realizable_entity>role**>actor>researcher
Technology	**entity>continuant>independent_continuant>material_entity>object_aggregate**>technology
Weather	**entity>occurrent>process**>weather

Table 2. Descriptions of the concepts within the energy demand ODP

ESO concept	Description
Behavior	Manner of acting or controlling yourself.- (behavioral attributes) the way a person behaves toward other people (WordNet, 2023).
Economic condition	The overall state of an economy, reflecting its performance, stability, and various key indicators (OpenAI, 2023).
Energy demand	Energy demand is a demand for energy (Booshehri, et al., 2021).
Energy efficiency policy	Energy efficiency policy refers to a set of government regulations, incentives, and initiatives aimed at promoting and achieving improved energy efficiency across various sectors of the economy (OpenAI, 2023).
Energy provider	An energy provider is an entity or company responsible for supplying and distributing various forms of energy, such as electricity, natural gas, or renewable sources, to consumers and businesses (OpenAI, 2023).
Policy maker	Individual or a group of individuals who are responsible for formulating and implementing policies that guide the actions and decisions of a government or an organization (OpenAI, 2023).
Population	Population refers to the total number of individuals, organisms, or entities within a specific geographical area or defined group (OpenAI, 2023)
Researcher	A researcher is an individual who systematically investigates, studies, and analyzes topics or questions to contribute new knowledge and insights to a particular field of study (OpenAI, 2023).
Technology	The concept of "technology" refers to the application of scientific knowledge, tools, techniques, and processes for practical purposes, usually in industries, commerce, and everyday life (OpenAI, 2023).
Weather	The atmospheric conditions of a specific location at a particular time, including the short-term variations in temperature, humidity, precipitation, wind speed and direction, cloud cover, and atmospheric pressure, marked by a day-to-day variation in the state of the atmosphere in terms of temperature and precipitation patterns (OpenAI, 2023).

2.4.4.2 Energy Form ontology design pattern (ESO-ODP-002)

The Energy form ODP signifies that energy has various forms that can be converted into one another (Smil, 2017).

Figure 19 shows the UML representation of the energy form ODP. The edge labelled as "*hasForm*" is used to indicate that energy can exist in different forms, including chemical, kinetic, thermal, and nuclear. The edges labelled as "*hasSource*" and "*hasDestination*" are used to indicate that energy passes from one form to another during an energy conversion process. For example, boiling is an energy conversion process in which thermal energy is converted into chemical energy; combustion is another energy conversion process that transforms chemical energy into thermal energy; and nuclear fission represents yet another energy conversion process, where nuclear energy is converted into thermal energy.

Finally,

Table 3 includes the ontology paths and connections with BFO foundational concepts for the concepts within the energy form ODP, while

Table 4 provides the description of these concepts.

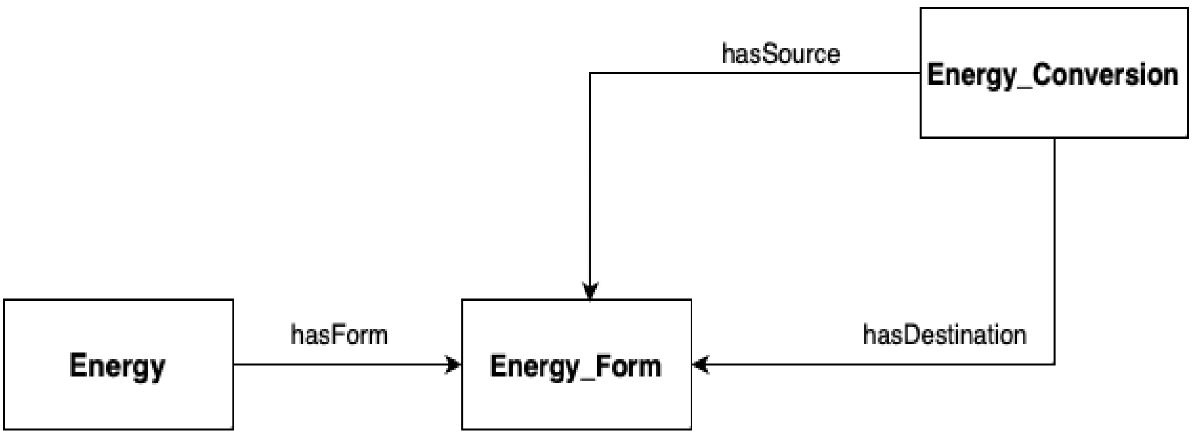


Figure 19. UML representation of the energy form ontology design pattern

Table 3. Ontology paths and connection with BFO foundational concepts for the concepts within the energy form ODP

ESO concept	Ontology path

Energy	**entity>continuant>specifically_dependent_continuant> quality**>energy
Energy conversion	**entity>occurrent>process**>System_internal_operation> energy_conversion_
Energy form	**entity>continuant>specifically_dependent_continuant> quality**>energy_form

Table 4. Descriptions of the concepts within the energy form ODP

ESO concept	Description
Energy	Energy is a quality of material entities which manifests as a capacity to perform work (such as causing motion or the interaction of molecules) (Booshehri, et al., 2021).
Energy conversion	Energy conversion is the process of transforming one form of energy into another, such as converting mechanical energy into electrical energy through a generator (OpenAI, 2023).
Energy form	An energy form is a specific manifestation or type of energy, such as thermal, mechanical, electrical, or chemical energy, which can be converted and transferred between different forms (OpenAI, 2023).

2.4.4.3 Energy infrastructure development ontology design pattern (ESO-ODP-003)

The energy infrastructure development ODP refers to the planning, design, construction, improvement, maintenance, and research and development activities of physical systems and facilities that are essential for the production, transport, distribution, and storage of energy resources. The primary objective of energy infrastructure development is to ensure economic growth. Furthermore, it aims at environmental sustainability by meeting energy demand. Energy infrastructure development is planned by stakeholders, such as governments, energy companies, and regulators.

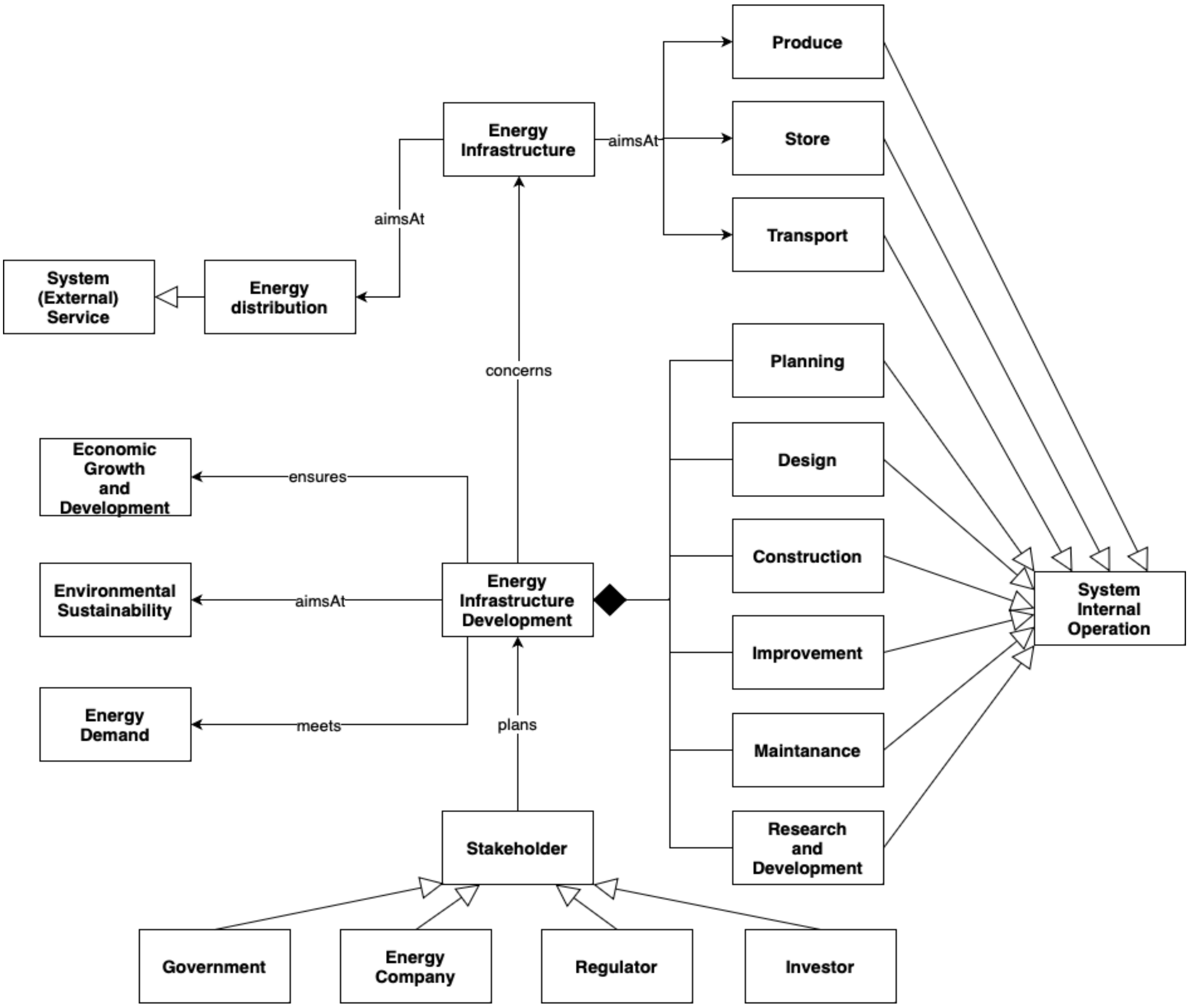


Figure 20. UML representation of the energy infrastructure development ODP

Figure 20**Errore. L'origine riferimento non è stata trovata.** shows the UML representation of the energy infrastructure development ontology design pattern. The edge labelled "*concerns*" is employed to signify that energy infrastructure development pertains to specific energy infrastructure entities, such as hydroelectric power stations or solar power plants. The edge labelled "*aimsAt*" linked to energy infrastructure is used to indicate that the primary objective of energy infrastructure is to produce energy (e.g., in the case of a solar power plant), store it (e.g., in a battery energy storage system), transport it (e.g., through a power grid), and distribute it. It is worth noting that the "*aimsAt*" edge also connects energy infrastructure development and environment sustainability, signifying the purpose of this activity. Encompasses various activities, including planning, design, construction, improvement, maintenance, and research and development. All these activities, as well as the related functions of producing, storing, and transporting energy, fall under the category of system operations. In contrast, energy distribution represents an external service within the system. The "*plans*" edge is used to indicate that various stakeholders in energy infrastructure development, including governments, energy companies, regulators, and investors, can engage in planning for such development. The "*meets*" edge is used to signify that energy infrastructure development addresses the need for energy demand. Lastly, the "*ensures*" edge is used to indicate that energy infrastructure development plays a crucial role in guaranteeing economic growth and development.

Finally, Table 5 includes the ontology paths and connection with BFO foundational concepts for the concepts within the energy infrastructure development ODP, while Table 6 provides the description of these concepts.

Table 5. Ontology paths and connection with BFO foundational concepts for the concepts within the energy infrastructure development ODP

ESO concept	Ontology path
Construction	**entity>occurrent>process**>System_internal_operation>construction
Design	**entity>occurrent>process**>System_internal_operation>design
Economic_growth_and_development	**entity>occurrent>process**>growth>economic_growth_and_development
Energy_company	**entity>continuant>specifically_dependent_continuant> realizable_entity>role**>actor>stakeholder>energy_company
Energy_demand	**entity**>System_aspect>Service_request>energy_demand
Energy_distribution	**entity>occurrent>process**>system_external_service> energy_distribution
Energy_infrastructure	**entity>continuant>independent_continuant>material_entity>** infrastructure>physical_infrastructure>energy_infrastructure
Energy_infrastructure_development	**entity>occurrent>process**>System_internal_operation> energy_infrastructure_development
Environmental_sustainability	**entity>continuant>specifically_dependent_continuant> quality**>System_property>Internal_system_conditions>Ility> Sustainability>environmental_sustainability
Government	**entity>continuant>specifically_dependent_continuant> realizable_entity>role**>actor>stakeholder>government
Improvement	**entity>occurrent>process**>System_internal_operation>improvement
Investor	**entity>continuant>specifically_dependent_continuant> realizable_entity>role**>actor> stakeholder>investor
Maintenance	**entity>occurrent>process**>System_internal_operation>maintenance
Planning	**entity>occurrent>process**>System_internal_operation>planning
Produce	**entity>occurrent>process**>System_internal_operation>produce
Regulator	**entity>continuant>specifically_dependent_continuant>**

	realizable_entity>role>actor> stakeholder>regulator
Research_and_develop ment	**entity>occurrent>process**>System_internal_operation>research _and_development
Stakeholder	**entity>continuant>specifically_dependent_continuant>** **realizable_entity>role**>actor>stakeholder
Store	**entity>occurrent>process**>System_internal_operation>store
System_external_service	**entity>occurrent>process**>system_external_service
System_internal_operatio n	**entity>occurrent>process**>System_internal_operation
Transport	**entity>occurrent>process**>System_internal_operation>transport

Table 6. Descriptions of the concepts within the energy infrastructure development ODP

ESO concept	Description
Construction	Construction is the practical and organized process of building or assembling physical structures, buildings, infrastructure, or facilities according to approved plans and designs, involving tasks such as excavation, installation, assembly, and finishing (OpenAI, 2023).
Design	Design is the creative and systematic process of conceptualizing, structuring, and creating solutions for various purposes, often involving aesthetics, functionality, and user experience, in fields such as architecture, product development, and graphic design (OpenAI, 2023).
Economic_growth_and_ development	Economic growth and development refer to the expansion and progress of a country's economy, encompassing increases in production, income, employment, and overall well-being, often accompanied by improvements in infrastructure, living standards, and the overall quality of life for its citizens (OpenAI, 2023).
Energy_company	A business entity that operates in the energy sector and is primarily engaged in the production, distribution, or sale of energy-related products and services (OpenAI, 2023).
Energy_demand	Energy demand is a demand for energy (Booshehri, et al., 2021).
Energy_distribution	Energy distribution refers to the transmission and delivery of energy from the point of production or generation to end-users or consumers.
Energy_infrastructure	The concept of energy infrastructure refers to the physical systems, facilities, and networks that are necessary for the production, transmission, distribution, and utilization of various forms of energy (OpenAI, 2023).
Energy_infrastructure_de velopment	Energy infrastructure development refers to the planning, construction, and improvement of various physical systems,

	facilities, and networks that enable the production, transmission, distribution, and utilization of energy resources, such as power plants, grids, pipelines, and storage facilities (OpenAI, 2023).
Environmental_sustainability	The responsible and balanced use of natural resources and the protection of ecosystems to meet the needs of the present generation without compromising the ability of future generations to meet their own needs and requires integrating environmental considerations into decision-making processes and adopting practices that promote long-term ecological balance, social equity, and economic prosperity (OpenAI, 2023).
Government	Government refers to the organized system or body responsible for making and enforcing laws, regulations, and policies, as well as managing public affairs and providing essential services to a society or country's citizens (OpenAI, 2023).
Improvement	Improvement refers to the act of making something better, more efficient, or more effective through modifications, changes, or enhancements, often resulting in higher quality, increased performance, or greater value (OpenAI, 2023).
Investor	An investor is an individual, organization, or entity that allocates financial resources, such as capital or funds, into various assets, securities, or ventures with the expectation of generating returns or profits over time (OpenAI, 2023).
Maintenance	Improvement refers to the act of making something better, more efficient, or more effective through modifications, changes, or enhancements, often resulting in higher quality, increased performance, or greater value (OpenAI, 2023).
Planning	Planning refers to the process of systematically organizing, strategizing, and making decisions to outline specific goals, objectives, and actions that guide the allocation of resources and activities in order to achieve desired outcomes (OpenAI, 2023).
Produce	To produce means to create, manufacture, or generate something, typically goods or items, through a process of fabrication or creation (OpenAI, 2023).
Regulator	A regulator is an authoritative entity or agency responsible for overseeing and enforcing rules, regulations, and standards within a specific industry, sector, or domain to ensure compliance, fairness, safety, and proper functioning (OpenAI, 2023).
Research_and_development	Research and development (R&D) is the systematic and innovative process of investigating, exploring, and creating new knowledge, technologies, products, or solutions, often involving scientific inquiry, experimentation, and experimentation, with the aim of advancing fields, industries, or capabilities (OpenAI, 2023).

Stakeholder	A person or organization that is interested in a system or its subsystems (Coletti, et al., 2020).
Store	To store means to keep or retain something, often in a designated place or container, for future use, safekeeping, or convenience (OpenAI, 2023).
System_external_service	Service provided by a system (Coletti, et al., 2020).
System_internal_operation	Internal activities performed in system and that are required preconditions to deliver services (Coletti, De Nicola, Vicoli, & Villani, 2019).
(Energy) Transport	Energy transport refers to the process of moving energy from its source to the places where it is needed for consumption (OpenAI, 2023)

2.4.4.4. Energy market ontology design pattern (ESO-ODP-004)

The energy market ODP refers to the complex system where participants, such as energy producers, suppliers, distributors, retailers, and end-consumers, interact to trade energy commodities, including electricity, and primary energy sources. The market price of energy commodities is determined by several factors, such as energy supply, energy demand, pricing mechanisms, policies, and regulations. Geopolitical factors, available technologies, and climate change concerns also influence the market price.

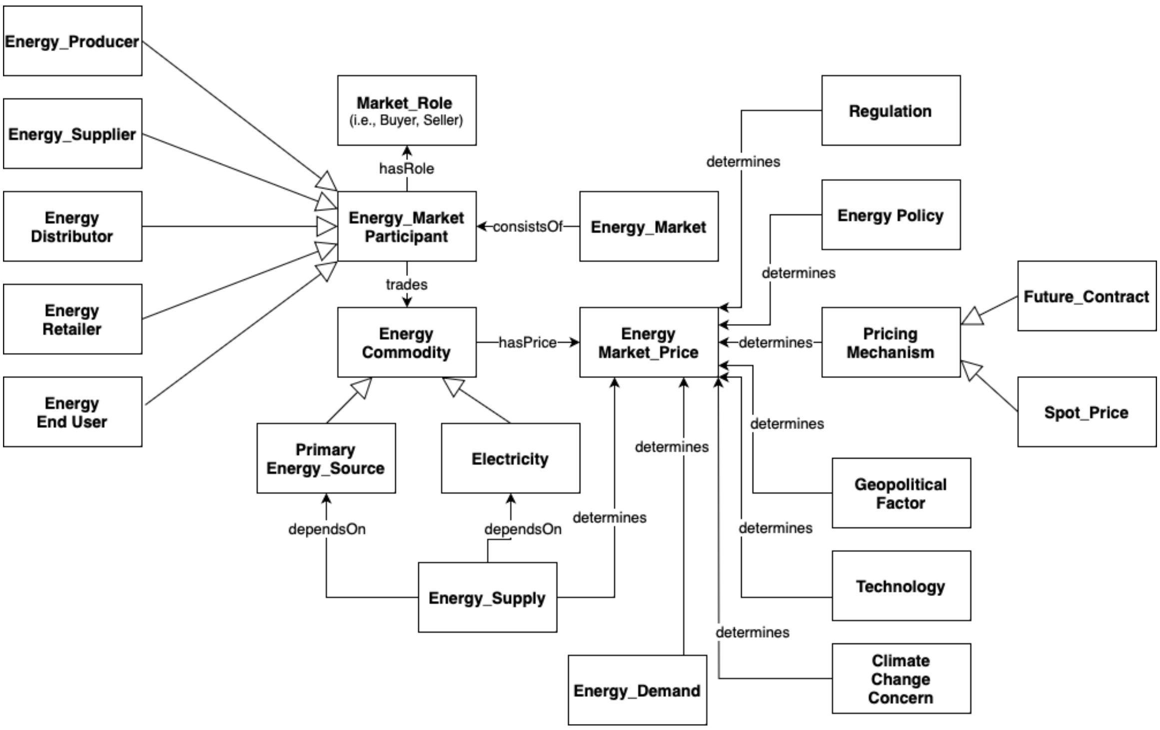


Figure 21. UML representation of the energy market ontology design pattern

Figure 21**Errore. L'origine riferimento non è stata trovata.** shows the UML representation of the energy market ontology design pattern. The "*consistsOf*" edge is employed to indicate that the energy market is composed of energy market participants. The "*trades*" edge in the diagram signifies that these energy market participants engage in trading commodities, such as primary energy sources and electricity. The "*hasRole*" edge is used to denote that an energy market participant can assume various market roles, such as a buyer or seller. The "*dependsOn*" edge is utilized to convey that energy supply relies on the availability of primary energy sources and electricity. Additionally, the "*determines*" edge is employed to indicate that energy market prices are influenced by the aforementioned factors. The figure also illustrates examples of market price mechanisms, including future contracts and spot prices.

Finally, Table 7 includes the ontology paths and connection with BFO foundational concepts for the concepts within the energy market ODP, while

Table 8 provides the description of these concepts.

Table 7. Ontology paths and connection with BFO foundational concepts for the concepts within the energy market ODP

ESO concept	Ontology path
Climate change concern	**entity>occurrent>process**>climate_change_concern
Electricity	**entity>continuant**>energy_commodity>electricity
Energy commodity	**entity>continuant**>energy_commodity
energy demand	**entity**>System_aspect>Service_request>energy_demand
Energy distributor	**entity>continuant>specifically_dependent_continuant> realizable_entity>role**>actor>market_participant> energy_market_participant>energy_distributor
Energy end user	**entity>continuant>specifically_dependent_continuant> realizable_entity>role**>actor>market_participant> energy_market_participant>energy_end_user
Energy market	**entity>continuant>specifically_dependent_continuant> realizable_entity>disposition>function**>market>energy_market
Energy market participant	**entity>continuant>specifically_dependent_continuant> realizable_entity>role**>actor>market_participant> energy_market_participant
Energy market price	**entity>continuant>specifically_dependent_continuant> quality**>energy_market_price
Energy policy	**entity>continuant>specifically_dependent_continuant> realizable_entity>disposition>function**>policy>energy_policy

Energy producer	**entity>continuant>specifically_dependent_continuant> realizable_entity>role**>actor>market_participant> energy_market_participant>energy_producer
Energy retailer	**entity>continuant>specifically_dependent_continuant> realizable_entity>role**>actor>market_participant> energy_market_participant>energy_retailer
Energy supplier	**entity>continuant>specifically_dependent_continuant> realizable_entity>role**>actor>market_participant> energy_market_participant>energy_supplier
Energy supply	**entity>occurrent>process**>system_external_service>energy_supply
Future contract	**entity>continuant>specifically_dependent_continuant> realizable_entity>disposition>function**>pricing_mechanism> future_contract
Geopolitical factor	**entity>occurrent>process**>geopolitical_factor
Market role	**entity>continuant>specifically_dependent_continuant> realizable_entity>role**>market_role
Pricing mechanism	**entity>continuant>specifically_dependent_continuant> realizable_entity>disposition>function**>pricing_mechanism
Primary energy source	**entity>continuant**>energy_commodity>primary_energy_source
Regulation	**entity>continuant>specifically_dependent_continuant> realizable_entity>disposition>function**>regulation
Spot price	**entity>continuant>specifically_dependent_continuant> realizable_entity>disposition>function**>pricing_mechanism>spot_pri ce
Technology	**entity>continuant>independent_continuant>material_entity> object_aggregate**>technology

Table 8. Descriptions of the concepts within the energy market ODP

ESO concept	Description
Climate change concern	Climate change concern refers to the awareness, worry, or apprehension about the ongoing and potential future impacts of anthropogenic (human-caused) climate change on the environment, ecosystems, weather patterns, sea levels, and overall planetary health. It involves recognizing the need for mitigation and adaptation strategies to address the negative consequences of climate change (OpenAI, 2023).
Electricity	Electricity is a form of energy resulting from the movement of charged particles, usually electrons, through conductive

	materials, such as wires. It is commonly used to power a wide range of devices, appliances, and systems, playing a fundamental role in modern life (OpenAI, 2023).
Energy commodity	An energy commodity refers to a raw material or resource that can be bought, sold, and traded in the marketplace, typically used to produce energy, such as oil, natural gas, coal, or electricity (OpenAI, 2023).
Energy demand	Energy demand is a demand for energy (Booshehri, et al., 2021).
Energy distributor	An energy distributor is an entity or company responsible for transporting and delivering energy resources, such as electricity, natural gas, or fuel, through infrastructure like power lines, pipelines, or distribution networks to end-users, homes, businesses, and other consumers (OpenAI, 2023).
Energy end user	An energy end-user is an individual, a household, a business, or an organization that consumes energy resources, such as electricity, natural gas, or fuel, for various purposes, including heating, cooling, lighting, industrial processes, transportation, and other activities (OpenAI, 2023).
Energy market	The economic system and platform where energy resources are bought and sold. It is a complex and dynamic marketplace where various energy resources, such as electricity, oil, natural gas, coal, and renewable energy, are traded among producers, consumers, and intermediaries (OpenAI, 2023).
Energy market participant	Energy market participant is used to describe individuals, organizations, or entities that are actively involved in the buying, selling, generation, transmission, distribution, or management of energy resources in a competitive energy market. It exists to facilitate the trading and distribution of electricity, natural gas, and other energy commodities. Energy market participants play different roles within these markets, and their activities are essential for ensuring a reliable and efficient energy supply (OpenAI, 2023).
Energy market price	Energy market price refers to the prevailing value or cost of buying or selling energy resources, such as electricity, natural gas, or oil, in the marketplace at a given time. It is determined by various factors including supply and demand dynamics, production costs, geopolitical influences, and regulatory policies (OpenAI, 2023).
Energy policy	Energy policy refers to the set of principles, strategies, and measures adopted by governments and policymakers to guide the management, regulation, and development of energy resources and the energy sector, as a whole (OpenAI, 2023).
Energy producer	An energy producer is an entity or company involved in the generation and supply of various forms of energy, such as electricity, heat, or fuel, typically through processes like power generation, extraction, or production (OpenAI, 2023).
Energy retailer	An energy retailer is a company or entity that sells energy resources, such as electricity, natural gas, or other fuels, directly to

	consumers and businesses, often offering various pricing plans, services, and customer support (OpenAI, 2023).
Energy supplier	An energy supplier is a company or entity responsible for providing energy resources, such as electricity, natural gas, or other fuels, to consumers and businesses for their energy needs and consumption (OpenAI, 2023).
Energy supply	Energy supply refers to the availability and provision of various forms of energy, such as electricity, natural gas, oil, or renewable sources, to meet the demands of consumers, industries, and other users for their energy needs and consumption (OpenAI, 2023).
Future contract	A pricing mechanism refers to the process or approach by which the cost or value of goods, services, or resources is determined within a market. It takes into account factors such as supply, demand, production costs, competition, and other economic considerations (OpenAI, 2023).
Geopolitical factor	A geopolitical factor refers to a political, social, or economic influence that arises from the interactions and relationships between different countries, regions, or global entities. Geopolitical factors can include factors such as international conflicts, alliances, trade agreements, economic sanctions, and other international dynamics that impact political decisions, economic stability, and security on a global scale (OpenAI, 2023).
Market role	The role (e.g., buyer, seller, ...) played by a market participant in the energy market.
Pricing mechanism	A pricing mechanism refers to the method or system used to establish the cost or value of goods, services, or resources in a market, often considering factors like supply, demand, production costs, competition, and other economic variables (OpenAI, 2023).
Primary energy source	A primary energy source is a natural resource that can be directly extracted or harnessed to produce energy in its raw form, such as fossil fuels (coal, oil, natural gas), renewable sources (solar, wind, hydro), and nuclear materials (uranium) (OpenAI, 2023).
Regulation	An authoritative rule. A principle or condition that customarily governs behavior. The state of being controlled or governed (WordNet, 2023).
Spot price	A spot price is the current market price at which a commodity, such as energy resources like electricity, natural gas, or oil, is bought or sold for immediate delivery and settlement. It reflects the current supply and demand dynamics in the market and can fluctuate based on various factors (OpenAI, 2023).
Technology	The concept of "technology" refers to the application of scientific knowledge, tools, techniques, and processes for practical purposes, usually in industries, commerce, and everyday life (OpenAI, 2023).

2.4.4.5 Energy policy ontology design pattern (ESO-ODP-005)

The energy policy ontology design pattern refers to a set of regulations that aim to address various aspects of energy production, distribution, consumption, and conservation within a country or a region.

Figure 22**Errore. L'origine riferimento non è stata trovata.** shows a UML representation of the energy policy ODP. An energy policy is a policy with a specific objective, such as increasing the adoption rate of electric vehicles, as represented in the diagram by the "*aimsAt*" edge. The "*considers*" edge is used to indicate that a policy takes various contextual factors into account, which can include economic and geographical considerations. Typically, a policy is part of a broader policy mix (as indicated by the "*part-of*" edge in the figure) that implements an energy strategy (see the "*implements*" edge). Examples of energy strategies include energy transition and energy security. The '*supports*' edge signifies that policy measures, such as incentives and penalties, are in place to bolster a policy's implementation. The "*makesPolicy*" edge is employed to indicate that policies are crafted by policymakers who may be influenced by various stakeholders (refer to the 'influences' edge). The "*hasConsequence*" edge is used to highlight that policies have specific implications, which may encompass both threats and opportunities (see the "*consistsOf*" relationship). Lastly, the "*isDerivedFrom*" edge signifies that these implications can be derived from specific policy scenarios, which can encompass backcasted, forecasted, and Business-As-Usual (BAU) scenarios.

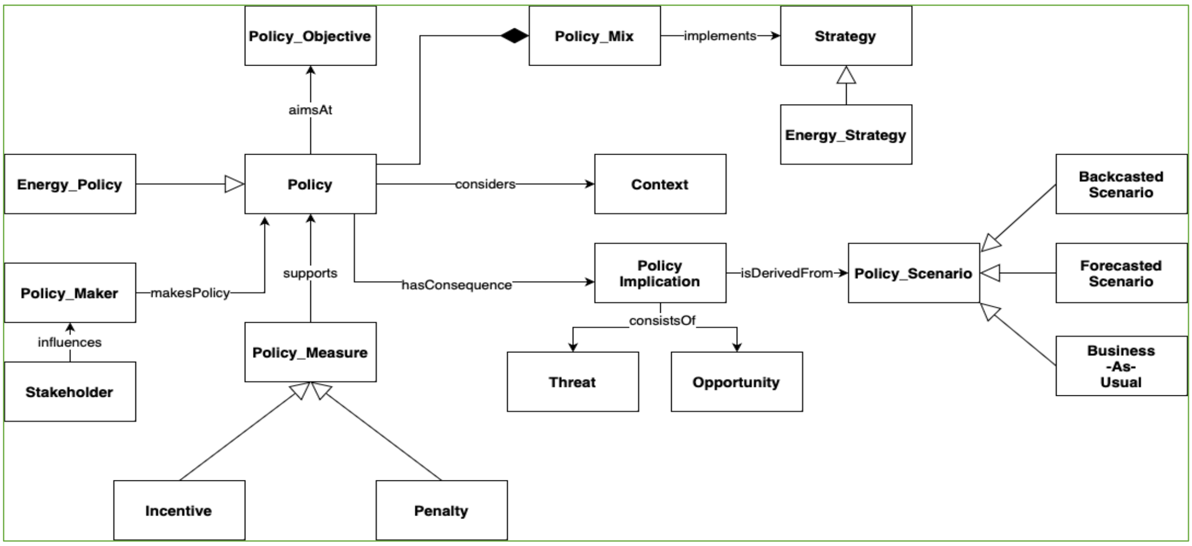


Figure 22. UML representation of the energy policy ontology design pattern

Finally, Table 9 includes the ontology paths and connection with BFO foundational concepts for the concepts within the energy policy ODP, while Table 10 provides the description of these concepts.

Table 9. Ontology paths and connection with BFO foundational concepts for the concepts within the energy policy ODP

ESO concept	Ontology path
Backcasted scenario	**entity>occurrent>process**>future_prospect >Policy_scenario>backcasted_scenario
Business-As-Usual	**entity>occurrent>process**>future_prospect >Policy_scenario>business-as-usual
Context	**entity>occurrent>spatiotemporal_region**>context
Energy policy	**entity>continuant>specifically_dependent_continuant> realizable_entity>disposition>function**>policy>energy_policy
Energy strategy	**entity>continuant>specifically_dependent_continuant> realizable_entity>disposition>function**>strategy>energy_strategy
Forecasted scenario	**entity>occurrent>process**>future_prospect >Policy_scenario>forecasted_scenario
Incentive	**realizable_entity>disposition**>behavior_driver> external_behavior_drive>policy-dependent_behavior_driver> policy_measure>incentive
Opportunity	**entity>occurrent>process**>Event>System_event>Potential_event > Opportunity
Penalty	**entity>continuant>specifically_dependent_continuant> realizable_entity>disposition>function**>policy_measure>penalty
Policy	**entity>continuant>specifically_dependent_continuant> realizable_entity>disposition>function**>policy
Policy implication	**entity>occurrent>process**>policy_implication
Policy maker	**entity>continuant>specifically_dependent_continuant> realizable_entity>role**>actor>policy-maker
Policy measure	**entity>continuant>specifically_dependent_continuant> realizable_entity>disposition>function**>policy_measure
Policy mix	**entity>continuant>specifically_dependent_continuant> realizable_entity>disposition>function**>policy_mix
Policy objective	**entity>continuant>specifically_dependent_continuant> quality**>target>policy_objective
Policy scenario	**entity>occurrent>process**>future_prospect>Policy_scenario
Stakeholder	**entity>continuant>specifically_dependent_continuant>**

	realizable_entity>role>actor>stakeholder
Strategy	**entity>continuant>specifically_dependent_continuant>** **realizable_entity>disposition>function**>strategy
Threat	**entity>occurrent>process**>Event>System_event>Potential_event > Threat

Table 10. Descriptions of the concepts within the energy policy ODP

ESO concept	Description
Backcasted scenario	A backcasted scenario is a type of scenario planning where the desired future outcome is envisioned first, and then the steps, strategies, and actions needed to achieve that outcome are determined by working backward from that future vision. This approach contrasts with forecasting or traditional scenario planning, where future possibilities are explored based on current trends or projections. Backcasted scenarios focus on defining a preferred future state and identifying the pathways to reach it (OpenAI, 2023).
Business-As-Usual	"Business As Usual" (BAU) is a term used to describe the normal or standard operations of a business or organization. It refers to the day-to-day routine and activities that are regularly carried out without significant changes or disruptions. in the context of business, it implies that operations are running smoothly without any major deviations from established practices or strategies (OpenAI, 2023).
Context	Context refers to the surrounding circumstances, conditions, or background information that provides a framework for understanding and interpreting something. It includes the environment, setting, and relevant factors that contribute to the meaning, significance, or interpretation of an event, statement, or situation (OpenAI, 2023).
Energy policy	Energy policy refers to the set of principles, strategies, and measures adopted by governments and policymakers to guide the management, regulation, and development of energy resources and the energy sector as a whole.
Energy strategy	Energy strategy refers to a comprehensive and integrated plan of action developed by governments, organizations, or businesses to guide their energy-related decisions and activities (OpenAI, 2023).
Forecasted scenario	A forecasted scenario is a type of scenario planning where potential future outcomes are envisioned based on current trends, data, and projections. It involves making predictions about possible future events, conditions, or developments by analyzing existing information and extrapolating trends. Forecasted scenarios provide insights into potential future situations but may not consider alternative or unexpected factors that could influence the outcomes (OpenAI, 2023).

Incentive	A positive motivational influence. An additional payment (or other remuneration) to employees as a means of increasing output (WordNet, 2023).
Opportunity	Favorable or advantageous situation, circumstance, or set of conditions that allow for the possibility of achieving a desired outcome or goal. Opportunities can arise in various aspects of life, including personal, professional, educational, and business domains (OpenAI, 2023).
Penalty	A penalty is a punitive consequence or punishment imposed for the violation of a law, rule, contract, or established code of conduct, often involving fines, imprisonment, or other sanctions (OpenAI, 2023).
Policy	- A plan of action adopted by an individual or social group.- A line of argument rationalizing the course of action of a government (WordNet, 2023).
Policy implication	Potential consequences or recommendations that arise from the findings, analysis, or evaluation of a particular policy, program, or research study.
Policy maker	Individual or a group of individuals who are responsible for formulating and implementing policies that guide the actions and decisions of a government or an organization (OpenAI, 2023).
Policy measure	Specific actions, interventions, or instruments that policymakers implement to achieve the objectives outlined in a policy (OpenAI, 2023).
Policy mix	Combination and coordination of multiple policies, strategies, and measures used by governments or organizations to address complex societal issues or achieve specific objectives (OpenAI, 2023).
Policy objective	Specific and measurable goals or outcomes that policymakers aim to achieve through the implementation of a particular public policy (OpenAI, 2023).
Policy scenario	Hypothetical or speculative representation of how a specific policy or set of policies might unfold and impact a given situation or issue (OpenAI, 2023).
Stakeholder	A person or organization that is interested in a system or its subsystems (Coletti, et al., 2020).
Strategy	An elaborate and systematic plan of action (WordNet, 2023).
Threat	Something dangerous for a system.

2.4.4.6. Energy research ontology design pattern (ESO-ODP-006)

The energy research ontology design pattern refers to the systematic and scientific investigation aimed at advancing knowledge and understanding of various aspects of energy production, distribution, storage, and consumption as well as environmental, policy and strategy aspects.

Figure 23 shows the**Errore. L'origine riferimento non è stata trovata.** UML representation of the energy research ODP. In the context of ESO, the energy domain comprises five subsystems: environment, energy operations, agent behavior, strategy, and policy. The "*addresses*" edge is employed to indicate that natural science research focuses on the environment subsystem and the energy operations subsystem. The latter is also the subject of study in design science research. In contrast, behavioral science research addresses agent behavior, strategy, and policy subsystems. The "*develops*" edge, linked to natural science research, signifies that it involves the development of models, theories, and laws. Additionally, the "*hasActivity*" edge, associated with natural science research, is used to indicate that this type of research employs two fundamental methods: discovery and justification. Design science research, on the other hand, involves the creation of constructs, models, methods, and implementations (as indicated by the "*builds*" edge) and employs two fundamental methods: evaluation and build (as indicated by the "*hasActivity*" edge linked to design science). Regarding behavioral science research, the "*develops*" edge is used to indicate that it is focused on developing and validating theories that predict human and organizational behavior (March & Smith, 1995). It is worth noting that this type of research utilizes the same methods as natural science research (as seen in the "*hasActivity*" edge connected to behavioral science research).

Finally, Table 11 includes the ontology paths and connection with BFO foundational concepts for the concepts within the energy research ODP, while Table 12 provides the description of these concepts.

Table 11. Ontology paths and connection with BFO foundational concepts for the concepts within the energy research ODP

ESO concept	Ontology path
Agent behavior subsystem	**entity>continuant>independent_continuant>material_entity> object_aggregate**>subsystem>agent_behavior_subsystem
Behavioral research	**entity>occurrent>process**>research>behavioral_research
Build	**entity>occurrent>process**>research_activity>build
Construct	**entity>continuant>specifically_dependent_continuant> realizable_entity>disposition>function**>research_artifact>construct
Design science research	**entity>occurrent>process**>research>design_science_research
Discovery	**entity>occurrent>process**>research_activity>discovery
Energy domain of interest	**entity>continuant>independent_continuant>material_entity> object_aggregate**>domain_of_interest>energy_domain_of_interest

Energy operations subsystem	**entity>continuant>independent_continuant>material_entity> object_aggregate**>subsystem>energy_operations_subsystem
Energy research	**entity>occurrent>process**>energy_research
Environment subsystem	**entity>continuant>independent_continuant>material_entity> object_aggregate**>subsystem>environment_subsystem
Evaluate	**entity>occurrent>process**>research_activity>evaluate
Implementation	**entity>continuant>specifically_dependent_continuant> realizable_entity>disposition>function**>research_artifact> implementation
Justification	**entity>occurrent>process**>research_activity>justification
Method	**entity>continuant>specifically_dependent_continuant> realizable_entity>disposition>function**>research_artifact>method
Model	**entity>continuant>specifically_dependent_continuant> realizable_entity>disposition>function**>research_artifact>model
Natural science law	**entity>continuant>specifically_dependent_continuant> realizable_entity>disposition>function**>research_artifact> natural_science_law
Natural science model	**entity>continuant>specifically_dependent_continuant> realizable_entity>disposition>function**>research_artifact> natural_science_model **entity>continuant>specifically_dependent_continuant> realizable_entity>disposition>function**>research_artifact>
Natural science research	**entity>occurrent>process**>research>natural_science_research
Policy subsystem	**entity>continuant>independent_continuant>material_entity> object_aggregate**>subsystem>policy_subsystem
Strategy subsystem	**entity>continuant>independent_continuant>material_entity> object_aggregate**>subsystem>strategy_subsystem
Subsystem	**entity>continuant>independent_continuant>material_entity> object_aggregate**>subsystem
Theory	**entity>continuant>specifically_dependent_continuant> realizable_entity>disposition>function**>research_artifact>theory

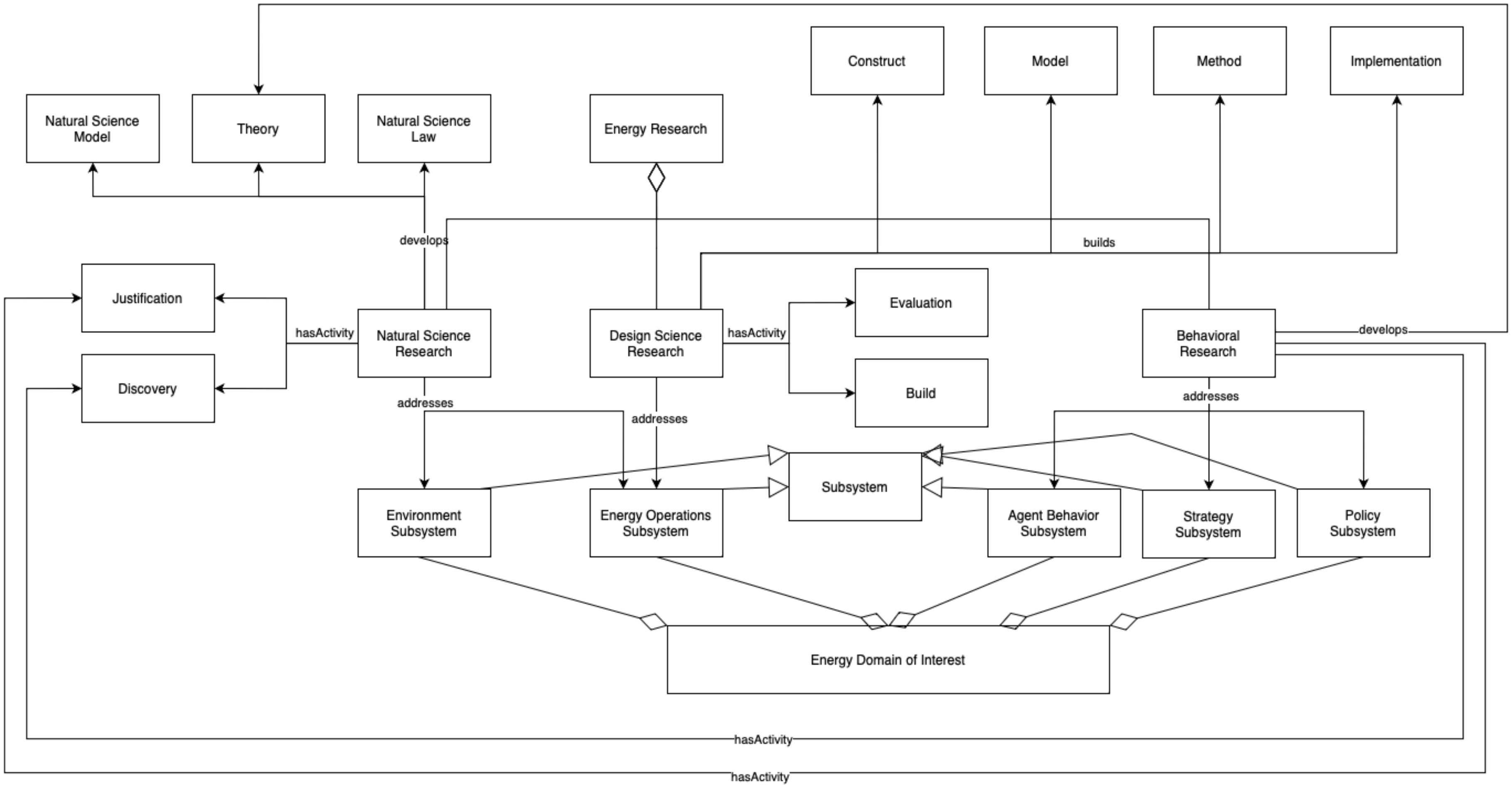


Figure 23. UML representation of the energy research ontology design pattern

Table 12. Descriptions of the concepts within the energy research ODP

ESO concept	Description
Agent behavior subsystem	It refers to a part of a system or software that is responsible for defining the behaviors, actions, and decision-making processes of an autonomous agent, such as a robot, computer program, or AI entity (OpenAI, 2023).
Behavioral research	Behavioral research is a scientific method used to study and understand human or animal behavior. it aims to explore and explain various aspects of behavior, including actions, thoughts, emotions, and interactions with the environment (OpenAI, 2023).
Build	"Build" can have different meanings depending on the context. Here are several definitions for different contexts: Construct: In this context, "build" means to create or assemble something by putting together different components or elements to form a complete structure or system. Model: In modeling, "build" refers to creating a physical or digital representation of an object, system, or concept, often for the purpose of studying its behavior, characteristics, or interactions. Implementation: When talking about software or systems, "build" refers to the process of developing and coding the software or system based on design specifications. Method: In scientific research, "build" might refer to the development or formulation of a new approach, technique, or method for conducting experiments or solving problems. (OpenAI, 2023)
Construct	Constructs or concepts form the vocabulary of a domain. They constitute a conceptualization used to describe problems within the domain and to specify their solutions. They form the specialized language and shared knowledge of a discipline or sub-discipline. Such constructs may be highly formalized as in semantic data modelling formalisms (having constructs such as entities, attributes, relationships, identifiers, constraints), or informal as in cooperative work (con- sensus, participation, satisfaction) (March & Smith, 1995).
Design science research	Design science research is a systematic and structured approach used in disciplines such as engineering, computer science, and information systems to create, develop, and evaluate innovative solutions, artifacts, or systems to address specific practical problems or challenges. It involves a cycle of designing, building, and testing artifacts while following established research methodologies to contribute new knowledge, methods, or tools to the field (OpenAI, 2023).
Discovery	Discovery refers to the act of finding, identifying, or uncovering something that was previously unknown, hidden, or not widely recognized. It often involves exploration, research, or observation that leads to the revelation of new information, insights, phenomena, or possibilities. Discoveries can occur in various fields such as science, history, art, and everyday life,

	contributing to the expansion of knowledge and understanding (OpenAI, 2023).
Energy domain of interest	The energy domain of interest refers to the specific area, field, or subject within the broader realm of energy-related topics that an individual, organization, or study focuses on or explores. It defines the scope and boundaries of the energy-related issues, technologies, or aspects that are being considered or investigated (OpenAI, 2023).
Energy operations subsystem	Its meaning may vary depending on the context in which it is used. In the context of energy systems and infrastructure, the "energy operations subsystem" could refer to a specific component or part of an overall energy management or distribution system (OpenAI, 2023).
Energy research	Energy research is a broad and multidisciplinary field of scientific investigation that focuses on the study, development, and advancement of various aspects related to energy production, consumption, efficiency, sustainability, and management. The primary goal of energy research is to address the challenges and opportunities associated with the production and use of energy resources while striving for economic, environmental, and societal benefits (OpenAI, 2023).
Environment subsystem	It refers to a specific component or part of a larger system or organization that is responsible for monitoring, managing, or addressing environmental factors, concerns, or aspects within a defined context (OpenAI, 2023).
Evaluate	To evaluate means to assess, analyze, or judge the value, quality, significance, or effectiveness of something based on specific criteria or standards. It involves critically examining the characteristics, attributes, or outcomes of an object, idea, process, or situation to form an informed judgment or decision. Evaluation often leads to conclusions, recommendations, or actions based on the findings of the assessment (OpenAI, 2023).
Implementation	An implementation or instantiation is the realization of an artifact in its environment (March & Smith, 1995).
Justification	Justification refers to the act of providing valid reasons, explanations, or evidence to support a decision, action, belief, or proposition. It involves presenting logical or factual arguments that demonstrate the validity or correctness of a particular choice, position, or course of action. Justification is often used to persuade or convince others of the soundness of one's ideas or choices (OpenAI, 2023).
Method	A method is a set of steps (an algorithm or guideline) used to perform a task (March & Smith, 1995).
Model	A model is a set of propositions or statements expressing relationships among constructs (March & Smith, 1995).
Natural science law	Natural science law refers to a fundamental principle or statement that describes a consistent and universal relationship or pattern observed in the natural world. Natural science laws

	are at the core of scientific understanding and are used to explain and predict natural phenomena (OpenAI, 2023).
Natural science model	The Natural Science model refers to a simplified representation or conceptual framework that scientists use to understand, explain, or predict natural phenomena (OpenAI, 2023).
Natural science research	Natural science research refers to systematic and empirical investigations conducted within disciplines such as physics, chemistry, biology, astronomy, and earth sciences to gain a deeper understanding of the natural world and its phenomena. This type of research involves observation, experimentation, data collection, and analysis to uncover fundamental principles, laws, and patterns governing the physical and biological aspects of the universe (OpenAI, 2023).
Policy subsystem	In the field of political science and policy analysis, a "policy subsystem" refers to a specific and relatively self-contained segment or component within the broader political system that focuses on the development, implementation, and evaluation of policies related to a particular issue or area of public concern (OpenAI, 2023).
Strategy subsystem	Strategy subsystem doesn't have a standardized definition. In a strategic management context, a "strategy subsystem" could refer to a specific component or element within an organization's overall strategy or strategic planning process (OpenAI, 2023).
Subsystem	A concept used in various fields to describe a component or part of a larger system. A subsystem is a smaller, specialized system that functions within the context of a broader or main system. It typically serves a specific purpose or performs certain functions within the larger system (OpenAI, 2023).
Theory	Theories - deep, principled explanations of phenomena - are the crowning achievements of natural science research. Products of natural science research are evaluated against norms of truth, or explanatory power. Claims must be consistent with observed facts, the ability to predict future observations being a mark of explanatory success. Progress is achieved as new theories provide deeper, more encompassing, and more accurate explanations) (March & Smith, 1995).

2.4.4.7 Energy saving ontology design pattern (ESO-ODP-007)

The energy saving ontology design pattern refers to the practice of reducing energy consumption or using energy more efficiently to achieve the same level of output or service by ensuring user satisfaction.

Figure 24 shows the UML representation of the energy saving ODP. The "*reduces*" edge is utilized to signify that energy saving, classified as a behavior of an energy end user (as indicated by the "*hasBehavior*" edge), leads to a reduction in energy consumption. The advantages of energy saving encompass lower energy costs, increased energy security, environmental benefits, and support for sustainable development (as indicated by the "*hasBenefit*" edge). The "*ensure*" edge emphasizes that energy saving should ensure user satisfaction. The "*isPerceivedBy*" edge is employed to indicate that the latter is recognized by an energy end user that has a behavior driver (as depicted in the corresponding diagram edge). In the diagram, the "*implies*" and "*isDueTo*" edges, respectively clarify that energy usage stems from an energy end user and results from energy consumption.

Finally, Table 13 includes the ontology paths and connection with BFO foundational concepts for the concepts within the energy saving ODP, while Table 14 provides the description of these concepts.

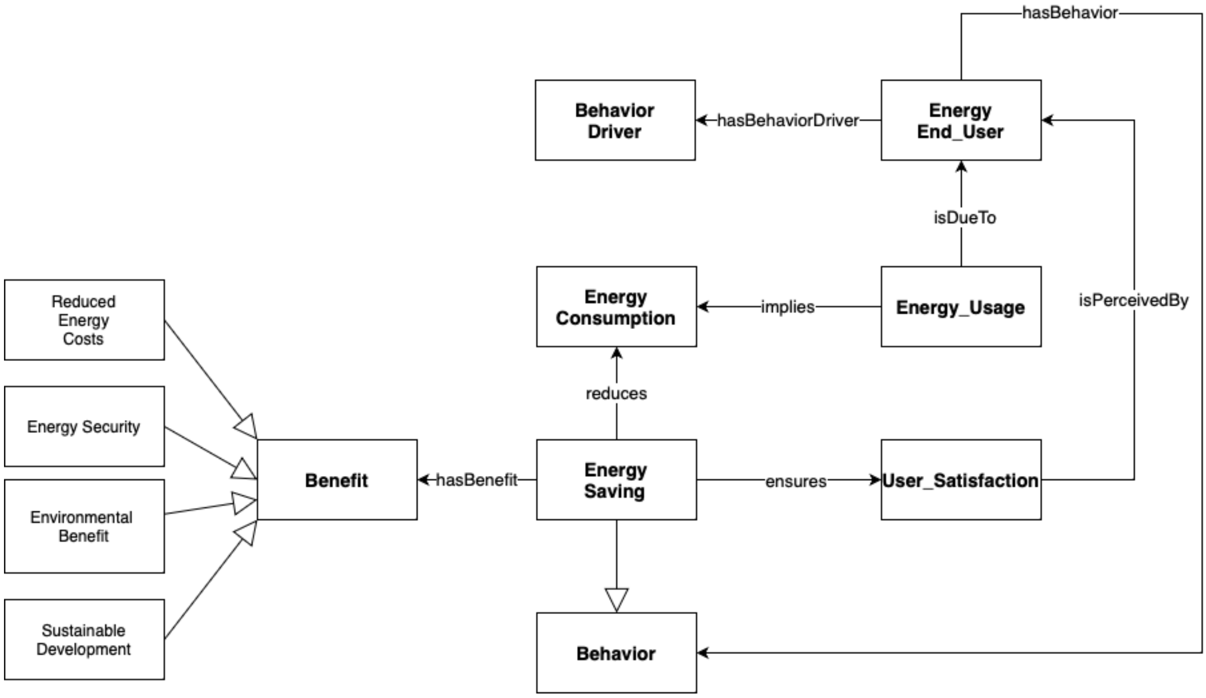


Figure 24. UML representation of the energy saving ontology design pattern

Table 13. Ontology paths and connection with BFO foundational concepts for the concepts within the energy saving ODP

ESO concept	Ontology path
Behavior	**entity>occurrent>process**>behavior
Behavior driver	**entity>continuant>specifically_dependent_continuant> realizable_entity>disposition**>behavior_driver
Benefit	**entity>continuant>specifically_dependent_continuant> quality**>benefit
Energy consumption	**entity>occurrent>process**>consumption>energy_consumption

Energy end user	**entity>continuant>specifically_dependent_continuant> realizable_entity>role**>actor>market_participant> energy_market_participant>energy_end_user
Energy saving	**entity>occurrent>process**>behavior>energy_saving
Energy security	**entity>continuant>specifically_dependent_continuant> quality**>benefit>energy_security
Energy usage	**entity**>System_aspect>Service_request>energy_usage
Environmental benefit	**entity>continuant>specifically_dependent_continuant> quality**>benefit>environmental_benefit
Reduced energy costs	**entity>continuant>specifically_dependent_continuant> quality**>benefit>reduced_energy_costs
Sustainable development	**entity>continuant>specifically_dependent_continuant> quality**>benefit>sustainable_development
User satisfaction	**entity>continuant>specifically_dependent_continuant> quality**>user_satisfaction

Table 14. Descriptions of the concepts within the energy saving ODP

ESO concept	Ontology path
Behavior	- Manner of acting or controlling yourself (behavioral attributes). The way a person behaves toward other people (WordNet, 2023).
Behavior driver	A behavior driver is a factor that influences and motivates individuals to engage in specific actions or make specific decision choices (OpenAI, 2023).
Benefit	A benefit refers to a positive outcome, advantage, or gain that is derived from a particular action, situation, decision, or circumstance. It is something that contributes positively to an individual, group, organization, or society, often improving well-being, satisfaction, efficiency, or overall quality of life. Benefits can be tangible, such as monetary rewards, or intangible, such as improved health or enhanced reputation (OpenAI, 2023).
Energy consumption	The amount of energy used by individuals, communities, industries, or countries to carry out various activities and meet their energy needs. The utilization of various forms of energy, such as electricity, fossil fuels, renewable energy sources, and other energy carriers, for different purposes in homes, industries, transportation, and other sectors (OpenAI, 2023).
Energy end user	An energy end-user is an individual, household, business, or organization that consumes energy resources, such as electricity, natural gas, or fuel, for various purposes, including heating,

	cooling, lighting, industrial processes, transportation, and other activities (OpenAI, 2023).
Energy saving	Also known as energy conservation or energy efficiency, refers to the practice of using less energy to achieve the same level of output or desired services (OpenAI, 2023).
Energy security	Energy security refers to the state of having a reliable and sufficient energy supply to meet the energy needs of a country, region, or community (OpenAI, 2023).
Energy usage	The amount of energy consumed by individuals, communities, industries, and societies to meet various needs and perform different activities.
Environmental benefit	The positive impacts or advantages that arise from actions, practices, policies, or technologies that promote environmental sustainability and conservation that contribute to the protection, preservation, and improvement of the natural environment, ecosystems, and biodiversity (OpenAI, 2023).
Reduced energy costs	Reduced energy costs refer to the situation where the expenses associated with consuming energy resources, such as electricity, natural gas, or fuel, are decreased or lowered. This reduction can result from various factors, including increased energy efficiency, the adoption of renewable energy sources, improved technologies, or changes in consumption patterns, ultimately leading to financial savings for individuals, businesses, or organizations (OpenAI, 2023).
Sustainable development	Development that meets the needs of the present without compromising the ability of future generations to meet their own needs (OpenAI, 2023).
User satisfaction	User satisfaction refers to the level of contentment, fulfillment, or positive feelings experienced by individuals or users who interact with a product, service, system, or experience. It reflects how well the expectations, needs, and preferences of users are met, often indicating the success of a product or service in delivering value and meeting user requirements. User satisfaction can be influenced by factors such as functionality, usability, quality, and overall user experience (OpenAI, 2023).

2.4.4.8. Energy security ontology design pattern (ESO-ODP-008)

The energy security ontology design pattern refers to the strategic goal of assuring that a country or region has access to a reliable, affordable, and uninterrupted supply of energy resources to meet its economic, social, and environmental needs.

Figure 25 shows the UML representation of the energy security ODP. The "*aimsAt*" edge signifies that the objective of an energy strategy is an energy strategy goal. Energy security is classified as an energy strategy goal. The "*encompasses*" edge is employed to indicate that this concept includes elements such as energy efficiency, reliability, accessibility, availability, sustainability, and an appropriate energy mix. Several factors impact energy security (as shown by the "*affects*" edge in the diagram) including energy import, international energy trade, and geopolitical tensions.

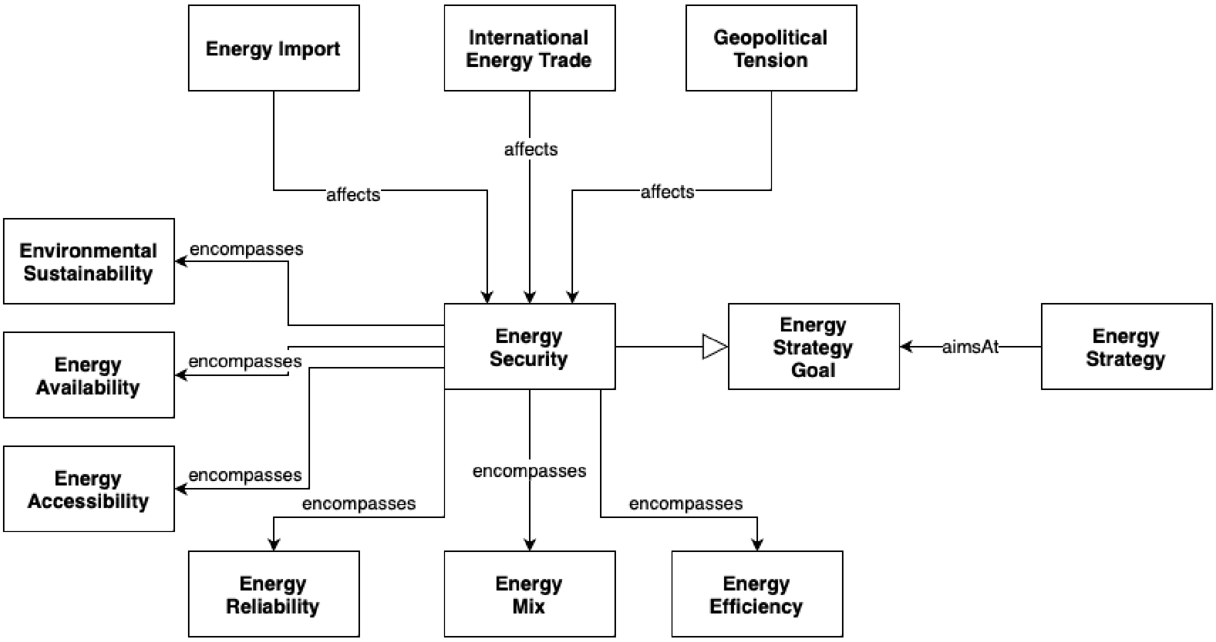


Figure 25. UML representation of the energy security ontology design pattern

Finally, Table 15 includes the ontology paths and connection with BFO foundational concepts for the concepts within the energy security ODP, while Table 16 provides the description of these concepts.

Table 15. Ontology paths and connection with BFO foundational concepts for the concepts within the energy security ODP

ESO concept	Ontology path
Energy accessibility	**entity>continuant>specifically_dependent_continuant> quality**>System_property>Internal_system_conditions>Ility> energy_accessibility
Energy availability	**entity>continuant>specifically_dependent_continuant> quality**>System_property>Internal_system_conditions>Ility> energy_availability
Energy efficiency	**entity>continuant>specifically_dependent_continuant> quality**>System_property>Internal_system_conditions>Ility> energy_efficiency
Energy import	**entity>occurrent>process**>energy_import
Energy mix	**entity>continuant>independent_continuant>material_entity> object_aggregate**>object_aggregate

Energy reliability	**entity>continuant>specifically_dependent_continuant> quality**>System_property>Internal_system_conditions>Ility> Reliability>energy_reliability
Energy security	**entity>continuant>specifically_dependent_continuant> quality**>benefit>energy_security
Energy strategy	**entity>continuant>specifically_dependent_continuant> realizable_entity>disposition>function**>strategy>energy_strategy
Energy strategy goal	**entity>continuant>specifically_dependent_continuant> quality**>target>energy_strategy_goal
Environmental sustainability	**entity>continuant>specifically_dependent_continuant> quality**>System_property>Internal_system_conditions>Ility> Sustainability>environmental_sustainability
Geopolitical tension	**entity>occurrent>process**>geopolitical_factor>geopolitical_tension
International energy trade	**entity>occurrent>process**>international_trade> international_energy_trade

Table 16. Descriptions of the concepts within the energy security ODP

ESO concept	Description
Energy accessibility	Availability and ease of access to energy resources, particularly electricity and clean cooking solutions, for individuals, communities, or entire populations (OpenAI, 2023).
Energy availability	Energy availability is a concept that relates to the accessibility and readiness of energy resources for use in a particular context, whether it's for individual, industrial, or societal needs. It refers to the presence and capability of energy sources to meet demand and perform work (OpenAI, 2023).
Energy efficiency	The concept of energy efficiency refers to the ability to accomplish a desired level of output, service, or performance while minimizing energy consumption. it is a measure of how effectively energy is utilized to achieve a specific goal or task (OpenAI, 2023).
Energy import	Energy import refers to the process by which a country or region purchases energy resources, such as crude oil, natural gas, coal, or electricity, from foreign sources to meet its energy needs (OpenAI, 2023).
Energy mix	The concept of the energy mix refers to the combination and proportion of different energy sources that are used to meet the energy demands of a particular region, country, or the world as a whole. it represents the diversity of energy resources and technologies that contribute to the overall energy supply (OpenAI, 2023).

Energy reliability	Energy reliability refers to the consistency, dependability, and stability of energy supply to meet the demands of consumers and businesses. It encompasses the ability of an energy system to provide power and resources consistently, without interruptions or disruptions, ensuring that energy is available when and where it is needed. Factors such as infrastructure resilience, maintenance practices, diversification of energy sources, and emergency response planning contribute to energy reliability (OpenAI, 2023).
Energy security	Energy security refers to the state of having a reliable and sufficient energy supply to meet the energy needs of a country, region, or community (OpenAI, 2023).
Energy strategy	Energy strategy refers to a comprehensive and integrated plan of action developed by governments, organizations, or businesses to guide their energy-related decisions and activities (OpenAI, 2023).
Energy strategy goal	An energy strategy goal is a specific and targeted objective or aim set within an overall energy strategy. It outlines a desired outcome or accomplishment that the energy strategy aims to achieve, such as increasing the share of renewable energy sources, improving energy efficiency, reducing carbon emissions, enhancing energy security, or promoting sustainable energy development. These goals guide the direction and actions of energy policies and initiatives (OpenAI, 2023).
Environmental sustainability	The responsible and balanced use of natural resources and the protection of ecosystems to meet the needs of the present generation without compromising the ability of future generations to meet their own needs and requires integrating environmental considerations into decision-making processes and adopting practices that promote long-term ecological balance, social equity, and economic prosperity (OpenAI, 2023).
Geopolitical tension	Geopolitical tension refers to the strained or uneasy relationships between countries, regions, or global entities due to political, economic, social, or territorial disputes. These tensions often arise from conflicting interests, power struggles, resource competition, historical grievances, or differing ideologies, and can manifest as diplomatic disagreements, trade conflicts, military posturing, or other forms of discord that have the potential to escalate into more serious conflicts (OpenAI, 2023).
International energy trade	International energy trade refers to the exchange and commerce of energy resources, such as oil, natural gas, electricity, and coal, between different countries or regions. It involves the buying, selling, importing, and exporting of energy commodities to meet the energy demands and supply shortages of various nations, often driven by economic considerations, geopolitical factors, and resource availability (OpenAI, 2023).

2.4.4.9 Energy sources exploitation ontology design pattern (ESO-ODP-009)

The energy sources exploitation ontology design pattern refers to the utilization of primary sources for a specific energy usage.

Figure 26**Errore. L'origine riferimento non è stata trovata.** shows the UML representation of the energy sources exploitation ODP. Energy policies determine how energy sources are utilized, as depicted by the "*determines*" edge in the diagram. The "*exploits*" edge indicates that the process of exploiting energy sources involves the use of primary energy sources. The "*aimsAt*" edge is utilized to signify that the goal of energy source exploitation is energy usage, while the "*hasImpactOn*" edge is employed to emphasize that this usage can have environmental consequences. It can be positive, as in the case of solar energy usage, or potentially negative, such as pollution resulting from oil spills or deforestation. The "*uses*" edge is employed to indicate that energy usage requires an energy input, and the "*hasSource*" edge indicates that energy is derived from primary energy sources.

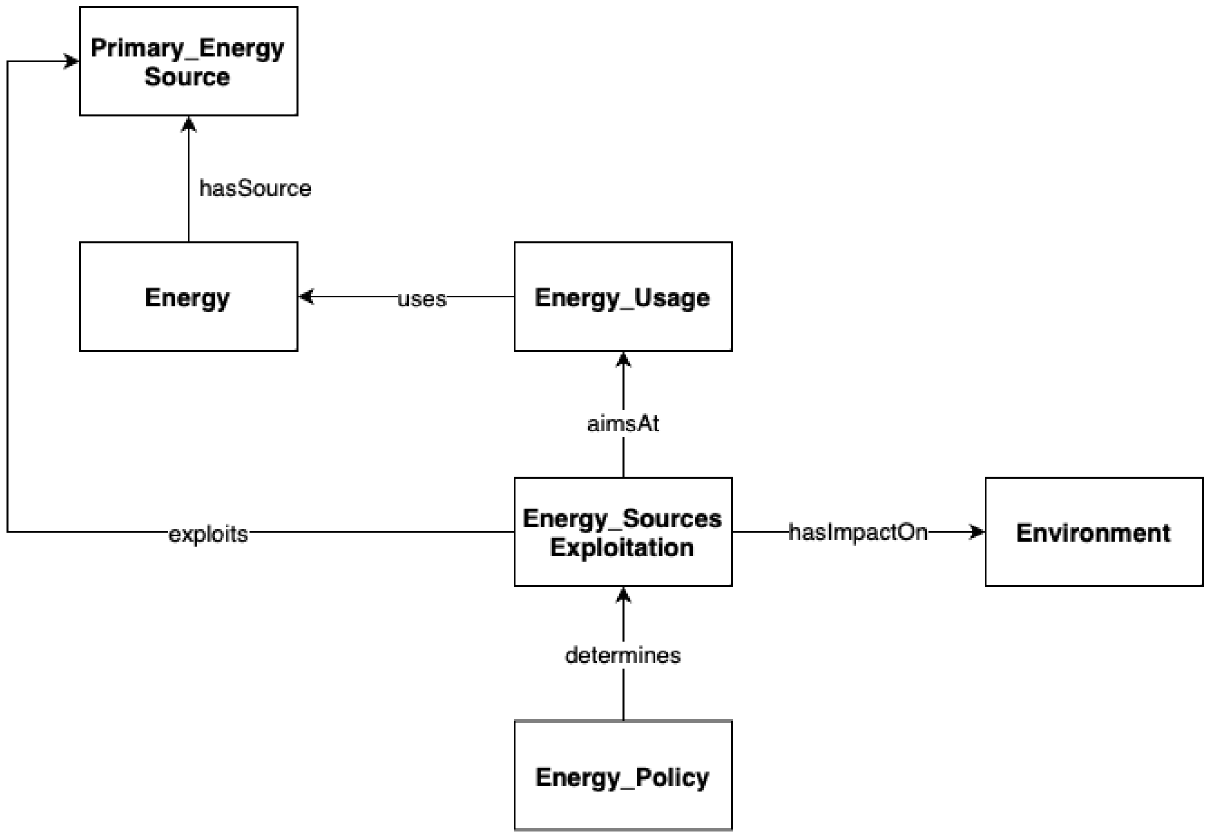


Figure 26. UML representation of the energy sources exploitation ontology design pattern

Finally, Table 17 includes the ontology paths and connection with BFO foundational concepts for the concepts within the energy sources exploitation ODP, while Table 18 provides the description of these concepts.

Table 17. Ontology paths and connection with BFO foundational concepts for the concepts within the energy sources exploitation ODP

ESO concept	Ontology path
Energy	**entity>continuant>specifically_dependent_continuant> quality**>energy
Energy policy	**entity>continuant>specifically_dependent_continuant> realizable_entity>disposition>function**>policy>energy_policy
Energy sources exploitation	**entity>occurrent>process**>energy_sources_exploitation
Energy usage	**entity**>System_aspect>Service_request>energy_usage
Environment	**entity>continuant>independent_continuant>material_entity> object_aggregate**>environment
Primary energy source	**entity>continuant**>energy_commodity>primary_energy_source

Table 18. Descriptions of the concepts within the energy sources exploitation ODP

ESO concept	Description
Energy	Energy is a quality of material entities which manifests as a capacity to perform work (such as causing motion or the interaction of molecules) (Booshehri, et al., 2021).
Energy policy	Energy policy Energy policy refers to the set of principles, strategies, and measures adopted by governments and policymakers to guide the management, regulation, and development of energy resources and the energy sector as a whole (OpenAI, 2023).
Energy sources exploitation	Energy sources exploitation refers to the utilization, extraction, and harnessing of various energy resources, such as fossil fuels (coal, oil, natural gas), renewable sources (solar, wind, hydro), and nuclear materials, for the purpose of generating energy. This process involves the extraction, conversion, and distribution of energy resources to meet the energy demands of society, industries, and other sectors. It can encompass activities ranging from drilling for oil to installing solar panels, all aimed at making the energy resources available for consumption (OpenAI, 2023).
Energy usage	The amount of energy consumed by individuals, communities, industries, and societies to meet various needs and perform different activities.
Environment	A concept which includes all aspects of the surroundings of humanity, affecting individuals and social groupings. The

	European Union has defined the environment as "the combination of elements whose complex interrelationships make up the settings, the surroundings and the conditions of life of the individual and of society, as they are or as they are felt". The environment thus includes the built environment, the natural environment and all natural resources, including air, land and water. It also includes the surroundings of the workplace. [Source: Glossary - Environment European Agency. https://www.eea.europa.eu/help/glossary#c4=10&c0=all&b_start=190&c2=environment]
Primary energy source	A primary energy source is a natural resource that can be directly extracted or harnessed to produce energy in its raw form, such as fossil fuels (coal, oil, natural gas), renewable sources (solar, wind, hydro), and nuclear materials (uranium) (OpenAI, 2023).

2.4.4.10 Energy strategy definition ontology design pattern (ESO-ODP-010)

The energy strategy ontology design pattern refers to a comprehensive and long-term plan or set of actions developed by governments, organizations, or entities to guide their decisions and initiatives regarding energy production, distribution, consumption, and management.

Figure 27 **Errore. L'origine riferimento non è stata trovata.**shows the UML representation of the energy strategy ODP. The "*aimsAt*" edge is employed to denote the specific objective of an energy strategy, such as transitioning to renewable energy sources or ensuring energy security. The "*implements*" edge , linked to the policy mix, signifies the requirement for a set of policies to put it into Subsequently, an energy strategy is formulated by policymakers (as indicated by the "*defines*" edge), and their decisions are influenced by stakeholders (as shown by the "influences" This strategy is put into action through an action plan (as indicated by the "involves" edge), typically encompassing tasks like assessing energy resources, analyzing demand, securing investments and funding, and establishing a system for monitoring and evaluation.

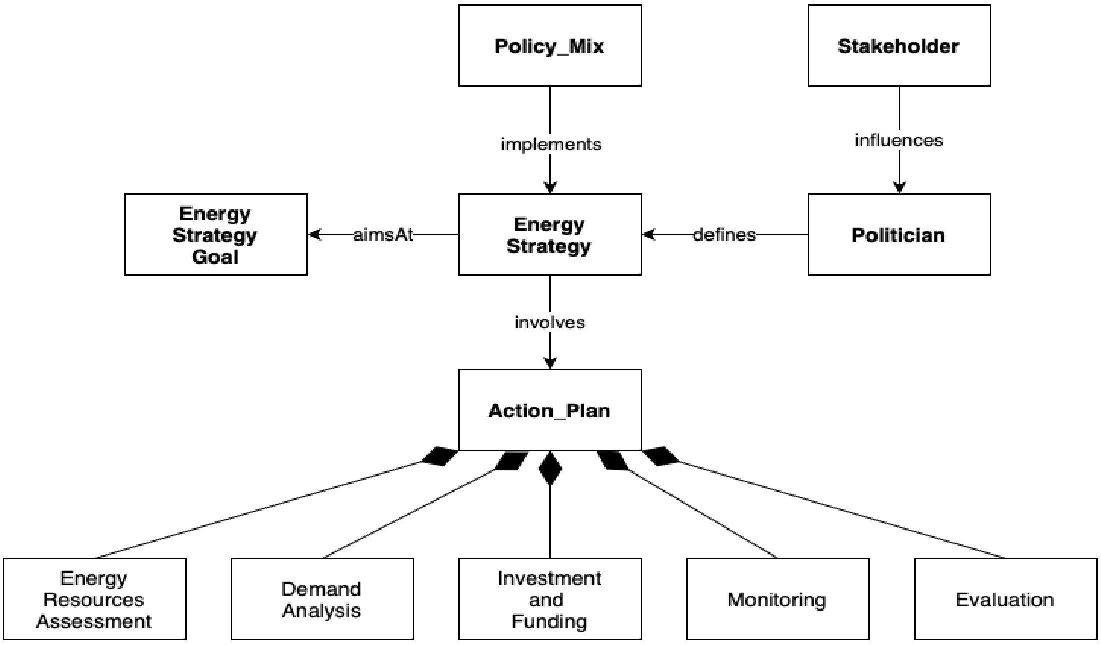


Figure 27 UML representation of the energy strategy ontology design pattern

Finally, Table 19 includes the ontology paths and connection with BFO foundational concepts for the concepts within the energy strategy ODP, while Table 20 provides the description of these concepts.

Table 19. Ontology paths and connection with BFO foundational concepts for the concepts within the energy strategy ODP

ESO concept	Ontology path
Action plan	**entity>continuant>specifically_dependent_continuant> realizable_entity>disposition>function**>action_plan
Demand analysis	**entity>occurrent>process**>system_internal_operation> demand_analysis
Energy resources assessment	**entity>occurrent>process**>energy_resources_assessment
Energy strategy	**entity>continuant>specifically_dependent_continuant> realizable_entity>disposition>function**>strategy>energy_strategy
Energy strategy goal	**entity>continuant>specifically_dependent_continuant> quality**>target>energy_strategy_goal
Evaluation	**entity>occurrent>process**>evaluation
Investment and funding	**entity>occurrent>process**> Investment_and_funding
Monitoring	**entity>occurrent>process**>monitoring
Policy mix	**entity>continuant>specifically_dependent_continuant> realizable_entity>disposition>function**>policy_mix
Politician	**entity>continuant>specifically_dependent_continuant>**

	realizable_entity>role>actor>politician
Stakeholder	**entity>continuant>specifically_dependent_continuant>** **realizable_entity>role**>actor>stakeholder

Table 20. Descriptions of the concepts within the energy strategy ODP

ESO concept	Description
Action plan	An action plan is a structured and detailed outline of the specific steps or activities that need to be taken to achieve a particular goal or objective (OpenAI, 2023).
Demand analysis	The examination and study of consumer behavior, preferences, and purchasing patterns to understand the factors influencing the quantity of goods or services that consumers are willing and able to buy at different price levels and under various market conditions (OpenAI, 2023).
Energy resources assessment	Energy resources assessment refers to the systematic evaluation and analysis of available energy sources within a specific region or area. It involves identifying and quantifying various energy resources, such as fossil fuels, renewable sources, and nuclear materials, to determine their potential for use as energy inputs. This assessment typically considers factors such as availability, accessibility, economic viability, environmental impact, and technological feasibility to inform decision-making and energy planning efforts (OpenAI, 2023).
Energy strategy	Energy strategy refers to a comprehensive and integrated plan of action developed by governments, organizations, or businesses to guide their energy-related decisions and activities (OpenAI, 2023).
Energy strategy goal	An energy strategy goal is a specific and targeted objective or aim set within an overall energy strategy. It outlines a desired outcome or accomplishment that the energy strategy aims to achieve, such as increasing the share of renewable energy sources, improving energy efficiency, reducing carbon emissions, enhancing energy security, or promoting sustainable energy development. These goals guide the direction and actions of energy policies and initiatives (OpenAI, 2023).
Evaluation	Evaluation refers to the process of assessing, analyzing, and judging the quality, effectiveness, or value of something based on specific criteria, standards, or objectives. It involves gathering relevant information, data, or evidence to form an informed judgment or conclusion about the performance, outcomes, or impact of a program, project, policy, product, service, or other initiative. Evaluation helps stakeholders make informed decisions, improve practices, and determine the success or areas for improvement of the subject being evaluated (OpenAI, 2023).
Investment and funding	The concepts are closely related in the context of finance, but they refer to different aspects of financial management. **Investment**: refers to the act of allocating money, resources, or capital to acquire an asset or undertake a financial endeavor

	with the expectation of generating returns or profits in the future. **Funding**: refers to the process of obtaining financial resources to support a specific activity, project, or business operation.
Monitoring	Monitoring involves the systematic and ongoing observation, tracking, and recording of specific activities, processes, or phenomena to gather information and ensure that they are proceeding as planned. It helps keep a continuous check on progress, performance, or changes and provides data that can be used for assessment, analysis, and decision-making. Monitoring is often used in various contexts, including projects, environmental conditions, processes, and systems, to ensure that they meet established goals, standards, or expectations (OpenAI, 2023).
Policy mix	Combination and coordination of multiple policies, strategies, and measures used by governments or organizations to address complex societal issues or achieve specific objectives (OpenAI, 2023).
Politician	A politician is an individual who is actively involved in politics, often as an elected or appointed representative of a government or political party. Politicians engage in activities related to policymaking, governance, legislation, and public administration. Their roles can include advocating for constituents, proposing and debating laws, making policy decisions, representing their constituents' interests, and participating in the political process to influence the direction and functioning of government and society (OpenAI, 2023).
Stakeholder	A person or organization that is interested in a system or its subsystems (Coletti, et al., 2020).

2.4.4.11 Energy value chain ontology design pattern (ESO-ODP-011)

The energy value chain ontology design pattern refers to the various stages and processes involved in the production, distribution, and consumption of energy.

Figure 28 shows the UML representation of the energy value chain ODP. Energy originates from a primary source (e.g., wind, fossil fuel, etc.), as indicated by the "*hasSource*" connection. It becomes available through energy generation, where it is converted from one form to another (see the "*isGeneratedBy*" connection). Subsequently, it is transmitted via an energy network, as denoted by the "*isTransmittedBy*" connection. Energy can also be stored in an energy storage system (refer to the "*isStoredBy*" connection), and ultimately, it is distributed by an energy provider to end-users.

Finally,

Table 21 includes the ontology paths and connection with BFO foundational concepts for the concepts within the energy value chain ODP, while

Table 22 provides the description of these concepts.

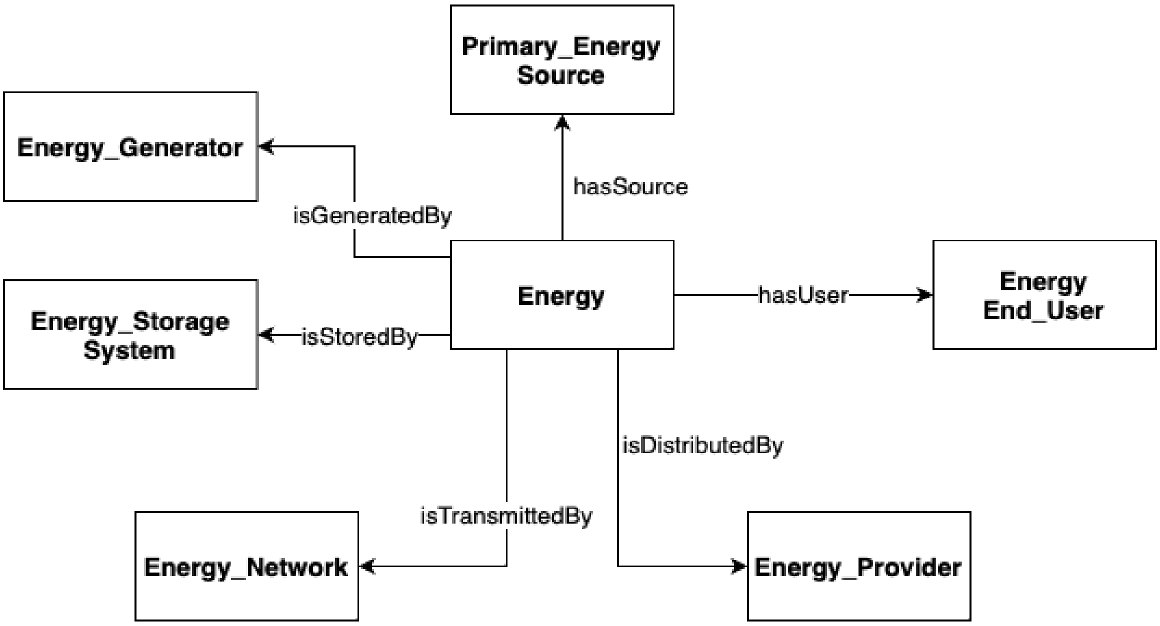


Figure 28. UML representation of the energy value chain ontology design pattern

Table 21. Ontology paths and connection with BFO foundational concepts for the concepts within the energy value chain ODP

ESO concept	Ontology path
Energy	**entity>continuant>specifically_dependent_continuant> quality**>energy
Energy end user	**entity>continuant>specifically_dependent_continuant> realizable_entity>role**>actor>market_participant> energy_market_participant>energy_end_user
Energy generator	**entity>continuant>independent_continuant>material_entity> object**>energy_generator
Energy network	**entity>continuant>independent_continuant>material_entity> object**>energy_network
energy provider	**entity>continuant>specifically_dependent_continuant> realizable_entity>role**>actor>market_participant> energy_market_participant>energy_provider
Energy storage system	**entity>continuant>independent_continuant>material_entity> object**>energy_storage_system
Primary energy source	**entity>continuant**>energy_commodity>primary_energy_source

Table 22. Descriptions of the concepts within the energy value chain ODP

ESO concept	Ontology description
Energy	Energy is a quality of material entities which manifests as a capacity to perform work (such as causing motion or the interaction of molecules) (Booshehri, et al., 2021).
Energy end user	An energy end-user is an individual, household, business, or organization that consumes energy resources, such as electricity, natural gas, or fuel, for various purposes, including heating, cooling, lighting, industrial processes, transportation, and other activities (OpenAI, 2023).
Energy generator	An energy generator, often referred to simply as a generator, is a device or system that converts mechanical, chemical, thermal, or other forms of energy into electrical energy. Generators play a crucial role in providing the electricity that powers our homes, businesses, industries, and various electronic devices. Generators operate based on the principle of electromagnetic induction, discovered by Michael Faraday in the 19th century. According to Faraday's law, a changing magnetic field induces an electrical current in a conductor. Generators utilize this principle to convert kinetic energy (mechanical motion) into electrical energy (OpenAI, 2023).
Energy network	An energy network refers to a complex interconnected system of infrastructure, facilities, and technologies used to generate, transmit, distribute, and deliver energy resources to consumers and end-users. It includes various components such as power plants, transmission lines, substations, pipelines, distribution networks, and smart grids that work together to ensure a reliable and efficient supply of energy, whether it's electricity, natural gas, or other forms of energy. Energy networks play a crucial role in meeting the energy demands of society and supporting economic activities (OpenAI, 2023).
Energy provider	An energy provider is an entity or company responsible for supplying and distributing various forms of energy, such as electricity, natural gas, or renewable sources, to consumers and businesses (OpenAI, 2023).
Energy storage system	An energy storage system refers to a technology or infrastructure designed to capture, store, and release energy for later use. It allows surplus energy generated during periods of low demand to be stored and then supplied during times of high demand or when the primary energy source is not available. Energy storage systems can take various forms, such as batteries, pumped hydro storage, compressed air storage, thermal storage, and more, and they contribute to enhancing grid stability, managing renewable energy fluctuations, and improving overall energy efficiency (OpenAI, 2023).
Primary energy source	A primary energy source is a natural resource that can be directly extracted or harnessed to produce energy in its raw form, such as fossil fuels (coal, oil, natural gas), renewable

	sources (solar, wind, hydro), and nuclear materials (uranium) (OpenAI, 2023).

2.4.4.12 Energy waste ontology design pattern (ESO-ODP-012)

The energy waste ontology design pattern refers to the unnecessary or inefficient use of energy resources, resulting in a loss of energy without achieving any useful output or work and, thus, satisfying the user.

Errore. L'origine riferimento non è stata trovata. Figure 29 shows the UML representation of the energy waste ODP. This pattern closely resembles the energy saving ODP. The "*increases*" edge linked to energy waste is used to signify that it leads to a rise in energy consumption. Energy waste is classified as the behavior of an energy end user (as indicated by the "*hasBehavior*" connection). The "*isPerceivedBy*" edge is employed to indicate that this behavior is recognized by an energy end user that has a behavior driver (as depicted in the corresponding diagram edge). In the diagram, the "*implies*" and "*isDueTo*" edges, respectively clarify that energy usage stems from an energy end user and results from energy consumption. Energy waste has an impact, as indicated by the "*hasImpactOn*" edge, on the environment, such as increased pollution. It can be attributed to technological choices and/or human behavior. The "*increases*" edge linked to energy consumption is used to signify that it leads to an increase in costs.

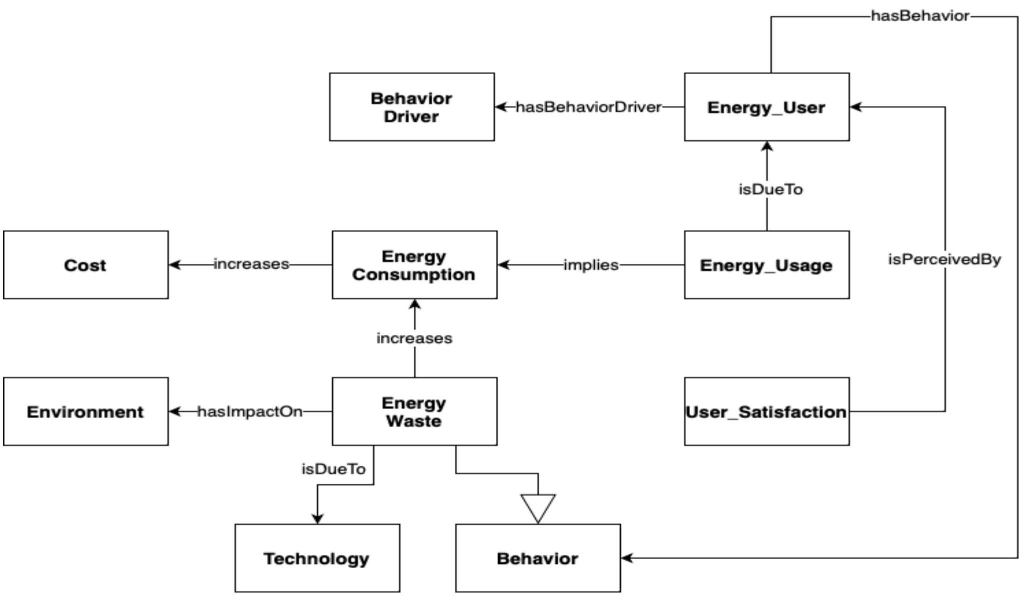


Figure 29. UML representation of the energy waste ontology design pattern

Finally, Table 23 includes the ontology paths and connection with BFO foundational concepts for the concepts within the energy waste ODP, while Table 24 provides the description of these concepts.

Table 23. Ontology paths and connection with BFO foundational concepts for the concepts within the energy waste ODP

ESO concept	Ontology path
Behavior	**entity>occurrent>process**>behavior
Behavior driver	**entity>continuant>specifically_dependent_continuant> realizable_entity>disposition**>behavior_driver
Cost	**entity>continuant>specifically_dependent_continuant> quality**>cost
Energy consumption	**entity>occurrent>process**>consumption>energy_consumption
Energy usage	**entity**>System_aspect>Service_request>energy_usage
Energy user	**entity>continuant>specifically_dependent_continuant> realizable_entity>role**>actor>market_participant> energy_market_participant>energy_end_user
Energy waste	**entity>occurrent>process**>behavior>energy_waste
Environment	**entity>continuant>independent_continuant>material_entity> object_aggregate**>environment
Technology	**entity>continuant>independent_continuant>material_entity> object_aggregate**>technology
User satisfaction	**entity>continuant>specifically_dependent_continuant> quality**>user_satisfaction

Table 24. Descriptions of the concepts within the energy waste ODP

ESO concept	Description
Behavior	Manner of acting or controlling yourself (behavioral attributes); the way a person behaves toward other people (WordNet, 2023).
Behavior driver	A behavior driver is a factor that influences and motivates individuals to engage in specific actions or making specific decision choices (OpenAI, 2023).
Cost	The property of having material worth (often indicated by the amount of money something would bring if sold); be priced at. Value measured by what must be given or done or undergone to obtain something. The total spent for goods or services including money and time and labor (WordNet, 2023).
Energy consumption	The amount of energy used by individuals, communities, industries, or countries to carry out various activities and meet their energy needs. The utilization of various forms of energy, such as electricity, fossil fuels, renewable energy sources, and other energy carriers, for different purposes in homes, industries, transportation, and other sectors (OpenAI, 2023).
Energy usage	The amount of energy consumed by individuals, communities, industries, and societies to meet various needs and perform different activities.

Energy user	An energy user is an individual, household, business, or organization that consumes energy resources, such as electricity, natural gas, or fuel, for various purposes, including heating, cooling, lighting, industrial processes, transportation, and other activities (OpenAI, 2023).
Energy waste	Energy waste refers to the unnecessary or inefficient use of energy resources, leading to increased consumption without corresponding benefits (OpenAI, 2023).
Environment	The area in which something exists or lives.- The totality of surrounding conditions (WordNet, 2023).
Technology	The concept of "technology" refers to the application of scientific knowledge, tools, techniques, and processes for practical purposes, usually in industries, commerce, and everyday life (OpenAI, 2023).
User satisfaction	User satisfaction refers to the level of contentment, fulfilment, or positive feelings experienced by individuals or users who interact with a product, service, system, or experience. It reflects how well the expectations, needs, and preferences of users are met, often indicating the success of a product or service in delivering value and meeting user requirements. User satisfaction can be influenced by factors such as functionality, usability, quality, and overall user experience (OpenAI, 2023).

2.4.4.13 International cooperation ontology design pattern (ESO-ODP-013)

The international cooperation ontology design pattern refers to the collaborative efforts and interactions among countries or international organizations to address shared challenges, such as climate change, pursue common goals, such as reduce CO_2 emissions or reduce energy price.

Figure 30**Errore. L'origine riferimento non è stata trovata.** shows the UML representation of the international cooperation ODP. The "*requires*" edge is used to indicate that international cooperation necessitates both diplomacy and negotiation. The "*involves*" edge signifies that international cooperation involves multiple countries and/or international organizations. International cooperation is typically facilitated through multilateral organizations and can be formalized through agreements (as indicated by the corresponding edges in the diagram).

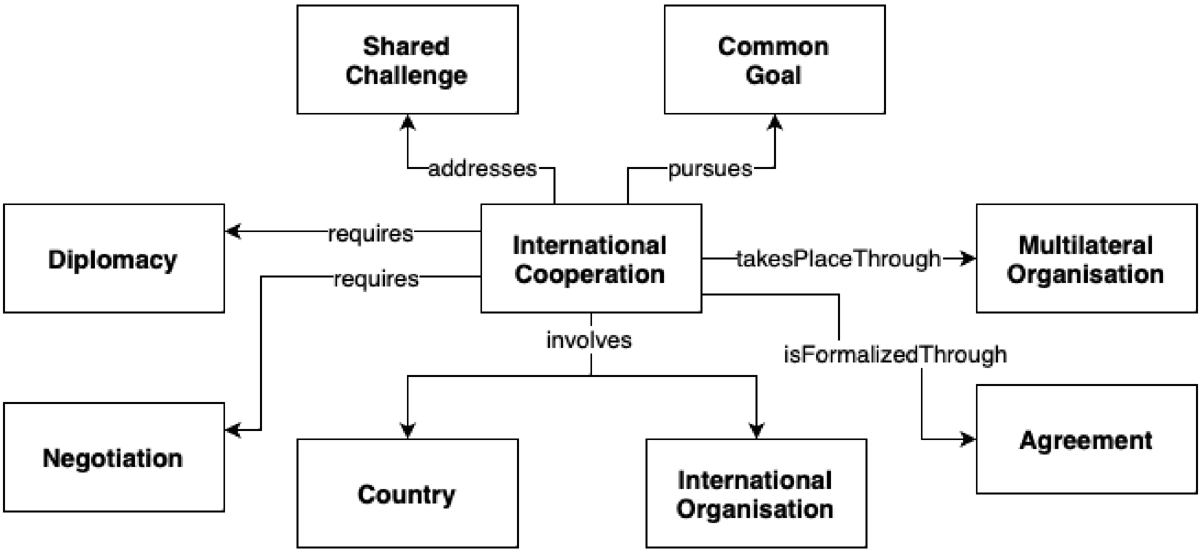


Figure 30. UML representation of the international cooperation ontology design pattern

Finally, Table 25 includes the ontology paths and connection with BFO foundational concepts for the concepts within the international cooperation ODP, while

Table 26 provides the description of these concepts.

Table 25. Ontology paths and connection with BFO foundational concepts for the concepts within the international cooperation ODP

ESO concept	Ontology path
Agreement	**entity>continuant>specifically_dependent_continuant> realizable_entity>disposition>function**>agreement
Common goal	**entity>continuant>specifically_dependent_continuant> quality**>target>common_goal
Country	**entity>continuant>independent_continuant>material_entity> object_aggregate**>country
Diplomacy	**entity>occurrent>process**>diplomacy

International cooperation	**entity>occurrent>process**>international_cooperation
International organization	**entity>continuant>specifically_dependent_continuant> realizable_entity>role**>international_organisation
Multilateral organisation	**entity>continuant>specifically_dependent_continuant> realizable_entity>role**>multilateral_organisation
Negotiation	**entity>occurrent>process**>negotiation
Shared challenge	**entity>continuant>specifically_dependent_continuant> quality**>shared_challenge

Table 26. Descriptions of the concepts within the international cooperation ODP

ESO concept	Description
Agreement	An agreement is a formal or informal arrangement between two or more parties where they come to a mutual understanding, consensus, or contract regarding a specific matter, often outlining the terms, conditions, rights, and responsibilities of each party involved (OpenAI, 2023).
Common goal	A common goal refers to a specific objective or outcome that is shared and pursued by multiple individuals, groups, or entities, often requiring coordinated efforts to achieve (OpenAI, 2023).
Country	A country is a distinct and sovereign geographical and political entity with recognized borders, its own government, and a defined population (OpenAI, 2023).
Diplomacy	Diplomacy is the practice of managing international relations, typically between sovereign states, through peaceful and constructive means. It involves the use of communication, negotiation, dialogue, and other diplomatic techniques to address conflicts, promote cooperation, and advance national interests (OpenAI, 2023).
International cooperation	The international cooperation concept refers to the collaborative efforts and interactions among countries and international actors to address shared challenges, promote common interests, and achieve mutually beneficial goals on the global stage. it involves nations working together through formal and informal mechanisms to tackle various issues that transcend national borders and require collective action (OpenAI, 2023).
International organization	An international organization is a cooperative entity formed by multiple countries to facilitate diplomatic dialogue, collaboration, and coordinated efforts on global issues of mutual concern (OpenAI, 2023).
Multilateral organisation	A multilateral organization is a collaborative entity comprised of multiple countries that work together to address shared global

	challenges and pursue common objectives through diplomatic cooperation and coordinated efforts (OpenAI, 2023).
Shared challenge	A shared challenge refers to a difficulty, issue, or problem that is faced by multiple individuals, groups, or entities and is commonly recognized as requiring collective efforts and cooperation to address or solve (OpenAI, 2023).
Negotiation	Negotiation is a concept that extends beyond international diplomacy and encompasses any process in which two or more parties with conflicting interests or goals seek to reach a mutually acceptable agreement or resolution (OpenAI, 2023).

2.4.4.14 Mitigation ontology design pattern (ESO-ODP-014)

The mitigation ontology design pattern, in the context of various fields such as climate change, disaster management, and environmental conservation, refers to the actions and strategies taken to reduce or prevent adverse impacts, risks, or negative consequences associated with specific challenges or problems. The goal of mitigation is to minimize the severity or extent of potential harm, thereby promoting resilience and sustainable development.

Figure 31**Errore. L'origine riferimento non è stata trovata.** shows the UML representation of the mitigation ODP. The "*isImplementedBy*" edge is used to indicate that mitigation is put into practice through specific actions. The "*refersTo*" edge signifies that mitigation is related to a particular strategy. The "*promotes*" edge indicates that the objective is to enhance the resilience of one or more systems. The "*reduces*" edge is employed to indicate a reduction in the impact of a critical event on a system. The "*hasImpact*" edge signifies that the impact is a consequence of a hazard. The "*hasImpactOn*" edge specifies the aspect of the system (e.g., a physical infrastructure or a system function) affected by an event. Stakeholders are concerned with critical events within the system (as shown by the "*takesCareOfEvent*" edge in the diagram). Typically, the system aspect may exhibit vulnerabilities, such as inadequate maintenance, that could result in a higher impact (as indicated by the "*hasVulnerability*" edge).

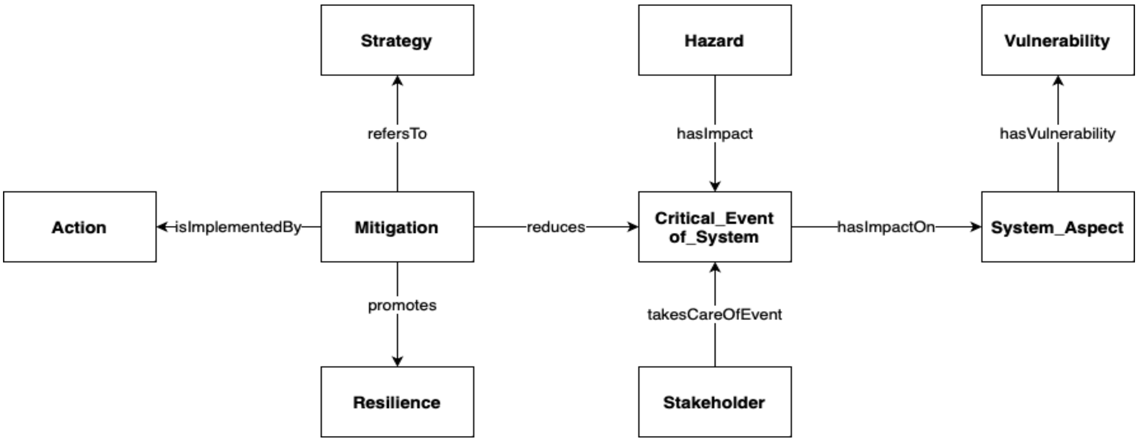


Figure 31. UML representation of the mitigation ontology design pattern

Finally, Table 27 includes the ontology paths and connections with BFO foundational concepts for the concepts within the mitigation ODP, while Table 28 provides the description of these concepts.

Table 27. Ontology paths and connection with BFO foundational concepts for the concepts within the mitigation ODP

ESO concept	Ontology path
Action	**entity>occurrent>process**>action
Critical event of system	**entity>occurrent>process**>Event>System_event>Actual_event> Critical_event_of_system or **entity>occurrent>process**>Event>System_event>Potential_event > Critical_event_of_system
Hazard	**entity>occurrent>process**>Event>System_event>Potential_event > Critical_event_of_system>hazard
Mitigation	**entity>occurrent>process**>system_internal_operation>mitigation
Resilience	**entity>continuant>specifically_dependent_continuant> quality**>System_property>Internal_system_conditions>Ility> resilience
Stakeholder	**entity>continuant>specifically_dependent_continuant> realizable_entity>role**>actor>stakeholder
Strategy	**entity>continuant>specifically_dependent_continuant> realizable_entity>disposition>function**>strategy
System aspect	**entity**>System_aspect
Vulnerability	**entity>continuant>specifically_dependent_continuant> quality**>System_property>Internal_system_conditions>vulnerabilit y

Table 28. Descriptions of the concepts within the mitigation ODP

ESO concept	Ontology path
Action	An activity that should be done to implement a decision.
Critical event of system	Event representing one or more effects on systems from exposure to a hazard; effects are mediated by the strength of the hazard and the vulnerability of the exposed system (Coletti, et al., 2020).
Hazard	Event or trend or their impacts (e.g., floods, droughts and sea level rise) with likely detrimental consequences to human systems (Coletti, et al., 2020).
Mitigation	Mitigation is the action to reduce any negative consequence of a particular event (refers to ISO/IEC Guide 73) by implementing security controls, taking assurance measures, avoiding the risk, or transferring the risk to another party (CIPRNet, 2023).
Resilience	Resilience is the ability of an individual, system, or community to withstand, adapt to, and recover from adversity, shocks, or challenges while maintaining functionality and well-being (OpenAI, 2023).
Stakeholder	A person or organization that is interested in a system or its subsystems (Coletti, et al., 2020).
Strategy	An elaborate and systematic plan of action (WordNet, 2023).
System aspect	A perspective that can be used to view a system. System aspects are: system service, system operation, asset, commons, infrastructure, managed object, and ecosystem service (Coletti, De Nicola, Vicoli, & Villani, 2019).
Vulnerability	The propensity of a system function to be adversely affected.

2.4.4.15 Policy acceptance ontology design pattern (ESO-ODP-015)

The policy acceptance ODP refers to the degree to which individuals, groups, or stakeholders affected by a particular policy or government decision support, agree with, or are willing to comply with that policy. In essence, policy acceptance concerns the level of approval, trust, and willingness to cooperate with the implementation of a specific policy. The success and effective implementation of a policy depends on its acceptance. On the other hand, low policy acceptance makes it difficult to achieve the intended policy outcomes.

Figure 32 **Errore. L'origine riferimento non è stata trovata.**shows the UML representation of the policy acceptance ontology design pattern.

Policy acceptance depends on the behavior of actors (as shown by the "*hasBehavior*" edge) that is due to certain drivers, which could be either internal or external. Internal behavior drivers include needs, principles, and concerns, such as awareness of energy issues and climate change anxieties. External ones are, for instance, social norms or the measures supporting the policy itself (see the "supports" edge), such as incentives and penalties.

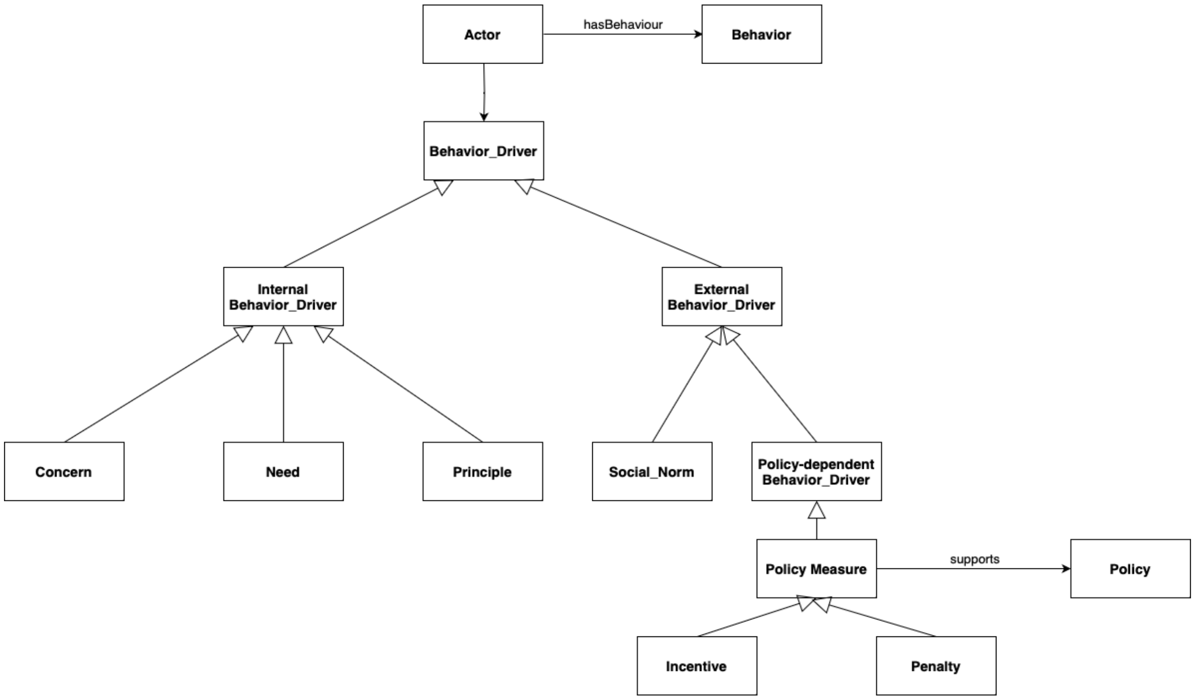


Figure 32. UML representation of the policy acceptance ontology design pattern

Finally, Table 29 includes the ontology paths and connection with BFO foundational concepts for the concepts within the policy acceptance ODP, while Table 30 provides the description of these concepts.

Table 29. Ontology paths and connection with BFO foundational concepts for the concepts within the policy acceptance ODP

ESO concept	Ontology path
Actor	**entity>continuant>specifically_dependent_continuant> realizable_entity>role**>actor
Behavior	**entity>occurrent>process**>behavior
Behavior driver	**entity>continuant>specifically_dependent_continuant> realizable_entity>disposition**>behavior_driver
Concern	**realizable_entity>disposition**>concern
External behavior driver	**entity>continuant>specifically_dependent_continuant> realizable_entity>disposition**>behavior_driver> external_behavior_driver
Fine	**realizable_entity>disposition**>behavior_driver> external_behavior_drive>policy-dependent_behavior_driver>

	policy_measure>fine
Incentive	**realizable_entity>disposition**>behavior_driver> external_behavior_drive>policy-dependent_behavior_driver> policy_measure>incentive
Internal behavior driver	**realizable_entity>disposition**>behavior_driver> internal_behavior_driver
Need	**realizable_entity>disposition**>behavior_driver> internal_behavior_driver>need
Penalty	**entity>continuant>specifically_dependent_continuant> realizable_entity>disposition>function**>policy_measure>penalty
Policy	**entity>continuant>specifically_dependent_continuant> realizable_entity>disposition>function**>policy
Policy measure	**entity>continuant>specifically_dependent_continuant> realizable_entity>disposition>function**>policy_measure
Policy-dependent behavior driver	**realizable_entity>disposition**>behavior_driver> external_behavior_drive>policy-dependent_behavior_driver
Principle	**realizable_entity>disposition**>behavior_driver> internal_behavior_driver>principle
Social norm	**realizable_entity>disposition**>behavior_driver> external_behavior_drive>social_norm

Table 30. Descriptions of the concepts within the policy acceptance ODP

ESO concept	Description
Actor	A person who acts and gets things done (WordNet, 2023).
Behavior	- Manner of acting or controlling yourself. (behavioral attributes) the way a person behaves toward other people (WordNet, 2023).
Behavior driver	A behavior driver is a factor that influences and motivates individuals to engage in specific actions or make particular choices (OpenAI, 2023).
Concern	The concept of "concern" typically refers to an issue, matter, or topic that causes worry, interest, or consideration due to its significance or potential impact (OpenAI, 2023).
External behavior driver	External behavior drivers are contextual and environmental influences such as cultural norms, regulatory policies, societal expectations, and situational factors that shape and impact individuals' decisions and actions, often by providing a framework or incentive for certain behaviors (OpenAI, 2023).

Fine	A fine is a monetary penalty or fee imposed by an authority, such as a government or a regulatory body, as a punishment for violating laws, regulations, or rules. Fines are often used to deter individuals or organizations from engaging in prohibited or unlawful activities and to generate revenue for the governing body (OpenAI, 2023).
Incentive	- A positive motivational influence. - An additional payment (or other remuneration) to employees as a means of increasing output (WordNet, 2023).
Internal behavior driver	An internal behavior driver refers to intrinsic factors such as personal beliefs, values, knowledge, emotions, and individual needs that influence and guide individuals' choices and actions towards specific behaviors (OpenAI, 2023).
Need	A condition requiring supply or relief (Merriam-Webster, 2023).
Penalty	A penalty is a punitive consequence or punishment imposed for the violation of a law, rule, contract, or established code of conduct, often involving fines, imprisonment, or other sanctions (OpenAI, 2023).
Policy	- A plan of action adopted by an individual or social group. - A line of argument rationalizing the course of action of a government (WordNet, 2023).
Policy measure	Specific actions, interventions, or instruments that policymakers implement to achieve the objectives outlined in a policy (OpenAI, 2023).
Policy-dependent behavior driver	A policy-dependent behavior driver refers to a factor that influences and shapes individuals' actions and decisions based on the regulations, rules, or guidelines set forth by governing bodies, institutions, or authoritative policies.
Principle	A principle is a fundamental guideline or rule that serves as a foundation for beliefs, actions, or behavior, often derived from ethics, values, or established truths (OpenAI, 2023).
Social norm	Shared beliefs or attitudes that guide behavior in a society (Fraunhofer, 2023).

2.4.4.16 Pollution ontology design pattern (ESO-ODP-016)

The pollution ontology design pattern refers to the introduction or presence of harmful or undesirable substances or pollutants into the environment, which can have adverse effects on living organisms, ecosystems, and the overall natural balance. These pollutants can be of various forms, including solid, liquid, or gaseous, and they can originate from both human activities and natural processes.

Errore. L'origine riferimento non è stata trovata. Figure 33 shows the UML representation of the pollution ODP. The "*concerns*" edge is used to indicate that pollution affects a specific aspect of an ecosystem, whether it be biotic or abiotic in nature. Pollution falls under the category of ecological load, as shown by the "*IsA*" relationship in the diagram, which refers to the pressures and demands that humans and other living organisms impose on ecosystems. The "*hasAdverseEffect*" edge linked to pollution signifies that the adverse consequence of pollution is its ecological impact, representing its effect on living organisms, including organisms and their non-living environment. The "*hasSystemAspect* edge connected to ecosystem is employed to illustrate that an ecosystem can be viewed from different standpoints. Ecosystems can also be nested within each other, as depicted by the aggregation relationship in the diagram. Indeed, larger ecosystems often encompass and include smaller ones, creating interconnected systems that influence each other. For example, a sandy beach may host smaller ecosystems such as insect colonies, turtle nests, and various types of vegetation.

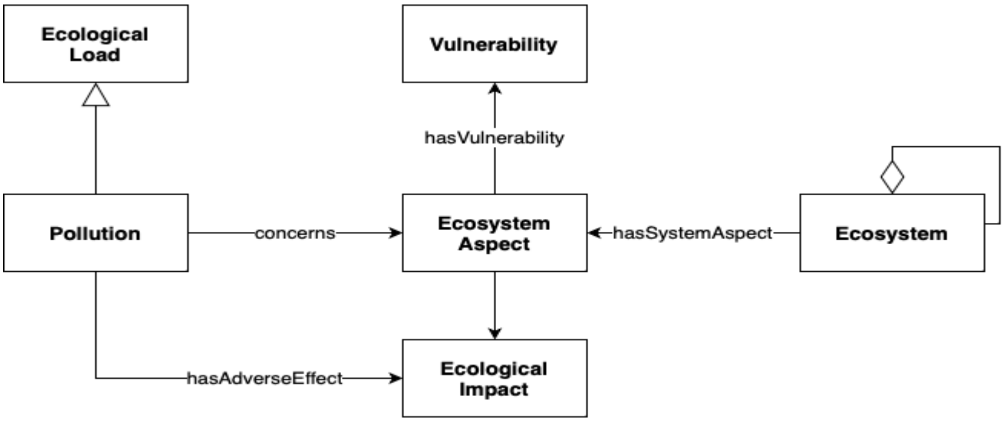


Figure 33. UML representation of the pollution ontology design pattern

Finally, Table 31 includes the ontology paths and connection with BFO foundational concepts for the concepts within the pollution ODP, while Table 32 provides the description of these concepts.

Table 31. Ontology paths and connection with BFO foundational concepts for the concepts within the pollution ODP

ESO concept	Ontology path
Ecological impact	**entity>occurrent>process**>ecological_impact
Ecological load	**entity>occurrent>process**>ecological_load
Ecosystem	**entity>continuant>independent_continuant>material_entity> object_aggregate**>ecosystem
Ecosystem aspect	**entity**>ecosystem_aspect
Pollution	**entity>occurrent>process**>ecological_load>pollution
Vulnerability	**entity>continuant>specifically_dependent_continuant>**

	quality>System_property>Internal_system_conditions>vulnerability

Table 32. Descriptions of the concepts within the pollution ODP

ESO concept	Description
Ecological impact	Ecological impact is the effect that something has on living beings, i.e., organisms, and their non-living environment. The term may refer to either the impact of human activities or natural events. When we study the ecological impact of something, we call it an Ecological Impact Assessment or EcIA. [Source: https://marketbusinessnews.com/financial-glossary/ecological-impact/]
Ecological load	Ecological load refers to the stress and demands that humans and other living organisms place on ecosystems. Pollution is an example of stress. Our food and water requirements, for example, are the demands that living organisms place. Humans' ecological load has been growing rapidly over the past one hundred years. The last century's growth has been significantly greater than the previous century's. [Source: https://marketbusinessnews.com/ecological-load/]
Ecosystem	A system formed by the interaction of a community of organisms with their physical environment (WordNet, 2023).
Ecosystem aspect	An ecosystem aspect refers to a specific component, element, or characteristic of an ecosystem that contributes to its overall structure, function, and dynamics. It encompasses the various living organisms, their interactions, physical features, and environmental conditions within a particular ecosystem (OpenAI, 2023).
Pollution	The introduction of harmful or undesirable substances into the natural environment, resulting in adverse effects on living organisms, ecosystems, and the overall balance of the ecosystem that can be physical, chemical, or biological agents that alter the natural environment and cause harm to human health, wildlife, and the environment (OpenAI, 2023).
Vulnerability	The propensity of a system function to be adversely affected.

2.4.4.17 Risk ontology design pattern (ESO-ODP-017)

A risk ontology design pattern refers to a critical event of system from the perspective of a particular stakeholde (Coletti, et al., 2020). We selected this pattern to the purpose of modelling the risk of a system due to hazards.

Figure 34 shows the UML representation of the risk ODP. This pattern is also a component of the mitigation ODP. The "*hasImpactOn*" edge specifies the aspect of the system affected by an event, which could be a physical infrastructure or a system function (e.g., in the case of a cyber-attack or an earthquake). Stakeholders, such as civil protection agencies, are concerned with critical events within the system (as illustrated by the "*takesCareOfEvent*" edge in the diagram). Typically, the system aspect may have vulnerabilities, such as inadequate maintenance, which could lead to a higher impact (as indicated by the "*hasVulnerability*" edge).

Finally, Table 33 includes the ontology paths and connections with BFO foundational concepts within the risk ODP while Table 34 provides the descriptions of these concepts.

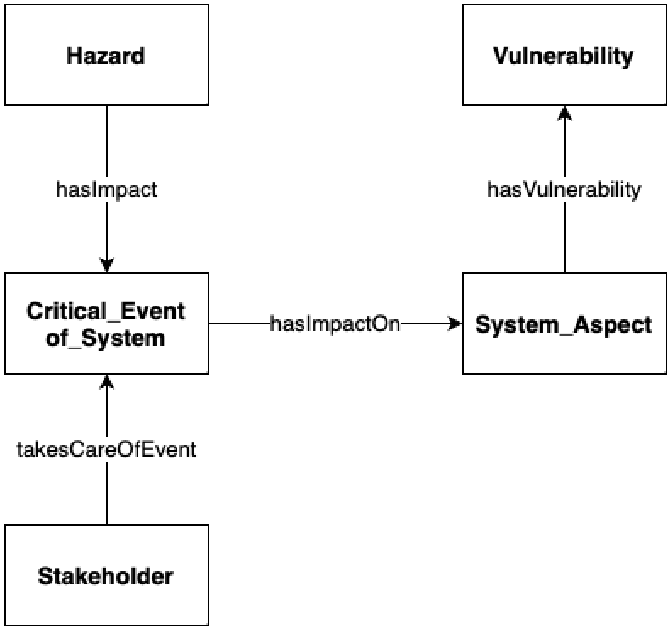


Figure 34. UML representation of the risk ontology design pattern

Table 33. Ontology paths and connection with BFO foundational concepts for the concepts within the risk ODP

ESO concept	Ontology path
Critical event of system	**entity>occurrent>process**>Event>System_event>Actual_event> Critical_event_of_system or **entity>occurrent>process**>Event>System_event>Potential_event > Critical_event_of_system
Hazard	**entity>occurrent>process**>Event>System_event>Potential_event > Critical_event_of_system>hazard
Stakeholder	**entity>continuant>specifically_dependent_continuant> realizable_entity>role**>actor>stakeholder
System aspect	**entity**>System_aspect
Vulnerability	**entity>continuant>specifically_dependent_continuant>**

	quality>System_property>Internal_system_conditions>vulnerability

Table 34. Descriptions of the concepts within the risk ODP

ESO concept	Ontology description
Critical event of system	Event representing one or more effects on systems from exposure to a hazard; effects are mediated by the strength of the hazard and the vulnerability of the exposed system (Coletti, et al., 2020).
Hazard	Event or trend or their impacts (e.g., floods, droughts and sea level rise) with likely detrimental consequences to human systems (Coletti, et al., 2020).
Stakeholder	A person or organization that is interested in a system or its subsystems (Coletti, et al., 2020).
System aspect	A perspective that can be used to view a system. System aspects are: system service, system operation, asset, commons, infrastructure, managed object, and ecosystem service (Coletti, De Nicola, Vicoli, & Villani, 2019).
Vulnerability	The propensity of a system function to be adversely affected.

2.4.4.18 System aspect ontology design pattern (ESO-ODP-018)

The system aspect ontology design pattern refers to the perspective from which a system is considered by a stakeholder (Coletti et al. 2019).

Figure 35 shows the UML representation of the system aspect ODP. Examples of systems are socio-technical systems as the water system, the energy system, and the transportation system. Larger systems often encompass and integrate smaller ones, creating interconnected systems that mutually influence each other. The "*hasSystemAspect*" edge is employed to indicate that a system can be viewed from the various perspectives, known as system aspects: system (external) service, system (internal) operation, operators, service request, asset, commons, infrastructure, and managed object. The "*isInterestedIn*" edge is used to show that stakeholders are interested in specific system aspects. System service refers to the output of a system provided to stakeholders, such as the distribution of energy to users (as demonstrated by the "*hasUser*" edge). System operations, like maintenance, are the internal activities performed within the system, which are essential prerequisites for delivering services. Operators are the individuals carrying out these system operations (as indicated by the "*performs*" edge). They can be either blunt-end operators, such as managers, or sharp-end operators, such as lathe turners. Service requests, such as energy demands, represent users' requirements for the service. Assets denote valuable items owned by the system. Commons refer to cultural and natural resources accessible to all members of society, including natural elements like air, water, and habitable land. Examples of the commons include lakes, water springs, rivers, and glaciers. Examples of commons are lake, water spring, river, and glacier. Infrastructures model the physical, technological, and organizational structures within a system. Managed objects represent the entities handled by the system, such as water in the case of a water system or fuel in the case of an oil system.

Finally,

Table 35 includes the ontology paths and connection with BFO foundational concepts for the concepts within the system aspect ODP, while Table 36 provides the description of these concepts.

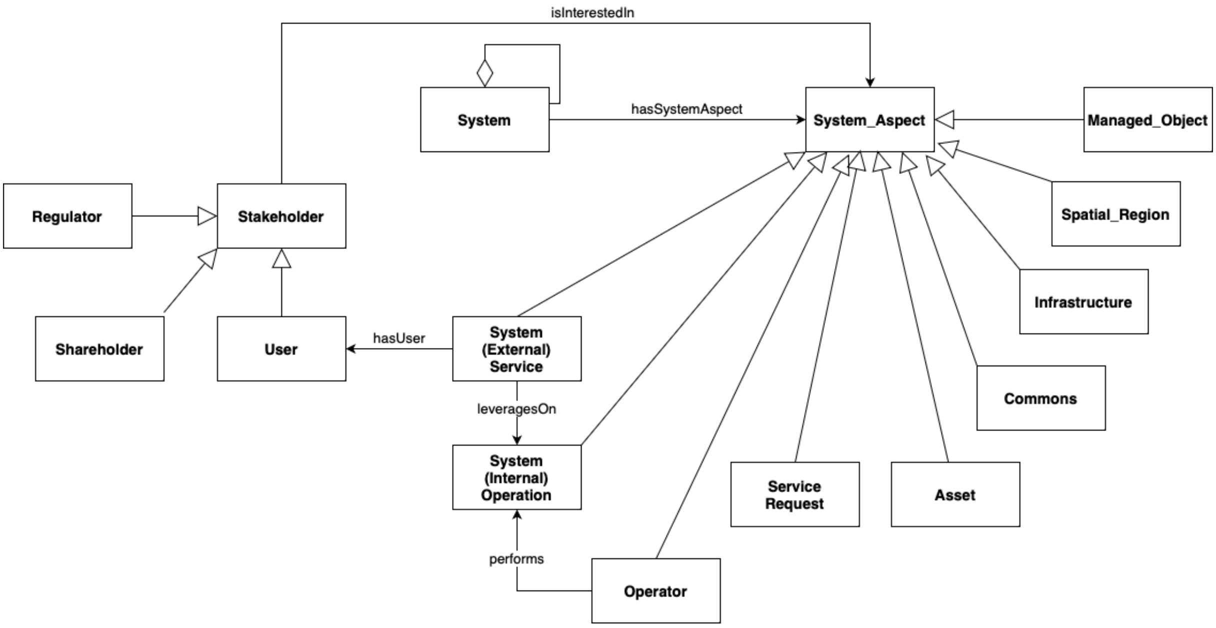


Figure 35. UML representation of the system aspect ontology design pattern

Table 35. Ontology paths and connection with BFO foundational concepts for the concepts within the system aspect ODP

ESO concept	Ontology path
Asset	**entity>continuant>specifically_dependent_continuant> quality**>asset and **entity**>System_aspect>Asset
Commons	**entity>continuant>specifically_dependent_continuant> quality**>commons and **entity**>System_aspect>Commons
Infrastructure	**entity>continuant>independent_continuant>material_entity>** infrastructure and **entity**>System_aspect>Infrastructure
Managed object	**entity**>System_aspect>managed_object and **entity>continuant>independent_continuant>material_entity**>
Operator	**entity**>System_aspect>operator

	and **entity>continuant>specifically_dependent_continuant> realizable_entity>role**>actor>operator
Regulator	**entity>continuant>specifically_dependent_continuant> realizable_entity>role**>actor> stakeholder>regulator
Service request	**entity**>System_aspect>Service_request and **entity>occurrent>process**>service_request
Shareholder	**entity>continuant>specifically_dependent_continuant> realizable_entity>role**>actor>stakeholder>stakeholder
Spatial region	**entity**>System_aspect>spatial_region and **entity>continuant>independent_continuant>immaterial_entity**> spatial_region
Stakeholder	**entity>continuant>specifically_dependent_continuant> realizable_entity>role**>actor>stakeholder
System	**entity>continuant>independent_continuant>material_entity> object_aggregate**>System
System aspect	**entity**>System_aspect
System external service	**entity>occurrent>process**>system_external_service and **entity**>System_aspect>system_external_service
System internal operation	**entity>occurrent>process**>System_internal_operation and **entity**>System_aspect>system_internal_operation
User	**entity>continuant>specifically_dependent_continuant> realizable_entity>role**>actor>stakeholder>user

Table 36. Descriptions of the concepts within the system aspect ODP

ESO concept	Description
Asset	An asset is an item of value owned by the system (Coletti, De Nicola, Vicoli, & Villani, 2019).
Commons	Cultural and natural resources accessible to all members of a society, including natural materials such as air, water, and a habitable earth. Examples of commons are lake, water spring, river, and glacier (Coletti, De Nicola, Vicoli, & Villani, 2019).
Infrastructure	Infrastructure refers to the fundamental physical and organizational structures and facilities needed for the functioning of a society, economy, or organization. it comprises the underlying systems, facilities, and networks that support various activities and services necessary for social and economic development (OpenAI, 2023).
Managed object	Any entity that is handled by a system, as water in case of water system or fuel in case of oil system (Coletti, De Nicola, Vicoli, & Villani, 2019).
Operator	One that operates: such as one that operates a machine or device or one that operates a business [8].
Regulator	A regulator is an authoritative entity or agency responsible for overseeing and enforcing rules, regulations, and standards within

	a specific industry, sector, or domain to ensure compliance, fairness, safety, and proper functioning (OpenAI, 2023).
Service request	A service request is a formal or informal communication made by an individual or an organization to request assistance or support from a service provider. It is a way for customers or clients to communicate their needs or issues to the service provider and seek resolution or action (OpenAI, 2023).
Shareholder	It is also known as a stockholder, is an individual, entity, or organization that owns shares or equity in a corporation. Shareholders are considered partial owners of the company and have a financial interest in its performance and success (OpenAI, 2023).
Spatial region	The term spatial region refers to a specific area or portion of space that is defined or delineated based on certain criteria or characteristics. It is a concept used in various fields, including geography, mathematics, and the sciences, to describe and analyze areas with distinct spatial attributes (OpenAI, 2023).
Stakeholder	A person or organization that is interested in a system or its subsystems (Coletti, et al., 2020).
System	A regularly interacting or interdependent group of items forming a unified whole, such as a group of devices or artificial objects or an organization forming a network especially for distributing something or serving a common purpose [8].
System aspect	A perspective that can be used to view a system. System aspects are: system service, system operation, asset, commons, infrastructure, managed object, and ecosystem service (Coletti, De Nicola, Vicoli, & Villani, 2019).
System external service	Service provided by a system (Coletti, et al., 2020).
System internal operation	Internal activities performed in system and that are required preconditions to deliver services (Coletti, De Nicola, Vicoli, & Villani, 2019).
User	It represents the entity using or consuming a resource entity (e.g., hospital). It is characterized by a wellness level (De Nicola, Tofani, Vicoli, & Villani, 2012).

2.4.6 *Example of use of ontology design patterns*

In this Section we describe how two ontology design patterns can be used to enrich the Energy Systems Ontology: the system aspect ODP (ESO-ODP-018) and the policy acceptance ODP (ESO-ODP-015).

2.4.6.1 *Use of the System Aspect ODP*

In this subsection, we show how the system aspect design pattern can be used to represent knowledge about the following energy systems: solar photovoltaic system (Table 37), electric power system (Table 38), coal system (Table 39), wind energy system (Table 40), water energy system (Table 41), hydrogen energy system (Table 42), gas energy (Table 43), and geothermal energy system (Table 44). Then, we show how the policy acceptance design patten can be used to represent the acceptance of new energy transition policies by some actors.

Table 37. Example of implementation of the system aspect ODP related to solar photovoltaic system

System	solar photovoltaic system
Managed object	solar energy, solar fuel, solar resource, solar thermal energy
Infrastructure	solar building, solar cell, solar cell arrays, solar concentrator, solar panel, solar park, solar power plant, organic solar cell
Commons	community participation, environmental sustainability, clean energy production
Asset	solar park
Service request	energy demand
System (internal) operation	solar energy transformation, solar power generation, photovoltaic installation
System (external) service	energy distribution
Stakeholder	consumer, end user, energy companies
Operator	solar panel installer

Table 38. Example of implementation of the system aspect ODP related to electric power system

System	electric power system
Managed object	electrical energy
Infrastructure	electric power plant, electric power system interconnection, electric power transmission network, electric substation, electric rectifier, electric transformer, electrical distribution network
Commons	electric power utilization, environmental sustainability
Asset	electric power industry
Service request	energy demand
System (internal) operation	electric network analysis, electric power generation, electric power measurement, electric power system control, electric power system planning, electric power system protection, electric power transmission, electrical storage, maintenance
System (external) service	energy distribution, electric power distribution
Stakeholder	consumer, electricity consumer, energy supplier
Operator	electrical engineer

Table 39. Example of implementation of the system aspect ODP related to coal system

System	coal system
Managed object	coal, coal deposit, coal-fired power
Infrastructure	coal fired power plant, coal fueled furnace, coal industry, coal mine
Commons	coal phase out
Asset	coal deposit
Service request	energy demand
System (internal) operation	coal combustion, coal consumption, coal gasification, coal production, coal storage, coal supply, maintenance

System (external) service	energy distribution, electric power distribution
Stakeholder	consumer, energy supplier
Operator	coal miner

Table 40. Example of implementation of the system aspect ODP related to wind energy system

System	wind energy system (or wind power system or wind turbine system)
Managed object	wind energy, wind, wind source, kinetic energy, electrical energy
Infrastructure	wind turbine, wind generator, wind park, wind farm, offshore wind, wind power plant, tower, anemometers, wind vanes, environmental sensors, safety system, batteries, control system, monitoring system
Commons	clean energy production, environmental sustainability, renewable energy source, reduction environmental pollution, reduction greenhouse gas emissions, reduction carbon dioxide emissions, global energy transition
Asset	wind park, wind farm
Service request	energy demand
System (internal) operation	wind energy transformation, wind power generation, maintenance
System (external) service	wind power production, grid integration service
Stakeholder	consumer, end user, energy companies
Operator	wind farm operator, wind power plant operator

Table 41. Example of implementation of the system aspect ODP related to water energy system

System	water energy system or hydropower system
Managed object	water, water energy, natural water sources, reservoir, river, water supply, kinetic energy, potential energy, mechanical energy
Infrastructure	hydroelectric generator, water turbine, dam, intake structure, pipes, conduits, control systems, monitoring systems, sensors, valves, pumps, flow meters
Commons	clean energy production, environmental sustainability, renewable energy source, reduction environmental pollution, reduction greenhouse gas emissions, reduction carbon dioxide emissions, global energy transition, green energy
Asset	water reservoirs, natural water sources, water resources
Service request	energy demand
System (internal) operation	energy conversion (falling object), maintenance
System (external) service	provision of electricity energy, water supply
Stakeholder	consumer, end user, energy companies
Operator	water power plant operator

Table 42. Example of implementation of the system aspect ODP related to hydrogen energy system

System	hydrogen energy system
Managed object	hydrogen fuel, liquefy hydrogen, gaseous hydrogen, solid state hydrogen
Infrastructure	electrolysers, hydrogen fuel cells, steam methane reformers (SMRs), biomass gasifiers, electrolysis cells, storage tank, pressure vessels, pipeline, transport containers, temperature control system, pressure control system
Commons	clean energy production, sustainable energy, low-carbon energy, renewable energy sources, green energy
Asset	storage tank
Service request	energy demand, hydrogen energy demand
System (internal) operation	hydrogen generation, hydrogen production, hydrogen storage, maintenance, water electrolysis
System (external) service	electricity generation, clean energy
Stakeholder	consumer, end user, industrial facilities, energy companies, hydrogen transport companies, industrial users
Operator	green hydrogen operator, grey hydrogen operator, hydrogen pipeline operator, hydrogen storage operator, fuel cell operator, grid operator

Table 43. Example of implementation of the system aspect ODP related to gas energy system

System	gas energy system
Managed object	gas source, natural gas, underground reservoirs, biogas, syngas (synthetic gas)
Infrastructure	wellheads, underground reservoirs, gas separators, gas filters, gas dehydrators, gas compressor, storage tanks, gas pipeline, gas turbine
Commons	reduction greenhouse emission, sustainable gas production
Asset	gas network, gas treatment plant, gas storage tanks
Service request	gas energy demand, energy demand
System (internal) operation	gas production, gas storage, gas extraction, maintenance
System (external) service	natural gas transport, natural gas production, biogas production, gas transportation, gas distribution, electricity generation
Stakeholder	consumer, end user, industrial user, local community
Operator	natural gas operator, Biogas operator, gas storage operator

Table 44. Example of implementation of the system aspect ODP related to geothermal energy system

System	geothermal energy system
Managed object	earth's geothermal resources, underground geothermal reservoirs, hot water, steam, geothermal fluids
Infrastructure	wells, heat exchangers, power plant, turbines, geothermal power plant, generator, heat pumps, pipes, pipelines
Commons	energy demand, emissions control
Asset	geothermal power plant, steam geothermal power plant, lamellar steam geothermal power plant
Service request	energy demand
System (internal) operation	resource assessment, exploration and drilling, fluid extraction, energy conversion, fluid reinjection, electricity transmission, maintenance, monitoring
System (external) service	electricity generation, heating generation, cooling generation, hot water production, geothermal energy distribution
Stakeholder	consumer, end user, residential user, commercial user
Operator	turbine operators, generator operators, geothermal wells operators

2.4.6.2 Example of use of the Policy Acceptance ODP

In this subsection, we show how the policy acceptance ontology design pattern can be employed to represent knowledge related to the acceptance of potential energy transition policies: petrol or diesel cars are not allowed to circulate in the city centre (see Table 45); bike sharing app for commuting to workplaces (see Table 46); public financing for the installation of the photovoltaic system in domestic units (see Table 47); a high percentage of the factory's products must come from renewable energy sources (see Table 48); and actors can formally establish themselves as an energy community, produce energy, consume it and feed it into the system (see Table 49).

Table 45. Example of implementation of the policy acceptance ODP related to the policy on "petrol or diesel cars are not allowed to circulate in the city centre"

Actor	car driver
Behavior	buy an electrical vehicle
Need	save money, mobility
Principle	leave a better world for young generation
Social norm	stop degrading the environment
Policy	petrol or diesel cars are not allowed to circulate in the city centre
Incentive	provide support for EV charging infrastructure
Penalty	Fine

Table 46. Example of implementation of the policy acceptance ODP related to the policy "bike sharing app for commuting to workplaces"

Actor	bike sharing user
Behavior	cycling to work
Need	speed up mobility, save money
Principle	leave a better world for young generation, do not pollute, reduce energy footprint
Social norm	stop degrading the environment
Policy	bike sharing app for commuting to workplaces
Incentive	Increasing cycle paths, bicycles available free of charge
Penalty	parking violation penalties

Table 47. Example of implementation of the policy acceptance ODP related to the policy on "public financing for the installation of the photovoltaic system in domestic units"

Actor	household
Behavior	install photovoltaic panels
Need	have electricity at home, save money
Principle	leave a better world for young generation, reduce energy footprint, energy security
Social norm	stop degrading the environment
Policy	public financing for the installation of the photovoltaic system in domestic units
Incentive	provide support for installation
Penalty	higher taxes of fossil fuels

Table 48. Example of implementation of the policy acceptance ODP related to the policy "a high percentage of the factory's products must come from renewable energy sources"

Actor	private factory/company
Behavior	produce and use renewable energy for the production
Need	save money, improve efficiency
Principle	leave a better world for young generation, reduce energy impact of production, reduce energy waste
Social norm	stop degrading the environment
Policy	a high percentage of the factory's products must come from renewable energy sources
Incentive	subsidies to convert energy source from fossil to renewable
Penalty	higher taxes on the use of fossil fuels

Table 49. Example of implementation of the policy acceptance ODP related to the policy "actors can formally establish themselves as an energy community, produce energy, consume it and feed it into the system"

Actor	energy community
Behavior	produce and consume renewable energy
Need	save money
Principle	energy security, energy autonomy
Social norm	stop degrading the environment
Policy	actors can formally establish themselves as an energy community, produce energy, consume it and feed it into the system
Incentive	reduced electricity bills
Penalty	fine for exceeding the fuel emissions threshold

2.4.7 Energy System Ontology

The final Energy System Ontology (ESO) has been implemented by means of the Protégé Ontology Management system (Stanford University, 2023) and is available in RDF (Resource Description Framework) (W3C, 2014) or OWL (Web Ontology Language) (W3C, 2012) formats. ESO has been conceived as a knowledge graph. As previously mentioned, it is connected to the BFO foundational ontology, TERMINUS (TERritorial Management and INfrastructures ontology for institutional and industrial Usage) (Coletti, et al., 2020), and the Open Energy Ontology (Figure 36). BFO was used to guarantee the semantic quality of the ontology. The system aspect ontology design pattern of TERMINUS was used as a template to model the operational aspects of energy systems, and the Open Energy Ontology was used to ensure interoperability with other relevant ontologies.

From a topological perspective, an ontology possesses a core structure that expands through specialization, as denoted by the '*IsA*' relationship. The core ontology of ESO is the result of amalgamating novel and interconnected ontology design patterns developed within the project or drawn from existing literature, including the risk and system aspect ODPs, alongside foundational concepts from BFO (e.g., process, quality, object) and the upper ontology of TERMINUS. Figure 37 illustrates the core ESO ontology, where concepts are depicted as spheres and relationships as labeled edges. BFO concepts are represented in azure, TERMINUS concepts in red, and ESO concepts in green.

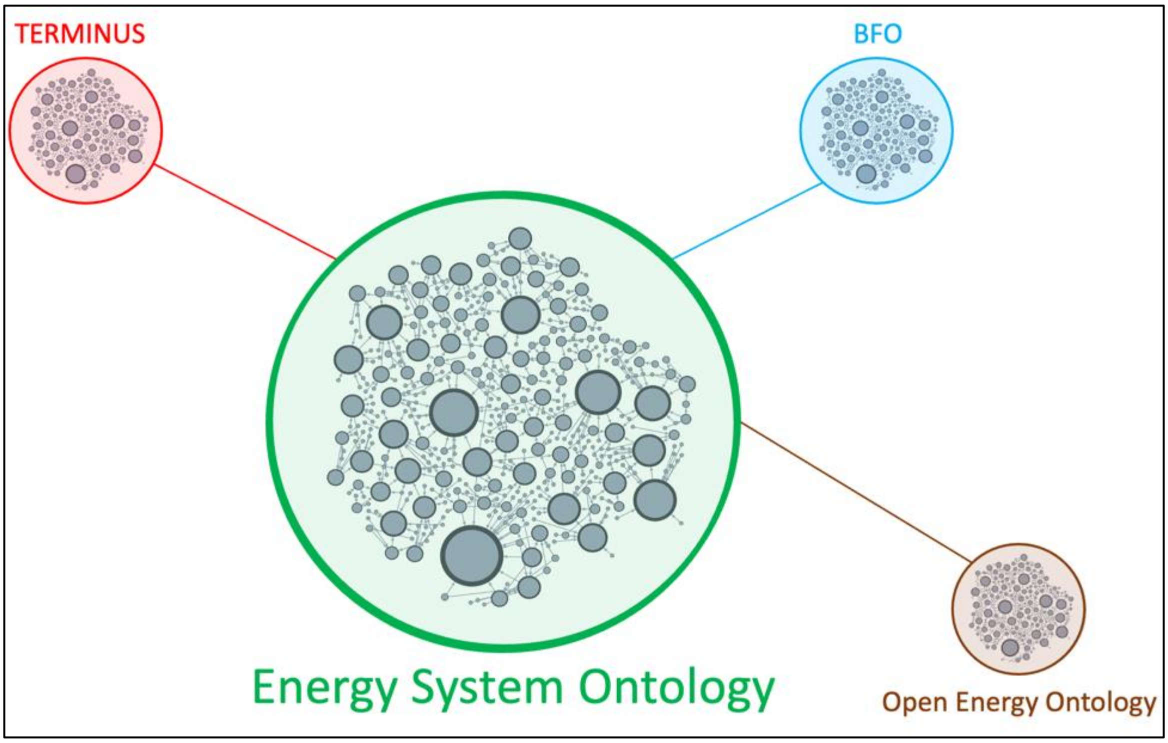


Figure 36. Interconnections among the Energy System Ontology, TERMINUS, BFO, and the Open Energy Ontology

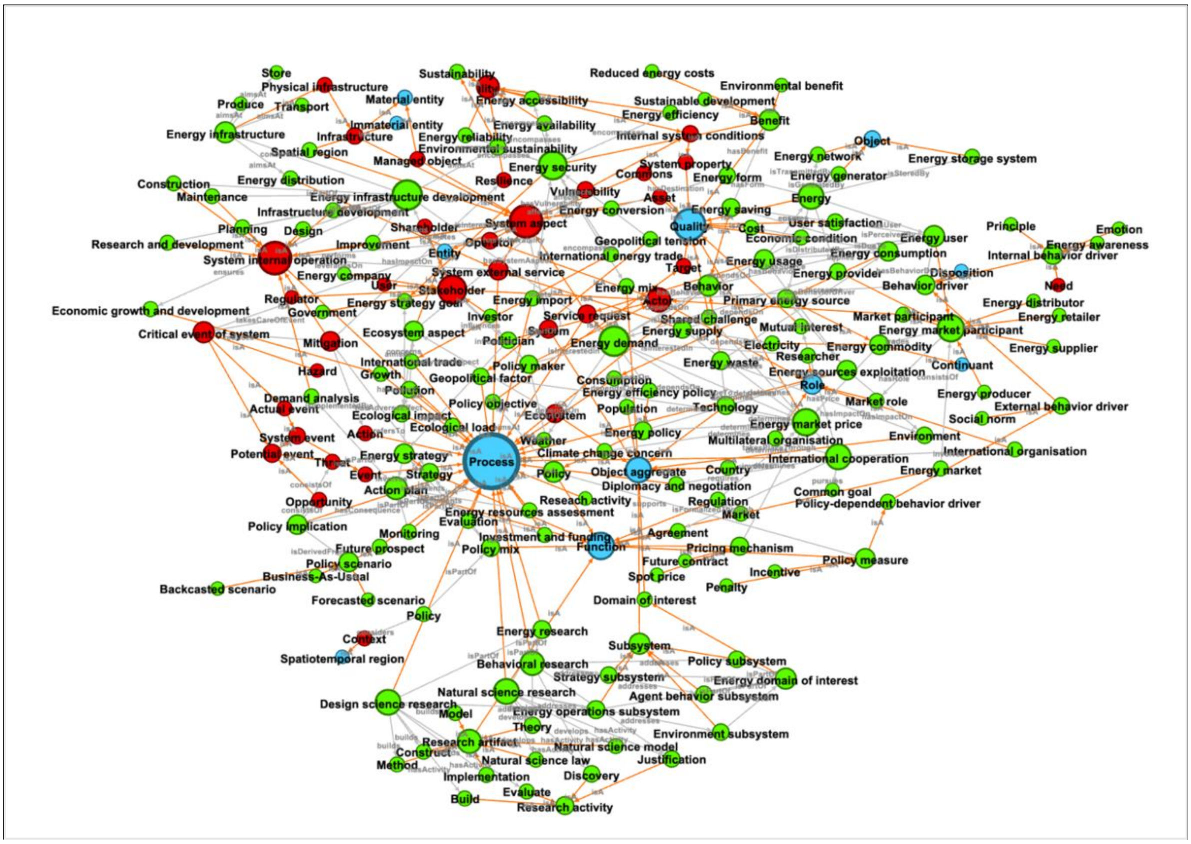


Figure 37. Core concepts of the ESO ontology and their relationships

The overall ontology gathers 2.272 classes (i.e., concepts), 83 object properties, 6 data properties, and 11951 axioms. The metrics of the Energy System Ontology as shown in Protégé are presented in Figure 38.

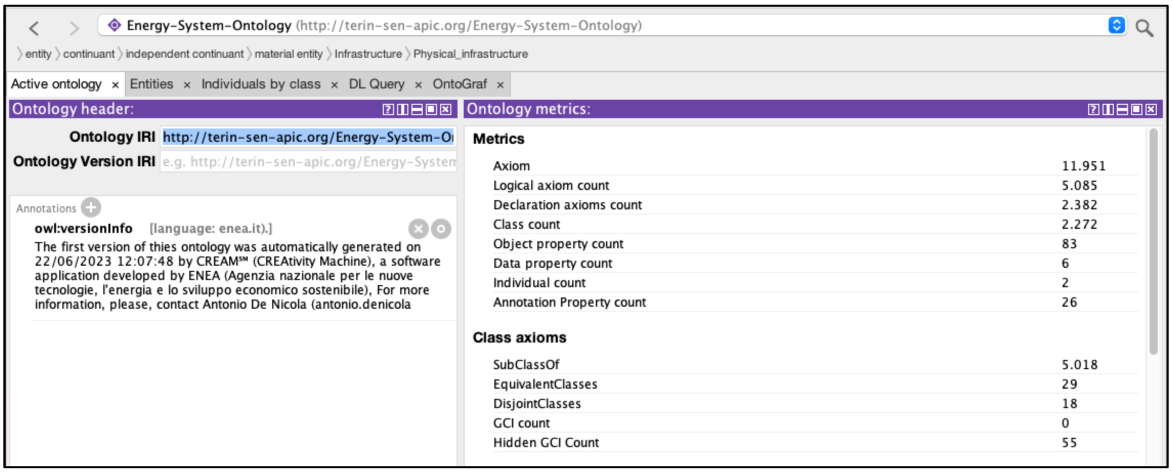


Figure 38. Energy System Ontology Metrics

Figure 39 shows a representation of the ontology as a hierarchical taxonomy visualized by means of the Fruchterman Reingold layout algorithm (Fruchterman & Reingold, 1991) and the Gephi software (Bastian, Heymann, & Jacomy, 2009). The large spheres are those proportional to the number of outcoming edges towards specialized concepts. These correspond to the core ESO concepts. A screenshot of the Energy System Ontology in Protégé is presented in**Errore. L'origine riferimento non è stata trovata.** Figure 40.

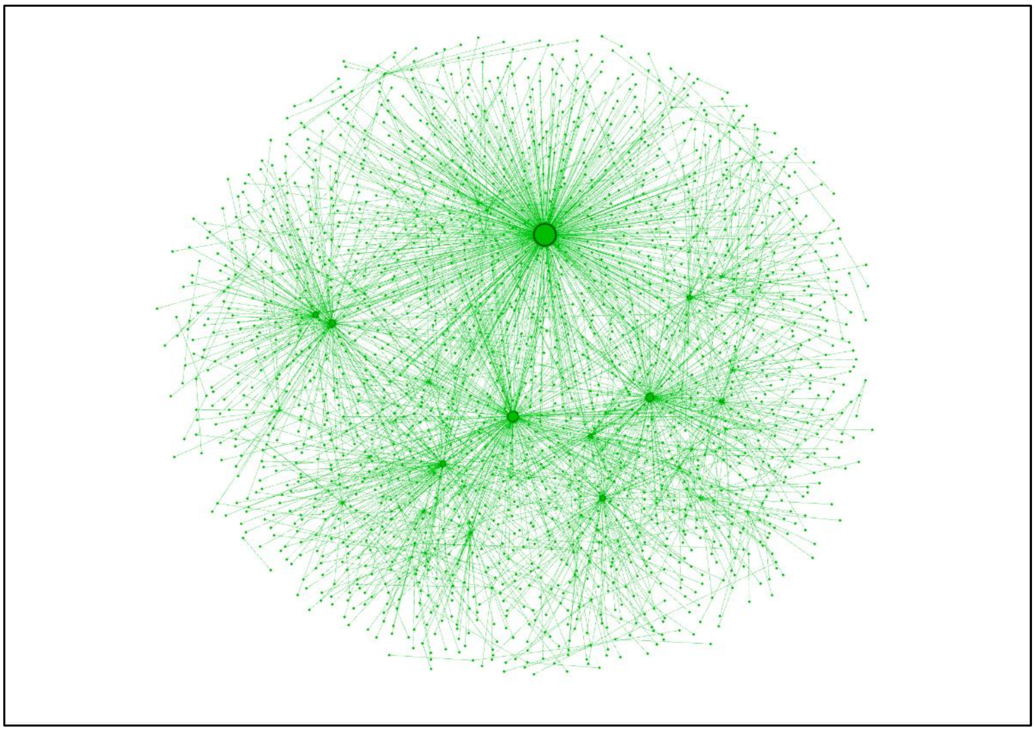


Figure 39. ESO taxonomy visualization through the Fruchterman Reingold layout

algorithm

The following code snippet shows an excerpt of the source file in owl format related to the concept energy market.

```
<!-- http://terin-sen-apic.org/Energy-System-Ontology#energy_market -->

<owl:Class rdf:about="http://terin-sen-apic.org/Energy-System-Ontology#energy_market">
    <rdfs:subClassOf rdf:resource="http://terin-sen-apic.org/Energy-System-Ontology#market"/>
    <rdfs:subClassOf>
      <owl:Restriction>
        <owl:onProperty rdf:resource="http://terin-sen-apic.org/Energy-System-Ontology#consistsOf"/>
        <owl:someValuesFrom rdf:resource="http://terin-sen-apic.org/Energy-System-Ontology#energy_market_participant"/>
      </owl:Restriction>
    </rdfs:subClassOf>
    <rdfs:subClassOf>
      <owl:Restriction>
        <owl:onProperty rdf:resource="http://terin-sen-apic.org/Energy-System-Ontology#related_To"/>
        <owl:someValuesFrom rdf:resource="http://terin-sen-apic.org/Energy-System-Ontology#agent_behaviour_subsystem"/>
      </owl:Restriction>
    </rdfs:subClassOf>
    <rdfs:isDefinedBy>The economic system and platform where energy resources are bought and sold. It is a complex and dynamic marketplace where various energy resources, such as electricity, oil, natural gas, coal, and renewable energy, are traded among producers, consumers, and intermediaries.
[Source: ChatGPT (https://chat.openai.com/).]</rdfs:isDefinedBy>
    <rdfs:label>energy_market</rdfs:label>
</owl:Class>
```

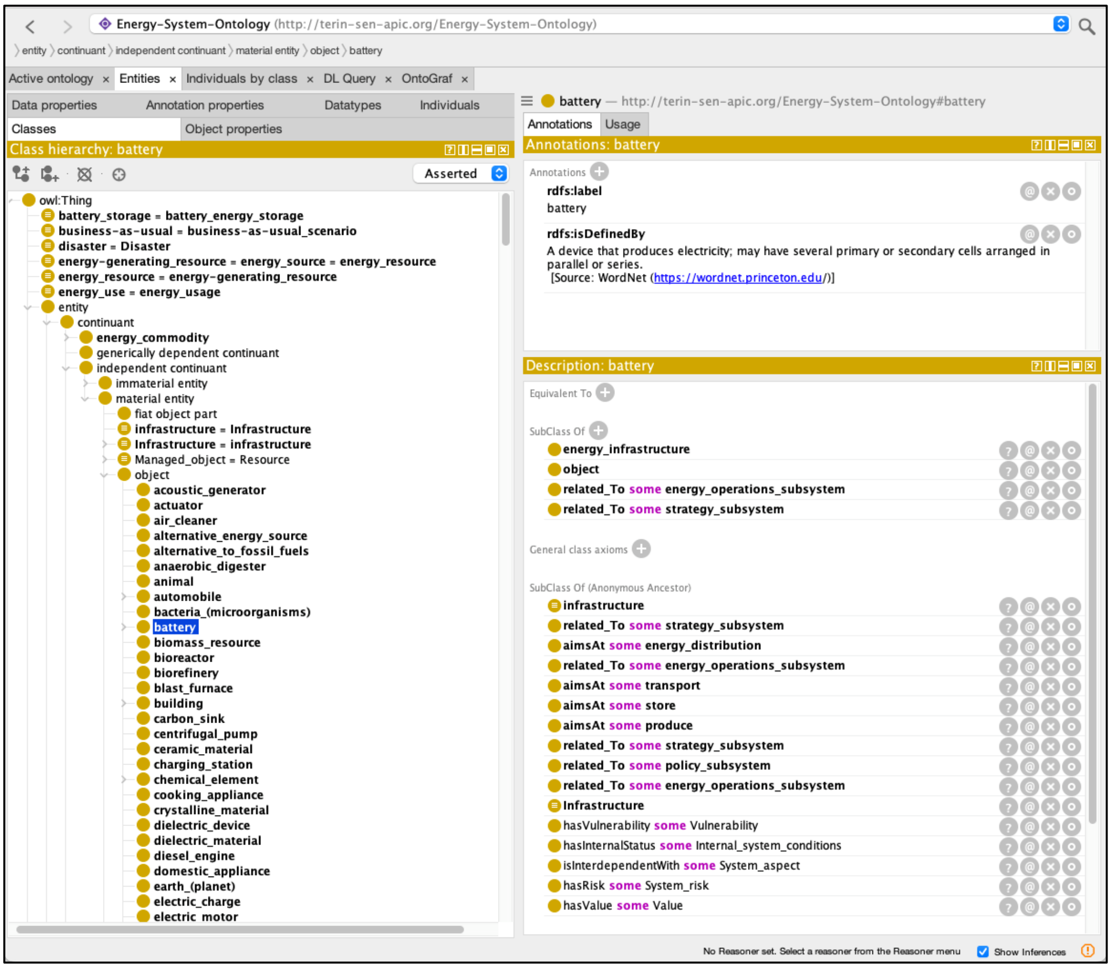


Figure 40. Screenshot of the Energy System Ontology in Protégé

The current version of the Energy Ontology is available at:

http://jerico.casaccia.enea.it/genesys/Energy-System-Ontology_v1.0

Discussion on the Assessment of the Energy System Ontology

As indicated in (Burton-Jones, Storey, Sugumaran, & Ahluwalia, 2005) (De Nicola, Missikoff, & Navigli, 2009), assessing the quality of an ontology requires a multidimensional approach. Specifically, an ontology should be assessed in terms of syntactic quality, semantic quality, pragmatic quality, and social quality. Syntactic quality assesses the ontology's formal style and its writing style. Semantic quality checks the absence of contradictory concepts. Pragmatic quality pertains to the usefulness of the ontology content for users, regardless of its syntax and semantics. Social quality refers to the level of acceptance of the ontology within both the community that has developed it and external communities.

Syntactic quality of ESO is guaranteed by the usage of the Protégé Ontology Management Systems and the encoding of the ontology in OWL (Web Ontology Language). The semantic quality of ESO has been checked by the reasoner *HermiT*

1.4.3.456 provided by Protégé and is also guaranteed by extending the BFO foundational ontology.

Pragmatic quality of the ESO will be evaluated during the project. In fact, ESO will be used for identifying the knowledge community to be considered for the gendered assessment (task T1.3) and for identifying the stakeholder organizations for the survey (task T1.5). Furthermore, it is also aimed at facilitating communication among the partners of gEneSys. Social quality of the ontology has been partially evaluated by checking the level of acceptance of the gEneSys project participants who were involved in either defining or validating the definitions of the concepts. Furthermore, we referred to other ontologies (such as BFO and OEO) to make it clear the contribution of ESO and with the hope that it will be used in the future by other communities.

2.5. Conclusions

The Energy System Ontology (ESO) offers a multidisciplinary perspective of the energy system, which defines the scope of the domain of interest. It is the result of an extensive and unprecedented analysis of existing scientific literature. In fact, unlike existing energy ontologies such as OEO and SAREF4ENER, which mainly address technical aspects of the sector, ESO places a special emphasis on the energy transition and encompasses concepts related to various subsystems, including environment, strategy, policy, human behavior (including aspects of energy markets, economics, and energy consumption attitudes), and energy operations, both from technological and organizational standpoints. It builds upon the BFO foundational ontology to ensure semantic precision, and it incorporates a set of 18 ontology design patterns, most of them defined for the purpose, which constitutes the core structure of the ontology. A diverse team of researchers with backgrounds spanning from social sciences to engineering, all part of the gEneSys consortium, collaborated to the final release of ESO to ensure both its scientific rigor and the multidisciplinary nature of the ontological model.

The segment of ESO dedicated to the environmental layer focuses on aspects related to CO_2 emissions, environmental protection, risks to ecosystems, with a specific emphasis on global warming, mitigation strategies, resilience, and climate change. Environmental concerns are increasingly shaping national and international energy-related strategies. Therefore, ESO comprehensively addresses this layer by incorporating concepts that deal with the political dimensions of the energy system, such as energy security, international cooperation, and agreements. Strategies are put into action through policies, which are extensively covered in the policy section of ESO. This section encompasses policy making, policy frameworks, policy implementation, policy acceptance, as well as the involvement of both central and local governments and considerations of social justice. The behavioral layer occupies a central role within ESO, covering aspects like energy consumption, energy demand, the energy market, and the behavior of people, households, and organizations. Lastly, the operational layer of ESO delves into the technological and organizational aspects of the energy domain. It includes general concepts related to energy infrastructures, as well as those specific to various energy systems, such as solar photovoltaic system, electric power system, coal system, wind energy system, hydropower system, hydrogen energy system, and gas energy system.

As mentioned at the beginning of this chapter, ESO will facilitate the identification of the energy system knowledge community, which will undergo gender-focused assessment using advanced semantic social network techniques (task **T1.3**). Additionally, it will aid in identifying the participants who will be engaged in the survey for assessing stakeholder organizations in sustainable energy systems from a gender perspective (task **T1.5**).

ESO will also serve as a shared language to enhance collaborative activities and mutual understanding among the gEneSys partners.

ESO should be viewed as a living entity that will continuously evolve and expand throughout the project's lifecycle, adapting to the requirements of other work packages. For example, it could serve as a valuable tool to support definition of *just energy transition pathways* by leveraging the semantic relationships within the ontology derived from the interdependencies among the different subsystems within the energy domain. It is worth noting that now only a few concepts in the ontology relate to gender. This is primarily because the objective of the task **T1.2** of WP1was to represent the current state of the field based on the existing literature. This underscores the pressing nature of the gEneSys research. The incorporation of additional concepts related to gender transversality into the various subsystems of the energy transition will be a collaborative effort with the other work packages, aligning with the project's achieved results.

The development of the Energy System Ontology (ESO) represents a significant achievement of the gEneSys project. ESO is unquestionably one of the most comprehensive ontologies in the field of energy. ESO aims to address a wide range of needs, encompassing those related to energy operations, individuals' and organizations' behavior, policy strategy, and environment as well as those related to the ones of multidisciplinary practitioners and researchers. ESO holds the potential to evolve into a knowledge graph by establishing connections with pertinent data sources, including information related to local energy infrastructures and societal data. ESO can find application in various contexts, including supporting the assessment of the sustainability and social impact of new policies, evaluating the implementation of different energy strategies, conducting analysis of risks and crisis situations affecting the energy system by means of semantic reasoning, and facilitating interoperability among sensors.

3. SYSTEMATIC LITERATURE REVIEW

The nexus between gender and energy transition/transformation has been increasingly investigated in the last decade. Several studies have been carried out to assess, in general terms, if, how, and to what extent: the energy transition is experienced and affects women and men differently and if and how it reinforces existing gender and intersectional inequalities; the contribution that women can bring to the development of the energy transition in terms of knowledge production and workforce; the decision-making processes and the policies concerning the development of energy transition incorporate a gender dimension. These three different dimensions have been then investigated by looking at different aspects within each of them.

In the context of how the energy transition is experienced and how it impacts on women and men, the research investigated the effects of transitioning from traditional to modern and cleaner energy sources in terms of health outcomes, time management, empowerment, and education among others. The term modern energy sources is used here to define those energy sources that are not traditional ones (such as wood or animal dung) but at the same time do not come from renewable sources. On the other hand, they investigated the factors that encourage or hinder clean energy uptake and the choices that guide the transition to clean energy, as well as the attitudes and behaviors regarding energy saving, consumption, and preferences concerning different kinds of energy sources.

With respect to the differences concerning the contribution that women can offer to the development of the energy transition the literature investigated on the one side, the role of women in the ideation, development and creation of the technologies used in the transition, while on the other side, this dimension incorporated research on the role of women in the job market related to the energy transition, looking at their level of participation in the market in the different kind of jobs that it offers, and at the stereotypes that still permeate the energy sector.

Concerning the research on the decision-making process that guide the development of the energy transitions, the research investigated the relation between the presence of women in the decision-making processes that guide energy transition and the outcome in terms of implementation of greener and gender-sensitive policies, as well as the different attitudes that men and women in policymaking have concerning the environment and renewable energy overall.

It is important to stress that the research on the nexus between gender and energy transition is very heterogeneous encompassing many different aspects and ranging between several different disciplines. The outcomes of such research are therefore very diverse and highlight how many aspects remain still contested.

To make an example of such disagreement in the results one can consider the research on the impact of photovoltaic technology on women. The development of photovoltaic has been found to improve women and communities' health as well as to prompt women's curiosity and creativity contributing to their psychological and intellectual development (Minnini, 2022); but at the same time other studies have highlighted how, in specific context, the construction of photovoltaic facilities can have negative impact by enclosing public wastelands and dispossessing resource-dependent women of access to firewood and grazing lands (Stock and Birkenholtz, 2020).

Being a relatively new but already rich strand of research, therefore, before carrying out the activities of the gEneSys project there is the need to navigate and systematize such a research corpus in order to understand what we know, what we still do not know, what results are mixed and inconclusive and what we need to investigate more intensively. To do so, often the best option is to carry out a systematic literature review (SLR), which allows to make sense of big bodies of research.

Several SLRs assessing the nexus between gender and energy transition have been carried out so far. However, such SLRs tend to be often limited in scope. Some of them are only focused on the effect of the transition on women, not considering the other side of the coin, namely how women contribute to the transition. For instance, Johnson et al. (2020) analyzing a sample of 90 publications, investigated to what extent the adoption and diffusion of low-carbon technologies impacts gender and social equity, leaving aside the role that women can actively have in the energy transition. Other studies debate the gender dimension just as a dimension or a variable among others. Dall-Orsoletta et al. (2022) systematically reviews the literature to identify the impacts of social innovations and bottom-up initiatives on sustainable energy transitions, in doing so they also consider the gender dimension but as dimension among others. Corradi, Sica and Morone (2023) assessed the behavior of actors within the road passenger transport sector by investigating roadblocks to the shift towards electric mobility, considering gender as an independent variable among others. Still other research has a limited country or regional focus, for instance Manjon, Merino and Cairns (2022) investigated the intersection between energy poverty, social innovation, and social entrepreneurship but focusing only on the Global North. Guta et al. (2022) on the other hand, focused their analysis on low- and middle-income countries while looking at household decision-making and the factors that influence decisions to adopt, or not, the use of clean fuels or improved biomass stoves. Finally, other studies have assessed only specific contextual aspects of the nexus, e.g., country-level conceptualization and problematization in the Indian context by Haldar, Peddibhotla and Bazaz (2023)

Still, to the best of our knowledge, no systematic review comprehensively assesses the nexus between gender and energy transition considering at the same time: the reciprocal effect of each dimension on the other; a cross-country and cross-region perspective, a multidisciplinary view; and a multiple scope perspective. This is why we decided to perform the present SLR before proceeding with the activities of the gEneSys project.

The SLR, in fact, will allow us to understand the state of the art of the research on the nexus between gender and energy transition, encompassing the different aspects in which the transition develops itself and the differences between diverse socio-economic contexts.

It is worth stressing that the present SLR has been performed through the collaboration of an interdisciplinary group of researchers from all the Consortium's partners, including researchers in social science and humanities as well as researchers in engineering and technological sectors.

The SLR is developed as follows: the next section will illustrate the materials used in the analysis and the methods driving the analysis itself. Section three will present the analysis and the relative results, in particular, the descriptive statistics and the qualitative analysis of the results of the publications selected. Section four, finally, will present and discuss the conclusions of the analysis.

3.1. Materials and methods

For the SLR, we performed a series of methodological steps essential to assure data quality as well as replicability. To facilitate some of these steps, such as the abstract screening and the performing of the consistency check, we employed the free online tool CADIMA.

Data has been extracted from Web of Science (WoS) (all databases) on April 12, 2023. The data extracted refer to publications starting from the year 2000. To grasp the highest number of publications assessing the nexus between gender and energy transition/transformation, a proper syntax has been developed. To develop the syntax, we have done several distinct tries refining it until all the significant terms and synonyms have been added.

The searching syntax used to extract the data from WoS is the following: (TI=((((gender OR women OR woman OR female OR feminism* OR sex) AND ("energy transition" OR "green transition" OR "energy transformation" OR "sustainable energy" OR "renewable energy")))) OR AB=((((gender OR women OR woman OR female OR feminis* OR sex) AND ("energy transition" OR "green transition" OR "energy transformation" OR "sustainable energy" OR "renewable energy")))) OR AK=((((gender OR women OR woman OR female OR feminis* OR sex) AND ("energy transition" OR "green transition" OR "energy transformation" OR "sustainable energy" OR "renewable energy")))))

The syntax employed to search the WoS database gave us 647 results. Before proceeding, the database has been cleaned by excluding the publications published before the year 2000, the types of publications that were deemed not relevant for the present SLR (editors' commentaries, reviews, etc.), the publications in languages other than English, and those publications that came without an abstract. This exclusion process reduced the sample as following:

- We excluded the items before the year 2000, coming up with 623 results.
- We excluded publications other than articles, data studies, books and book's chapters, early access, data paper, and other and unspecified, coming up with 518 results.
- We excluded publications in languages other than English, coming up with 425 results.
- We excluded those items that came without an abstract, coming up to 419 results.

Once excluded the publication based on their characteristics, we proceed to setup a list of exclusion criteria, based on our research questions, to guide the inclusion and exclusion of publications based on the reading of their abstract.

We therefore proceed with the creation of a list of inclusion/exclusion criteria:

- Does the publication assess the gender/sex dimension? Either with a clear focus on gender/sex (e.g., women's access to energy sources) or where gender/sex is one variable among others that are studied (e.g., gender, age and education have an impact on the use of financial services for sustainability)
- Does the publication assess the transition of the energy system? For example, in one of its different manifestations such as renewable energies, energy policies, energy consumption patterns, etc. (Not applicable if it has no clear link to energy)

Such a criteria allow us to select those publications that are relevant to fulfil the core aim of the SLR.

Before proceeding to the abstract selection, to assess the validity and coherence of the two criteria selected, we performed a consistency check. The consistency check has been done using CADIMA. In detail, we set up CADIMA by adding the 9 reviewers participating in the abstracts' screening to the CADIMA project and by setting each reviewer to review 5 abstracts. CADIMA randomly selected the 5 abstracts, to be reviewed by the 9 reviewers, among the database of 419 publications' abstracts imported in CADIMA. To evaluate the consistency of the reviews we calculated the level of agreement resulting in an 86% of level of agreement, meaning that the strength of agreement among the reviewers is good. For this reason, we confirm the list of criteria created and proceeded to the actual evaluation of the 419 abstracts included in our DB.

The abstracts' screening versus the selected criteria resulted in the selection of 302 publications and the exclusion of 117 publications. The preliminary analysis of the abstract selected revealed the presence of 3 items that were duplicated and 1 item that was an editorial material (type of publication preliminarily excluded from the present SLR). The items selected included 298 publications and 9 databases. Indeed, the databases are excluded from the analysis. We then proceeded to download the selected publications. In this process we have been able to download 288 publications. On the contrary, 1 publication was not available to be downloaded by any of the institutions within the consortium remaining beyond a paywall. After contacting the corresponding author asking to share the publication and not receiving any answer, we decided to eliminate the paper from the analysis. Therefore, the total number of publications downloaded and analysed is 288.

The 288 publications included have then been analysed by a pool of 18 reviewers from five of the consortium's partner institutions.

Before starting the publications' analysis and the extraction of information, several meetings have been held among the 18 reviewers in order to elaborate the research template to use for gathering information as well as to elaborate a shared strategy to deal with the information extraction itself.

Table 1 reports the categories included for the extraction of the information, and the relative explanation.

Table 1. categories included for the extraction of the information

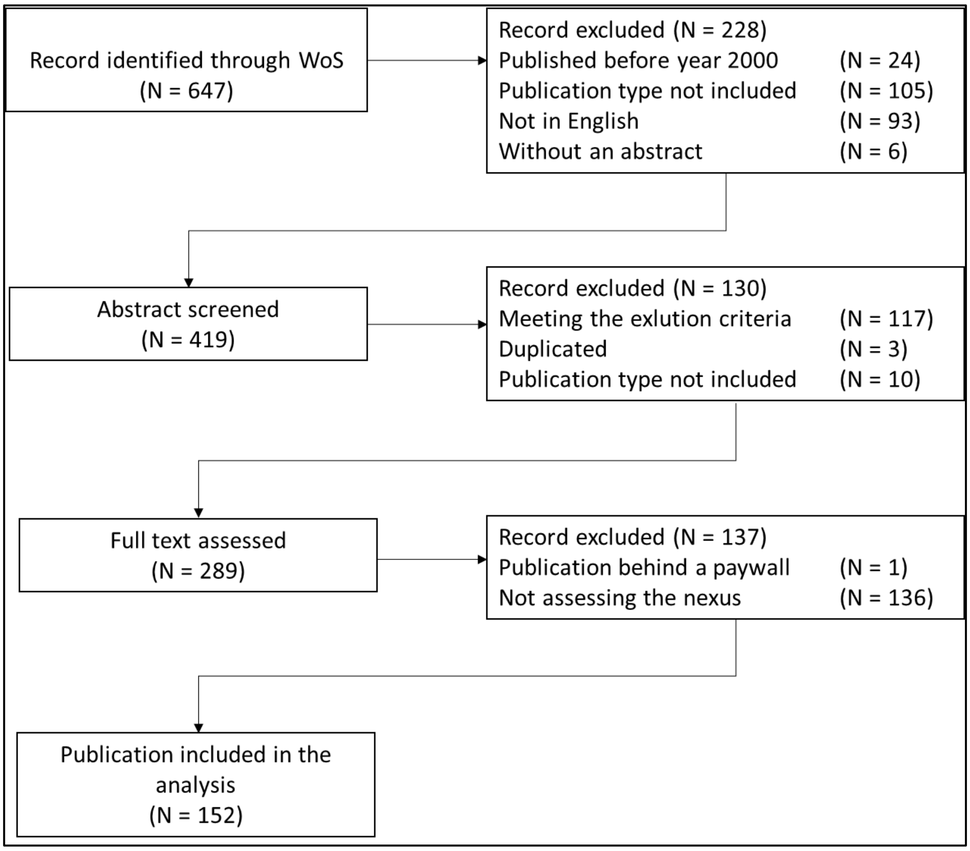
Category	Explanation
Does the publication actually assess the nexus between gender and energy transition/transformation (Yes/No)	to assess whether the publication relates to our research questions and to exclude those publications that even passing the abstract screening does not match with the scope of the SLR
Subsystems: political economic socio-ecological technological (Bell et al. 2020)	to assess the subsystem or subsystems considered, based on the four subsystems proposed by Bell et al., 2020
Gender-related Research Findings	to report the gender related results of the publication
Gender-related Research Gap addressed	to report the gender related research gap assessed by the publication
Research Gap identified / Further research proposed	to report the research gap identified by the publication for further research
Types of gender issue(s) addressed	to assess the type of gender issue addressed by the publication, based on the EIGE index: 1) Work; 2) Knowledge; 3) Time; 4) Health; 5) Power; 6) Safety and Trust; 7) Quality; 8) Other
Mentioned Technologies, Infrastructures and Material Systems	to assess the technology mentioned in the publication, for instance, wind, solar, hydro, coal, etc.
Does the paper analyse specific country/ies? (yes/no)	to assess if the publication considers one or more specific countries
If Yes: Which country/ies?	to assess which country or countries are assessed by the publication
Spatial Context	to assess the spatial context of the analysis: international, national, inner-country, peri-urban, rural
Research method	to assess the nature of the research method employed: qualitative, quantitative, mixed, theoretical
Research Methods_2	to assess the specific method of analysis employed, for instance, experimental, survey, secondary data, ethnography, interview etc.
Sample Size (n) total	to assess the sample size of the analysis
Policy Recommendations given (yes/no)	to assess the presence of policy recommendation
If Yes: Which Policy Recommendations were given	to report the policy recommendation if present in the publication
Gender Injustices identified? (Yes/No)	to assess the presence of gender injustice within the analysis
Theoretical Approaches for gender injustices	to assess the employment of a specific theoretical framework for gender injustice
Other Social / Vulnerability Categories interacting with Gender (Intersectional Approach)	to assess the presence of an intersectional analysis and what characteristics are included
Pathways	to assess the presence of a pathways analysis within the publication

Source: Authors' elaboration

Once an agreement over both the template to be filled with publications' information and the strategy to do so has been reached, we distributed the publications among the reviewers. To make a fair distribution, publications have been divided based on the number of pages to be reviewed, so each reviewer reviewed a different number of publications within an average of 227 pages.

It is important to stress that the publication reading allowed us to further exclude 136 publications that, notwithstanding passing the abstract screening, did not actually assess the nexus between gender and energy transition/transformation, which in contrast is the focus of the present SLR. The total number of publications analysed is therefore 152. Figure XXX summarized the exclusion steps undergone

Figure 1. Steps for the exclusion/inclusion of publications to be analyzed



Source: Authors' elaboration

The data collected have been analysed with a mix of quantitative and qualitative methods. In particular, the first part of the analysis has been carried out quantitatively by calculating several descriptive statistics of most of the variables reported in Table 1. The second part of the analysis has been carried out qualitatively by performing a manual text analysis of the variables related to the publications' results, as well as the research gap to be assessed by future research and the policy recommendations highlighted by the publications analysed.

Before proceeding to the analysis of the information collected from the publications analysed, for the sake of analysability, some of the categorical variables included in the analysis have been re-coded. In particular:

- The variables "subsystem" and "type of gender issue addressed" have been exploded into their categories and coded as multiple dummy variables. This became necessary since many publications have been coded in more than one subsystem.
- The variable "mentioned technology" have been re-coded by creating different macro-categories and then exploding them and coding them as multiple dummy variables. Table 2 reports the aggregation into these macro-categories. Also in this case, the re-coding process became necessary since many publications were coded in more than one category.
- The variable "research method_2" have been re-coded by aggregating the several residual research methods employed into the new category "other". The new categories are therefore the following: Ethnography; Document analysis; Interview; Focus group; Survey; Literature review; Case study; Secondary data; and other (Meeting; Storytelling; Workshop; Roundtable; Post-evaluation; Theoretical; Experiment; Roundtable).

Table 2. Aggregation matrix

Grids	**Bio**	**Fossil**	**Renewable**	**General energy**	**Nuclear**	**stoves**	**n/a**
Grids	Biomass	Diesel	Renewable Energy	Energy	Nuclear	Stoves	
Microgrids	Biodigester	Fossil	Solar	Electricity			
Smart Grids	Pee-powered	Oil	Wind	Solid fuel			
	Biogas	Coal	Geothermal	Non-solid Cooking Fuels			
	Biofuel	Gas	Hydro				
	Firewood		Hydrogen				
	Waste						
	Biochar						

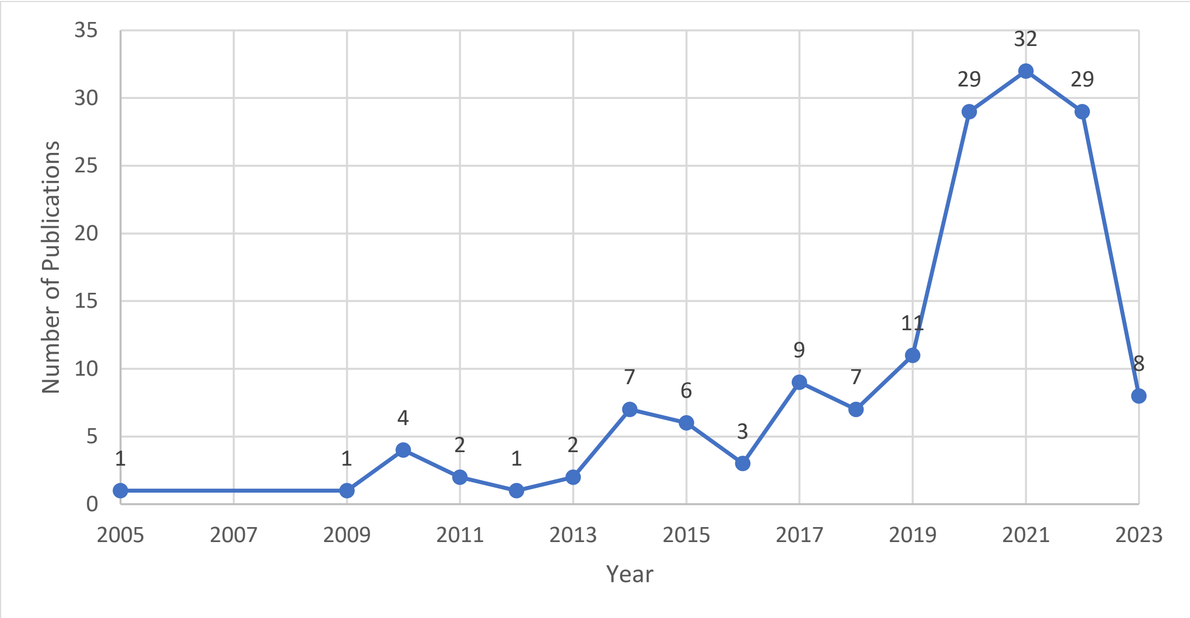
Source: Authors' elaboration

3.2. Data analysis

3.2.1 Descriptive Statistics

Figure 2 reports the number of publications by publication's year. The data show how most of the publications included in the analysis (98) have been published between the years 2020-2023, while the remaining publications (54) have been published between the years 2005-2019. It is interesting to notice that most of the publications related to the nexus between gender and energy transition/transformation have been published within the last four years.

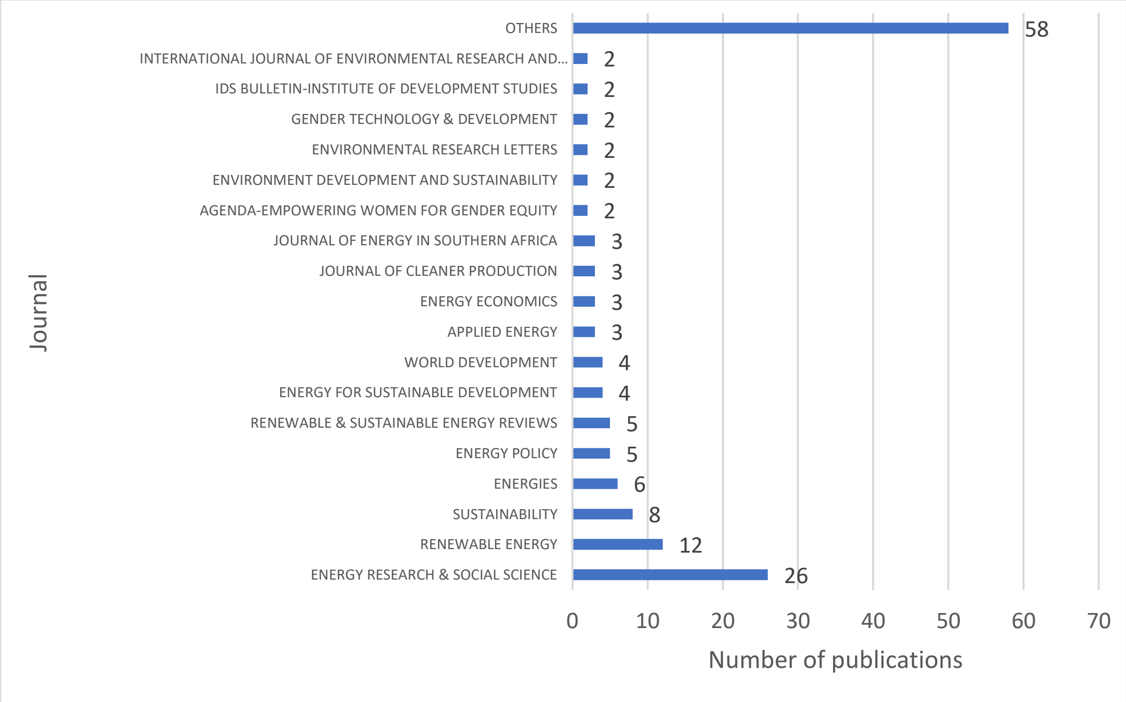
Figure 2. Number of publications by year



Source: Authors' elaboration

Figure 3 shows the number of publications by the scientific journal in which they have been published. The publications included in our sample have been published in many several different scientific journals and, in fact, the amplest category including 58 publications is represented by "others" meaning that there are 58 journals that published just one article included in our sample. However, it is interesting to notice that 18 scientific journals published more than one article, and in particular the journals "Energy Research & Social Science", "Renewable Energy", and "Sustainability" accounted respectively for 26, 12 and 8 publications.

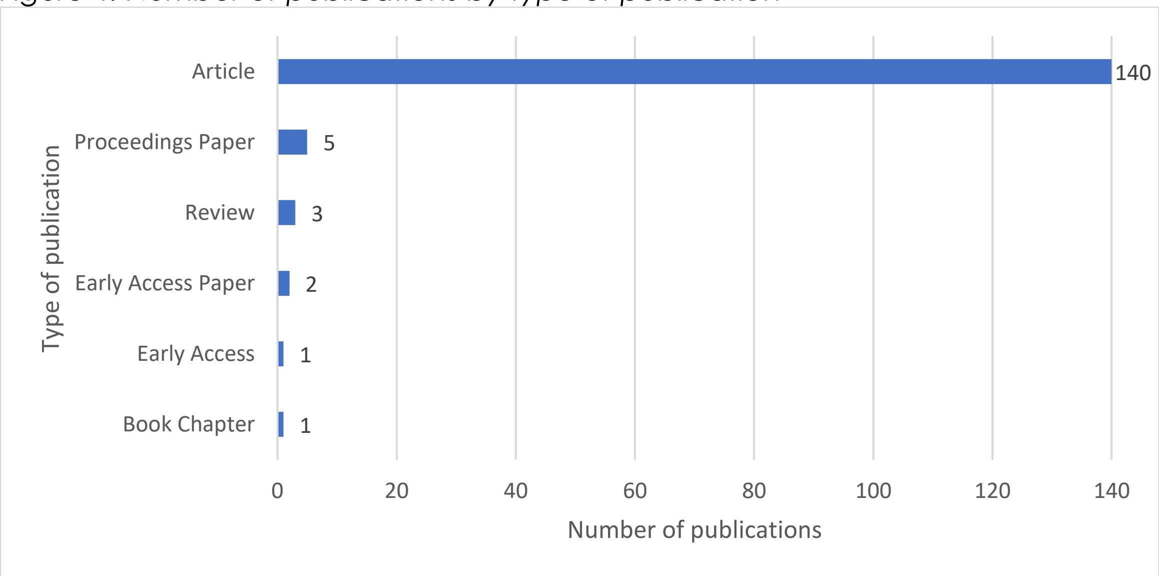
Figure 3: Number of publications by journal



Source: Authors' elaboration

Figure 4 plots the number of publications by publications' type. As we can see from the figure, the outstanding majority of the publications included in our sample (140 out of 152) are research articles. The 12 remaining publications included are proceeding papers (5), review (3), early access articles (2), early access publications (1), and book chapters (1).

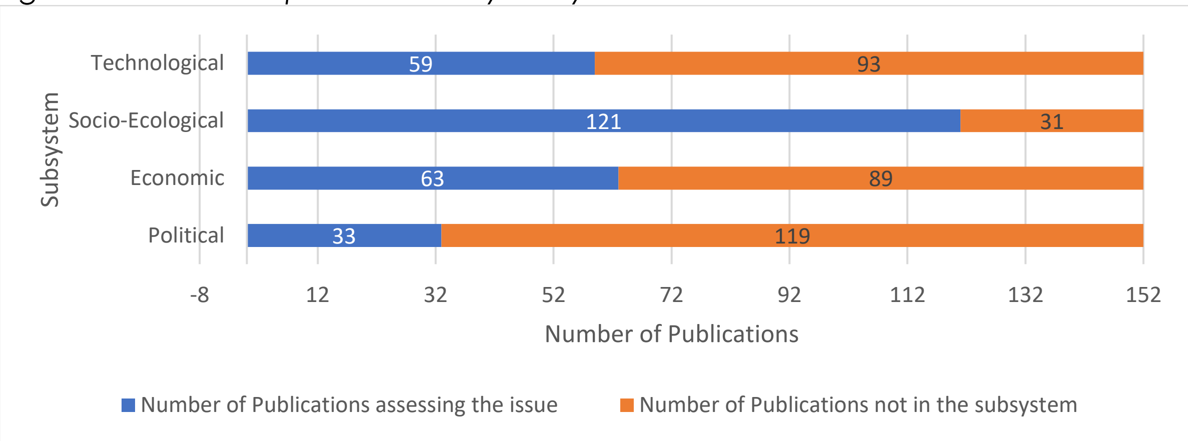
Figure 4. Number of publications by type of publication



Source: Authors' elaboration

Figure 5 reports the number of publications by the subsystems employed in the analysis. Since, as we already pointed out, many publications have been assigned to more than one subsystem, data have been reported as dummy variables showing whether a publication has been assigned to a certain subsystem or not. As shown by the data, the "socio-ecological" subsystem is the largest one, including 121 publications. 63 publications have been included in the "economic" subsystem while 59 in the "technological" one. The smallest subsystem, on the other hand, is the "political" one including only 33 publications.

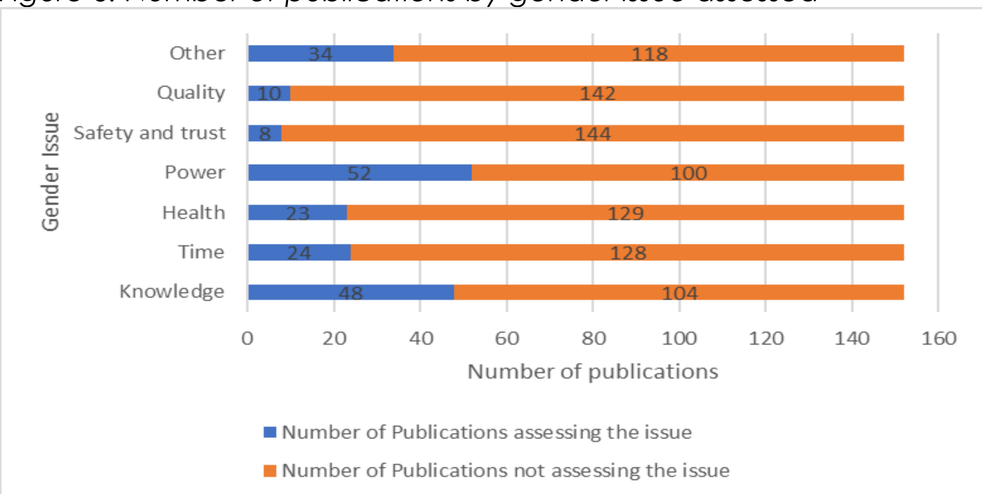
Figure 5. Number of publications by subsystem



Source: Authors' elaboration

Figure 6 reports the number of publications by the gender issue assessed. Also in this case, each category has been converted into a dummy variable. According to the data, the gender issues most assessed within the publications considered have been "power" and "knowledge" with 52 and 48 publications respectively. 24 publications assessed the "time" issue while 23 the "health" issue. The "quality" and the "time issue" have been assessed by 8 and 10 publications, while 34 publications also assessed "other issues" different from the one considered in the analysis.

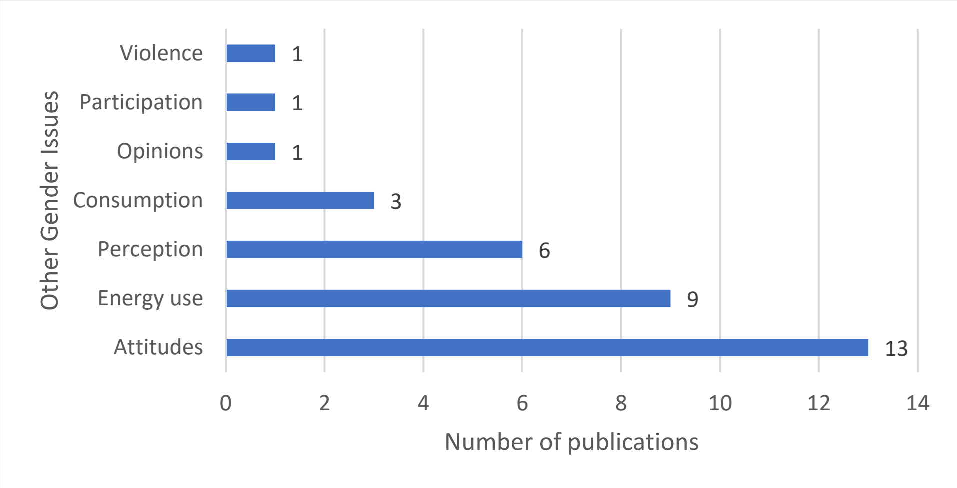
Figure 6. Number of publications by gender issue assessed



Source: Authors' elaboration

Figure 7 reports the number of publications included in the "other" category of the gender issue by the type of other gender issue assessed. As we can see, out of 34 publications included in the "other" category, 13 assess "attitudes", 9 "energy use", 6 "perception", 3 "consumption2, and the remaining 3 assess "violence", "participation" and "opinions".

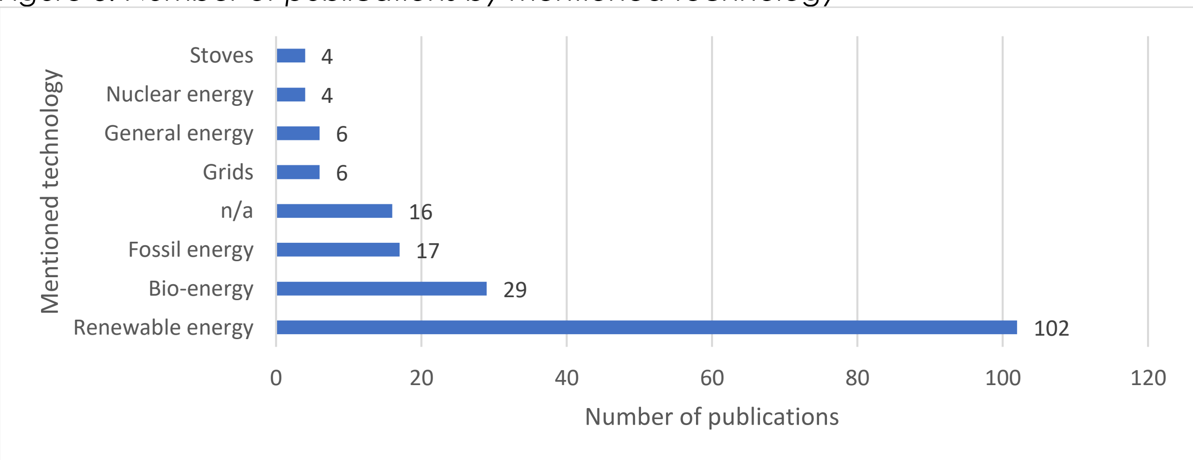
Figure 7. Number of publications by "Other" gender issue assessed



Source: Authors' elaboration

Figure 8 describes the number of publications by the mentioned technology. The data shows how most of the publications (102) do not assess a specific technology but rather they consider the renewable energy sector overall or more than one specific technology at once. The remaining publications mention different specific technology, from bio-energy (29) to stoves (17).

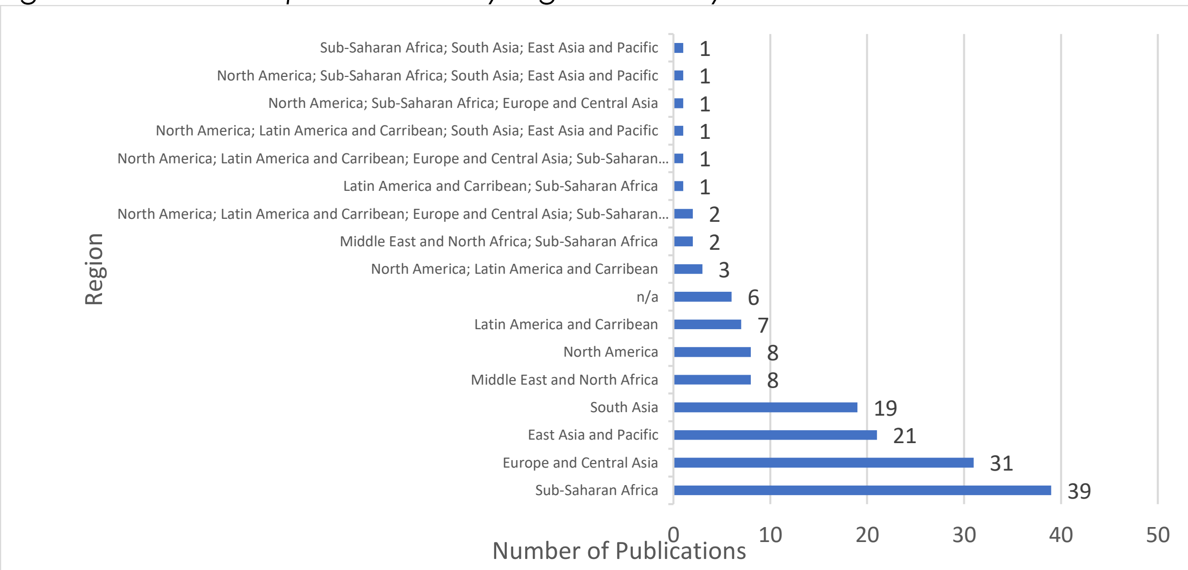
Figure 8. Number of publications by mentioned technology



Source: Authors' elaboration

Out of the 152 publications analysed 141 address a specific country or multiple countries. Figure 9 reports the data about the number of publications analysed by geographic region of analysis. The classification of the countries into regions has been done following the World Bank regional classification of countries[3]. Most of the publications in our sample analysed cases within Sub-Saharan Africa (39), Europe and Central Asia (31), East Asia and Pacific (21), and South Asia (19). It is interesting to notice that only 13 publications simultaneously analyse multiple regions.

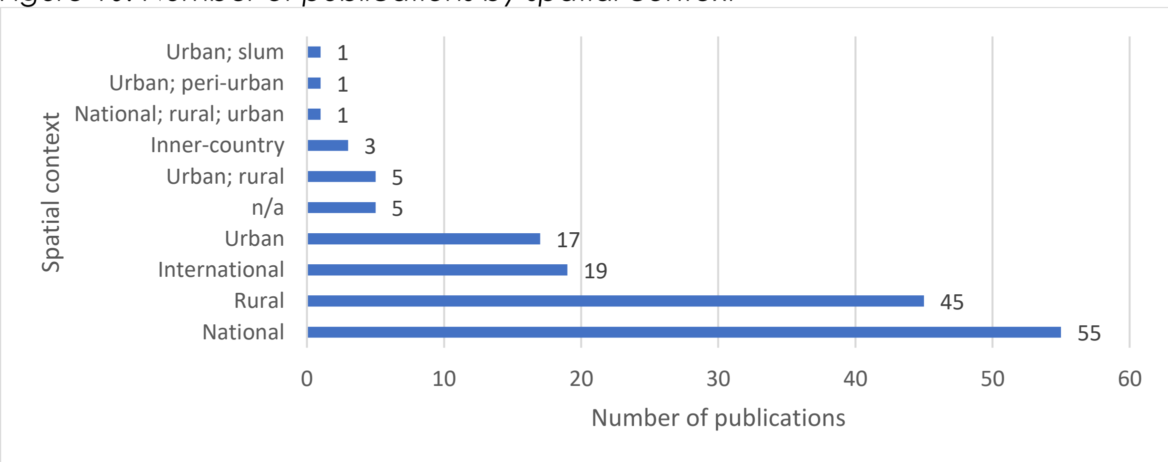
Figure 9. Number of publications by region of analysis



Source: Authors' elaboration

Looking at the spatial context analysed by publications within the regions and countries considered, Figure 10 shows how the majority of them uses the national (45), the rural (45), the international (19), and the urban (17) as their spatial context of analysis. On the other hand, only 11 publications assess a mixed spatial context.

Figure 10. Number of publications by spatial context

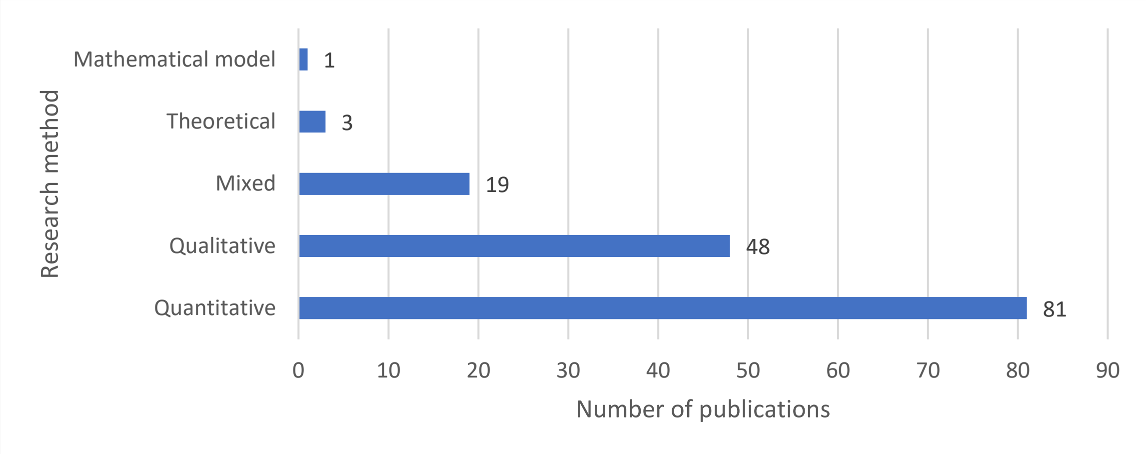


Source: Authors' elaboration

[3] See: https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups

Moving to the analysis of the methodologies employed, Figure 11 shows how the quantitative methods are the most employed methods of analysis accounting for 81 publications out of 152. It is followed by the qualitative methods that account for 48 publications. Just a minority of publications (19) use a mixed method approach, while residually, 3 publications employ a pure theoretical approach, and 1 publication employed a mathematical modelling approach.

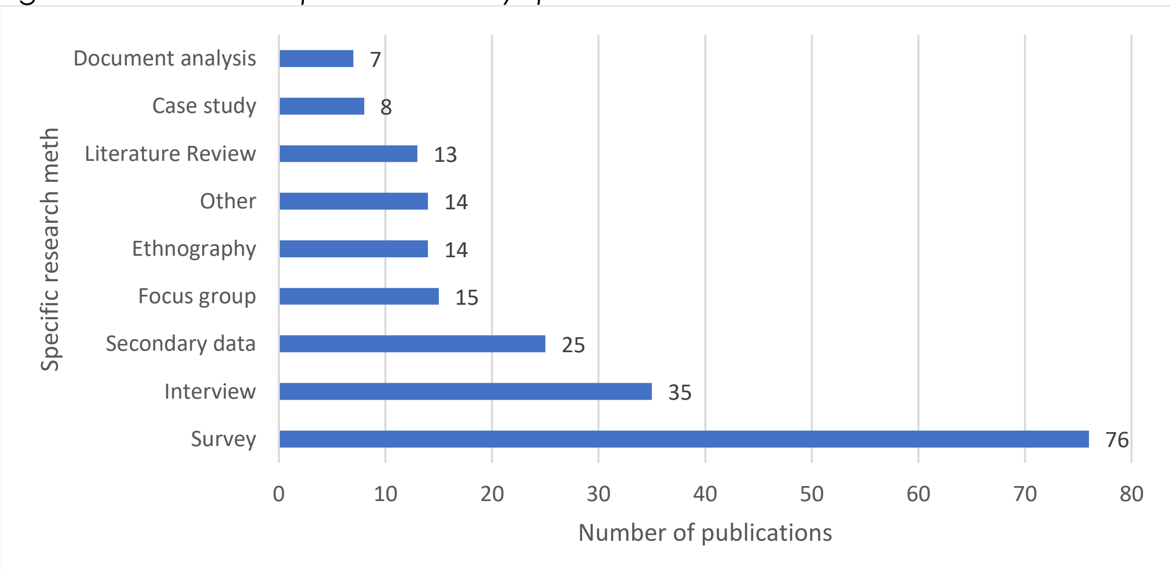
Figure 11. Number of publications by research method



Source: Authors' elaboration

Looking more closely at what specific methods the considered studies employ, Figure 12 highlights how the survey is the preferred method employed by 76 publications. Also Interviews (35) and secondary data analysis (25) are largely employed. Less used and residual appear to be the employment of focus groups (15), ethnography (14), literature reviews (13), case study analysis (8), and document analysis (7).

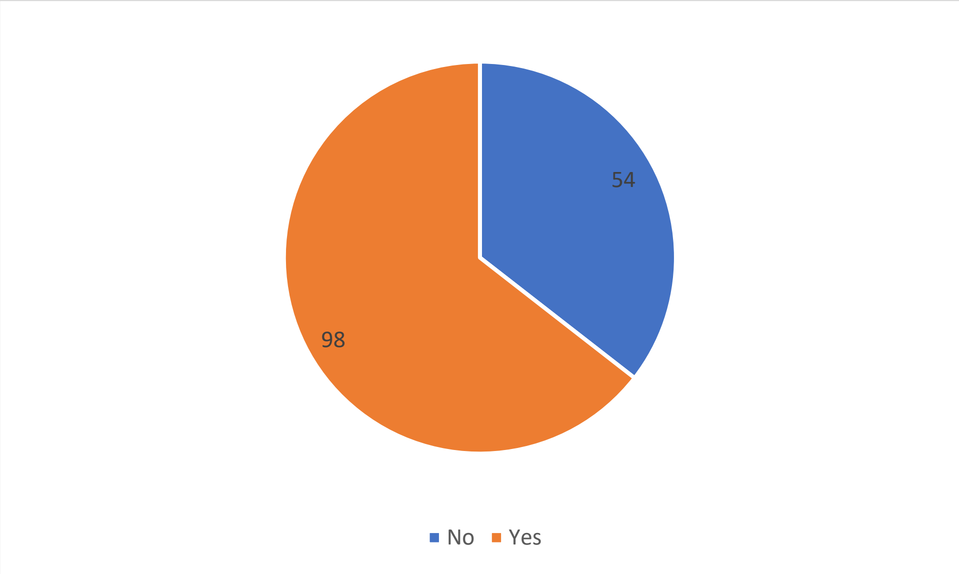
Figure 12. Number of publications by specific research method



Source: Authors' elaboration

Lastly, figure 13 shows how the majority of the publications considered presents policy recommendations.

Figure 13. Number of publications presenting policy recommendations

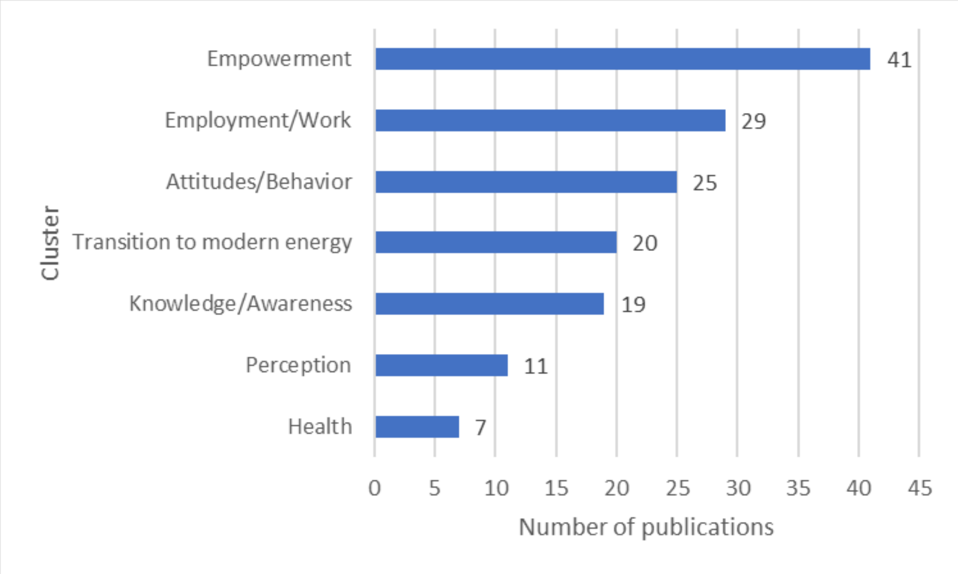


Source: Authors' elaboration

3.2.2 Qualitative analysis of the publications' results, policy recommendations and research gaps for future research highlighted

The gender-related results in the selected publications illuminated several macro-themes that were used to build the clusters for the analysis. Due to the high number of publications analysed and to their heterogeneity in terms of subjects covered, the clustering process was essential to make sense of this huge corpus of knowledge on the relation between gender and energy transition/transformation. Such analysis allowed us to divide up the publications considered into seven clusters: 1. Transition to modern energy; 2. Employment/work; 3. Knowledge/awareness; 4. Perception; 5. Attitudes/behavior; 6. Health; 7. Empowerment. While the content and main topics of categories 2, 3, 4, 5, 6, and 7 are quite self-evident, the content of category 1 needs further explanation. The category "transition to modern energy" in fact, contains those papers that address multiple topics at the interface between energy transition and other clusters (e.g., work, time, health and empowerment). The herein publications had as common topic the transition per se and therefore could not be assigned to the other clusters. Figure 15 presents the distribution of the publications by clusters.

Figure 15. Number of publications by cluster



Source: Authors' elaboration

In the next subsections, we will summarise the results by cluster as well as the research gaps for future research identified and the policy recommendations proposed. Also, for each cluster, we added a dedicated box presenting the two most influential publications in the cluster in terms of citations. Finally, at the end of each cluster sections, a dedicated table summarized the cluster findings.

Cluster 1 – Empowerment

The gendered complexities of energy transition and justice span a global tapestry of diverse social, economic, and cultural contexts. Unearthing the intricacies of this interplay reveals a nuanced and multifaceted picture of how energy transition is experienced, and its impact on men and women around the world.

In various regions, the transition to renewable energy can be a double-edged sword for women. On the one hand, it can bring about socio-economic benefits that translate into higher levels of empowerment for women. On the other hand, it disrupts traditional livelihood activities, such as grazing livestock and collecting firewood, making those not benefiting from the new employment opportunities opened by the renewable energy power plants more vulnerable. Women often find themselves wrestling with this paradox. They shoulder the repercussions of change but are frequently left out of the decision-making processes that guide such transition. Similar results are found in studies conducted in Sub-Saharan Africa, where small scale electrification projects in rural contexts have been found to have the potential to bring significant impacts on people's lives and women empowerment but also to produce unintended consequences, especially on women, when they are not properly guided by appropriate policies.

Most cited articles in Empowerment

The demand for charcoal and fuelwood in Mozambique's urban areas has led to unprecedented forest degradation. Solid fuels dominate the country's energy demand, with few urban households using clean energy sources for cooking. This disproportionately affects women, whose needs are often overlooked in policy design. The paper suggests the need for a gender perspective and a theoretical framework to address solid fuel dependence in urban environments. It proposes using liquified petroleum gas and electricity as potential alternatives.

Chicombo, A. F. F. & Musango, J. K. (2022). Towards a theoretical framework for gendered energy transition at the urban household level: a case of Mozambique. *Renewable & Sustainable Energy Reviews*, 157, 112029.

Renewable energy increases the total amount of energy produced, but it does not replace fossil fuel use on a one-to-one basis. A feminist perspective on energy can help design just energy systems by analyzing energy along four intersecting coordinates: political, economic, socio-ecological, and technological. Feminist energy systems prioritize human well-being and biodiversity over profit and unlimited growth, relationality over individualism, and distributed and decentralized fuel power and people power. Such systems can help resolve impasses of jobs and overpopulation.

Bell, S. E., Daggett, C. & Labuski, C. (2020). Toward feminist energy systems: Why adding women and solar panels is notenough. *Energy Research & Social Science*.

The power of decision-making, a recurring theme across various contexts, emerges as a critical component of gendered energy justice. In Gujarat, India, for instance, while the Solar Park's development presents gender-positive policies, it does not necessarily translate into equitable outcomes on the ground, often creating a surplus population of landless peasants who do not find employment within the solar park. This disconnection between policy and practice points out the need for more gender-responsive implementation strategies. Technology uptake also brings to light the gender dynamics at play. For instance, men predominantly own radios and mobile phones in many contexts, potentially widening the gender digital divide and affecting women's ability to access information related to energy development and therefore limiting their empowerment, as well as increasing the knowledge gap, including on energy.

Within the household context, the bargaining power of women can influence energy choices, particularly the shift towards cleaner fuels. This power dynamic seems more pronounced in urban areas, underlining the influence of local socio-economic conditions and access to resources on the gender-energy nexus. Some studies proved how access to clean fuels and electricity can be a solid driver for women empowerment, for instance, the presence of lights in homes have been found to increase the number of activities performed throughout the day but, at the same time, other studies highlight how the activities performed are often very different between genders in those contexts where a strong patriarchal structure of society is present. In those contexts, it has been noted how men tend to extend their time spent on leisure activities, while women extend their working time.

In the realm of energy cooperatives in the European Union, despite advancements in promoting gender equality, energy continues to be perceived as a male-dominated field. This reveals a persistent challenge in increasing female representation in STEM fields and in energy decision-making bodies. An examination of citizen participation schemes in renewable electricity production reveals how the gender investment gap can be greater than the wealth gap itself. Institutional and cultural factors can either accelerate or mitigate this gap, emphasizing the crucial interplay of these dimensions in shaping gender relations within energy transformations. Interestingly, evidence suggests that greater female representation in national parliaments correlates positively with improved access to electricity and potential increases in sustainable energy consumption and energy efficiency. This underscores the importance of women's voices in legislative bodies to guide and influence energy policy.

However, energy transitions do not always yield negative or challenging outcomes for women. Solar electrification projects have shown positive impacts on women's empowerment, allowing them to seize new opportunities. Yet, these experiences can significantly vary along the renewable energy lifecycle, indicating the need for sustained support and inclusive policies.

As we seek to build more resilient, sustainable, and equitable energy systems, we must contend with the gendered realities that shape energy experiences worldwide. Energy democracy remains incomplete if gendered perspectives are not incorporated. Recognizing the diverse gendered aspects of everyday energy use practices and securing energy services is crucial, especially for improving energy security in poor urban environments. Despite some women managing to exert their agency at local levels, they often remain marginal actors with limited decision-making authority, highlighting the urgent need to mainstream gender in energy development and policymaking.

In essence, energy transition can both reinforce and challenge existing gender inequalities, contingent on a variety of factors such as local socio-economic conditions, cultural norms, policy environments, and the technologies and energy sources involved. This highlights the importance of context-specific and gender-responsive approaches in energy transition policies and strategies to promote a more equitable energy future.

The analysis of the papers selected also suggest several research gaps to be addressed in the future: the identified themes emphasize the significance of gender-inclusive policies, understanding social dynamics, and conducting comprehensive analyses to achieve a just and equitable energy transition. One key aspect is understanding the intersectionality of gender with other social dimensions, such as race, ethnicity, age, education, and economic status. By considering these multiple dimensions, researchers can better grasp the specific benefits or challenges faced by different groups in accessing and benefiting from renewable energy resources. Collaborative research efforts should also be undertaken to investigate the gender dynamics in different renewable energy technologies, such as solar, wind, and bioenergy. By understanding the nuances of gendered energy practices across various technologies, interventions can be designed to cater to diverse energy needs and preferences. To strengthen the evidence base and support gender-inclusive energy policies, researchers must prioritize the collection and dissemination of sex-disaggregated data on employment in renewables. Analysing trends and making comparisons based on such data can illuminate existing gender gaps and inform strategies to promote employment equity.

Some of the papers analysed also present important policy recommendation: according to these papers, women's empowerment in the energy sectors can be realised by including them in the energy-related decision-making spaces, particularly in the responsibility positions. Microenterprises and supervisory boards could have a mandatory quota of women's participation in decision making panels and the participation of female technical staff should be equally promoted. In the same vein, policies should plan for incentives to companies that hire female staff and financial support for energy engineering programs for women. Regarding this last point, research also suggests that, in order to empower women, ad-hoc educational programmes for women should be created, possibly taking into consideration also the disparities emerging out of the interaction between gender and other factors (e.g., income or ethnicity) and the related energy preferences and energy uptake barriers. Policies should clearly state the importance of these non-technical issues in the energy transition.

Table 3 summarizes the results of the Empowerment cluster

Table 3. Aggregation matrix summarizing the results of the Empowerment cluster

Women in STEM	*In the realm of energy cooperatives in the European Union, despite advancements in promoting gender equality, energy continues to be perceived as a male-dominated field.*
Women & sustainability	Evidence suggests that greater female representation in national parliaments correlates positively with improved access to electricity and potential increases in sustainable energy consumption and energy efficiency. This underscores the importance of women's voices in legislative bodies to guide and influence energy policy.
Disconnection between policy and practice	In Gujarat, India, for instance, while the Solar Park's development presents gender-positive policies, it does not necessarily translate into equitable outcomes on the ground, often creating a surplus population of landless peasants who do not find employment within the solar park.
Empowerment of electricity	For instance, the presence of lights in homes have been found to increase the number of activities performed throughout the day. But, at the same time, other studies highlight how the activities performed are often very different between genders in those contexts where a strong patriarchal structure of society is present. E.g., Men tend to extend their time spent on leisure activities, while women extend their working time.
Future Research	• Understanding the intersectionality of gender with other social dimensions, such as race or age. • Investigation of the gender dynamics in different renewable energy technologies, such as solar, wind, and bioenergy, so that interventions can be designed to cater to diverse energy needs and preferences. • Analysing trends and making comparisons based on sex-disaggregated data can illuminate existing gender gaps and inform strategies to promote employment equity.
Policy Recommendations	Women's empowerment in the energy sectors can be realised by • including them in the energy-related decision-making spaces, • supporting companies that hire female staff financially, • creating educational programs for women, possibly taking into consideration the disparities emerging out of the interaction between gender and other factors (e.g., income or ethnicity).

Source: Authors' elaboration

Cluster 2 – Employment/Work

> **Most cited articles in Employment/Work**
>
> Women's participation in renewable energy industries falls short of that in other areas of the economy that require similar levels of training and experience, particularly in the wealthiest nations. The share of women in the renewable energy workforce is about 32%, compared to 22% in the energy sector overall. Women's participation in STEM jobs in renewables is far lower than in administrative jobs. To address these issues, the relationship between gender and the natural environment, especially energy conservation, should be reviewed, and the role of women's professional development via networking organizations should be discussed.
>
> Allison, J. E., McCrory, K. & Oxnevad, I. (2019). Closing the renewable energy gender gap in the United States and Canada: The role of women's professional networking. *Energy Research & Social Science*.
>
> Just transition emerged from the labor movement to describe measures to support workers laid off due to environmental policy. The article argues that compensation for job loss is insufficient to address historical exclusions of people of color and women from energy industry employment or secure the livelihoods of dislocated workers given increasing precarity. The author draws from interviews and field work with energy justice campaigns in Atlanta to center a just transition framework that reconstitutes a social wage to address the uneven spatial development of the U.S. labor market.
>
> Luke, N. (2022). Just transition for all? Labor organizing in the energy sector beyond the loss of "Jobs property". *Annals of the American Association of Geographers*, 113(1), 94–109.

The data collected presents a multifaceted narrative about gender and employment in the context of energy transitions, particularly emphasizing the need for active efforts towards achieving gender equity. Existing gender imbalances in the energy industry are illustrated by the predominance of male representation in the coal industry. It is worthy to stress that several publications highlight how sex-disaggregated data are scarce and often do not allow correlating them with social and gender indicators. In contrast, the renewable energy sector is seen to be more gender diverse, with potential to yield increased job creation and economic growth if gender equity improves. Nevertheless, barriers such as gender-based discrimination and existing power structures hinder women's participation and advancement in this field.

Studies also mention the existence of a stereotyped idea of the entrepreneur in which the male gender represents himself, excluding women from this representation. This male-dominated idealization reproduces gender inequalities in the energy industry.

Studies have shown that gender stratification persists in technology-oriented employment patterns, which could reflect similarly on the renewable energy sector. Women are often relegated to lower-paid positions far removed from creative design, management, and policymaking roles. However, gender-related initiatives can bring about meaningful changes. For example, women-led village level enterprises have been found to outperform their male-led counterparts, possibly because women value these roles highly and are strongly motivated to succeed. There is also evidence that women entrepreneurs can compete and even outperform men, contrasting findings in earlier studies. The role of renewable energy in fostering women's empowerment, particularly in rural areas, is quite evident. The availability of renewable energy encourages members to develop eco-friendly businesses, and the green loan conditions of microfinance institutions favour women's participation in the labour market.

Apparently, considerations of gender equity and social justice often do not yet permeate the mainstream public or policy consciousness in the energy transition in Global South nor Global North countries. In Global North countries it has been seen that the socio-technical transitions of the recent past did not lead to more gender equal employment patterns and if not properly guided a similar destiny can be followed in the case of the energy transition. A just transition, which is a concept that revolves around job creation and workforce transition that aligns with national development priorities, is seen as a solution to energy poverty among women. This could bring about significant changes in the labour market, particularly in regions that rely heavily on mining, an industry that is still male dominated.

Despite these advancements, it is vital to note that structural impediments still exist. Gender-based investment risks and barriers are still prevalent for women entrepreneurs. Patterns of employment for women in the renewable energy sector differ across industrialized, emerging, and developing economies. Therefore, efforts to create livelihoods for women in this sector need to be supported by wider socially progressive pro-women policies and societal shifts in gender roles. Moreover, research indicates a link between female participation in the workforce and renewable energy consumption, while it has been noted how increasing female participation in renewable energy related jobs contributes to lower CO_2 emissions. This implies that women, being more environmentally friendly, can influence a shift towards greener energy consumption in corporate and household affairs.

In terms of gaps to be addressed by future research, the analysis shed light on several important issues related to employment and work in the context of renewable energy and energy transition. Understanding how women's professional networking organizations can contribute to closing the gender gap in renewable energy and how concerns for the environment influence women's education and career choices can pave the way for more gender-inclusive energy practices. The lack of sex-disaggregated data on employment in renewables, globally, poses challenges to understanding trends and making sector- or country-level comparisons. Understanding the gender gaps in energy employment and promoting employment equity requires additional research and empirical evidence, and therefore the need to collect more gendered data. Additionally, research should focus on the economic benefits of closing the gender gap in renewable energy by quantifying the potential job creation and economic growth associated with gender equality in the sector, so that policymakers and investors can recognize the value of investing in women's participation and leadership in renewable energy projects.

In terms of policy recommendations, studies suggest that employment opportunities of women in the energy sectors should be promoted through strategies developed at local level and accounting for in-context structural constraints. Rather than advocating for inclusive practices at a high level, policies should clearly address the social and institutional factors that underpin these constraints by, for example, fostering pro-women hiring practices or designing employment protection schemes. Other forms of inequalities in energy access and use can be tackled through the provision of energy subsidies to vulnerable households, or offer a reward system to farmers who use renewable energy. In other words, policies should adopt an ecosystem approach that provides direct support to female entrepreneurs while also considering the factors in the wider environment that enable or hinder female participation in the energy sector. This implies a proactive and concrete set of actions to redress historically built inequalities and the collaboration with gender-focused institutions and specialists. The policies should promote multifaceted strategies to expand women's participation, spanning from training programs that allow to better fulfill the needs of the renewable energy job market to initiatives that address cultural norms and lack of experience through, for example, follow-up support, induction, trial engagement and apprenticeship.

Table 4 summarizes the results of the Employment/Work cluster.

Table 4. Aggregation matrix summarizing the results of the Employment/Work cluster

Gender imbalances in the energy sector	*Existing gender imbalances in the energy industry: predominance of male representation in the coal industry and the male-dominated idealization of entrepreneurs. In contrast, the renewable energy sector is seen to be a little more gender diverse*
Stereotypical jobs	Even if the average female salary has reached men's one for the same position, women are often relegated to lower-paid positions far removed from creative design, management, and policymaking roles.
Good performance of women-led enterprises	Gender-related initiatives can bring about meaningful changes. For example, women-led village level enterprises have been found to outperform their male-led counterparts, possibly because women value these roles highly and are strongly motivated to succeed. There is also evidence that women entrepreneurs can compete and even outperform men, contrasting findings in earlier studies.
Renewable energy fosters women's empowerment	The role of renewable energy in fostering women's empowerment, particularly in rural areas, is quite evident. The availability of renewable energy encourages members to develop eco-friendly businesses, and the green loan conditions of microfinance institutions favour women's labour empowerment.
Women & CO2 emissions	It has been noted how increasing female participation in renewable energy related jobs contributes to lower CO2 emissions. This implies that women, being more environmentally

	friendly, can influence a shift towards greener energy consumption in corporate and household affairs.
Future research	• Understanding the gender gaps in energy employment and promoting employment equity requires the collection of more sex-disaggregated data. • Understanding how women's professional networking organizations can contribute to closing the gender gap in renewable energy and how concerns for the environment influence women's education and career choices. • Focus on the economic benefits of closing the gender gap in renewable energy by quantifying the potential job creation and economic growth associated with gender equality in the sector.
Policy recommendations	• Adoption of an ecosystem approach that provide direct support to female entrepreneurs while also considering the factors in the wider environment that enable or hinder female participation in the energy sector. • Promotion of multifaceted strategies to expand women's participation, spanning from training programs that allow to better fulfill the needs of the renewable energy job market to initiatives that address cultural norms and lack of experience through, for example, follow-up support, trial engagement and apprenticeship.

Source: Authors' elaboration

Cluster 3 – Attitudes/Behavior

In the vast sphere of renewable energy adoption and its subsequent behaviors, the role of gender has emerged as a significant focal point. A remarkable trend that threads through multiple studies is the propensity of women to be more supportive of environmental protection measures. This support manifests in various ways, such as a preference for renewable energy, the practice of eco-friendly behaviors, and even a willingness to pay extra taxes for the sake of the environment, as well as accepting having renewable energy facilities production locally. Women's environmental consciousness appears to be more heightened, often linking to a deeper concern about looming issues like global warming. Also, a study found that women are opposed to nuclear and coal power plants more often than men.

Most cited articles in Attitudes/Behavior

One study finds that gender intersects with age, geographical location, and other inequalities to shape the adoption of solar home systems SHSs. The adoption of SHSs may reproduce the structures that determine power and resource allocation at the local level. The uptake of SHSs has implications for how and when women perform household chores. The adoption of SHSs in several communities in sub-Saharan Africa is also grounded in class-based and status-based explanations. Culture both fosters and hinders the adoption of SHSs.

Ojöng, N. (2021). The rise of solar home systems in Sub-Saharan Africa: Examining gender, class, and sustainability. *Energy Research & Social Science*, 75, 102011.

A study in Queensland, Australia used a questionnaire based on the Theory of Planned Behaviour (TPB) to evaluate intention to invest in a Community Owned Renewable Energy (CORE) project. 67% of respondents indicated an inclination to invest in the project, and beliefs related to the community benefits that the initiative would provide were the most reliable attitudinal predictor of intention to invest. The findings suggest that "not in my back yard" (NIMBY) concerns are not a significant influence on negative attitudes towards renewable energy in Australia.

Proudlove, R., Finch, S. & Schierl, T. (2020). Factors influencing intention to invest in a community owned renewable energy initiative in Queensland, Australia. *Energy Policy*, 140, 111441.

However, when we delve into the relationship between gender and the technical aspects of energy technologies, a different trend surfaces. It appears that the technical rationality often associated with energy technologies is predominantly masculinized. From initiating the adoption of a new technology at home, such as rooftop solar systems, to getting involved in the nitty-gritty of implementation and monitoring, men are usually at the helm. But this is not a rigid or universal norm. There is a discernible acknowledgement in many studies that women are equally capable of managing these processes if they have access to the necessary training and if they choose to, and it could be considered as a driver of change.

While exploring the landscape of renewable energy, it is also essential to consider the underlying socio-cultural factors and gendered stereotypes that continue to influence perceptions and behaviors. These deep-seated ideas, often shaped during childhood, play a substantial role in shaping attitudes towards energy technologies. A reflection of these stereotypes can be seen in the division of roles at home, with women often coordinating housework-related tasks and men taking up more of the physical refurbishment work and monitoring energy systems.

When we consider the willingness to adopt new energy-saving behaviors and pay for renewable energy initiatives, the picture gets even more complex, and results are mixed. Women are generally more prone to adopting energy-saving behaviors, but some studies found no differences among genders. However, their willingness to pay for green electricity or invest in community-owned renewable energy varies. Gender also influences the adoption of Photovoltaic (PV) systems and grid-electricity, often intertwined with other socioeconomic variables.

A crucial insight is that the adoption of renewable energy technologies does not automatically equate to positive experiences for all, particularly for women and other marginalized groups. Multiple factors, such as class, age, and geographical location, intersect with gender, significantly shaping these experiences. These impacts can, in turn, influence household dynamics and energy consumption behaviors, potentially exacerbating inequality and health risks. For example, the COVID-19 pandemic's impact on energy justice and gender-energy inequality in informal settlements warrants further research post-pandemic. It calls for a deeper understanding of how limited resources and increased domestic unpaid work affect the energy transition in vulnerable communities. This research should consider social, economic, political, and cultural factors shaping energy access and transition in marginalized communities.

Lastly, the role of gender in renewable energy adoption goes beyond attitudes and behaviors to the realm of communication. It has been noted that messaging around renewable energy needs to be more meticulously tailored when addressing women, highlighting the importance of demographic-sensitive communication strategies.

In summary, gender plays a complex and multifaceted role in renewable energy adoption and associated behaviors. These insights offer valuable pointers, but they also underscore the need for more nuanced research to fully understand the dynamics at play.

In terms of policy recommendations, the papers analysed suggest that positive attitudes and behaviors toward the use of renewable energy sources can be incentivised by educational and awareness-raising campaigns especially at local level. This is also realised by highlighting the environmental impacts of traditional energy sources and making the scientific knowledge about climate change more accessible and understandable (e.g., through advertising slogans or expert lecturers). However, scientific evidence underlines that these educational campaigns should be more focused on highlighting the potential benefits of the use of new renewable sources and the possible solutions to existing barriers than on the gravity of the climate change effects. In any case, community participation and involvement in energy transition processes is key for this transition to be successful. Experts and policymakers should strive to involve all the members of the community, particularly considering those who are reluctant to use renewable sources. Furthermore, the papers shed light on the importance of considering how social, economic and cultural factors shape attitudes and behaviors from an intersectional viewpoint. Thus, educational campaigns should tailor their messages based on the audience's socio-demographic characteristics. In conclusion, policies should promote energy transition practices that are inclusive and that acknowledge social differences in energy use and access. This will be especially important to advance gender equality as it will allow to create ad-hoc strategies to overcome the barriers that prevent women's access and use of renewable energy, including, for example, the recruitment of women into STEM education and occupations.

Table 5 summarizes the results of the Attitude/Behavior cluster.

Table 5. Aggregation matrix summarizing the results of the Attitude/Behavior cluster

Tendency of women to show more eco-friendly behavior	*Tendency of women to be more supportive of environmental protection measures. This support manifests in various ways, such as a preference for renewable energy, the practice of eco-friendly behaviors, and even a willingness to pay extra taxes for the sake of the environment, as well as accepting having renewable energy facilities production locally.*
Women have higher environmental consciousness	Women's environmental consciousness appears to be more heightened, often linking to a deeper concern about looming issues like global warming. Also, a study found that women are opposed to nuclear and coal power plants more often than men.
Energy technologies are a "men's topic"	It appears that the technical rationality often associated with energy technologies is predominantly seen as the domain of men. From initiating the adoption of a new technology at home, such as rooftop solar systems, to getting involved in the nitty-gritty of implementation and monitoring, men are usually at the helm. But this is not a rigid or universal norm. There is a discernible acknowledgement in many studies that women are equally capable of managing these processes if they choose to.
Underlying socio-cultural factors and gendered stereotypes	While exploring the landscape of renewable energy, it is also essential to consider the underlying socio-cultural factors and gendered stereotypes that continue to influence perceptions and behaviors. These deep-seated ideas, often shaped during childhood, play a substantial role in shaping attitudes towards energy technologies. A reflection of these stereotypes can be seen in the division of roles at home, with women often coordinating housework-related tasks and men taking up more of the physical refurbishment work and monitoring energy systems.

Communication about renewable energy must be tailored to women	The role of gender in renewable energy adoption goes beyond attitudes and behaviors to the realm of communication. It has been noted that messaging around renewable energy needs to be more meticulously tailored when addressing women, highlighting the importance of demographic-sensitive communication strategies.
Future Research	The COVID-19 pandemic's impact on energy justice and gender-energy inequality in informal settlements warrants further research post-pandemic. This research should consider social, economic, political, and cultural factors shaping energy access and transition in marginalized communities.
Policy Recommendations	• Positive attitudes and behaviors toward the use of renewable energy sources can be incentivised. o by educational and awareness-raising campaigns especially at local level, o by highlighting the environmental impacts of traditional energy sources, and o by making the scientific knowledge about climate change more accessible and understandable (e.g., through advertising slogans or expert lecturers). • Promotion of energy transition practices that are inclusive and that acknowledge social differences in energy use and access.

Source: Authors' elaboration

Cluster 4 – Transition to modern energy

The transition to modern energy sources significantly influences women's lives in several ways in developing countries. This transition process is marked by several challenges, including financial ones, where women struggle with consistent payments for electricity or the cost of connection. For this reason, it has been noted that often women prefer to use a gas stove only once firewood is depleted since gas is more expensive. There's also a cultural preference for cheaper traditional fuels, such as firewood, over modern fuels like gas stoves, even though the procurement of firewood has associated health risks and financial costs.

Most cited articles in Transition to modern energy

Renewable energy transitions are happening in the Global South, but many large-scale renewable energy infrastructures are developed on public lands with unknown impacts on commons access and usage. The Gujarat Solar Park (GSP) in India is one of the world's largest solar photovoltaic facilities, situated on 2,669 acres of previously common property that has historically been used by female pastoralists for firewood collection. The enclosure of public 'wastelands' to develop the Gujarat Solar Park has dispossessed resource-dependent women of access to firewood and grazing lands, reinforcing asymmetrical social power relations at the village scale. Affected women embody this dispossession through inter- and intra-village emotional geographies that cut across caste, class and gen-der boundaries.

Stock, R. & Birkenholtz, T. (2020). Photons vs. Firewood: Female (dis)empowerment by Solar Power in India. *Gender Place and Culture*, 27(11), 1628–1651.

The Solar Mamas' program of the Barefoot College in rural Rajasthan trains rural women in small-scale energy technology, promoting entrepreneurship in energy technology and supporting the transition to clean energy technology in rural areas. The program facilitated the transformative empowerment of women, but a challenge is often the lack of a market in rural areas, and issues also emerged regarding the design and affordability of the solar cookers.

Mininni, G. M. (2022). The Barefoot College 'eco-village' approach to women's entrepreneurship in energy. *Environmental Innovation and Societal Transitions*, 42, 112–123.

However, the transition to modern energy also presents opportunities. Utilizing biogas, for instance, saves women time from collecting firewood, thereby allowing them to engage in other productive activities such as education and social involvement. For instance, several studies pointed out how the reduction in workload for women and children is one of the most significant benefits of switching to biogas, however, as it has already been noted, in contexts where patriarchal norms are strong, men tend to extend their time spent on leisure activities, while women extend their working time in domestic burdens. Yet not all outcomes of this energy transition are positive. For example, the installation of solar arrays in certain areas has displaced women from their traditional areas of firewood collection, with poor women being the most affected.

There are gender differences in perceptions and acceptance of modern energy solutions, with men often showing more willingness to adopt technologies like biodigesters. Factors like gender, experience, and family size significantly influence the adoption of such technologies. This could be due to men having more spare time for training as women are typically more burdened with household chores.

The level of education and intra-household bargaining power of women significantly influences the transition away from traditional fuels. With higher educated women with higher levels of bargaining power, households are more likely to use modern fuels, signifying that women's empowerment within the household can influence energy choices. The narrative also reveals the complexity of the energy transition in specific contexts, such as sub-Saharan Africa. Single women and their families often face greater challenges in accessing electricity due to lower income levels and less influence over household decisions. Despite these challenges, women in many countries stand to benefit immensely from electricity, as it can enhance their access to crucial services such as water pumping, health services, and education facilities. Small-scale solar photovoltaic (PV) systems, for instance, has been found to present opportunities for women to make independent decisions. The energy ladder hypothesis has also been validated, with evidence showing that the likelihood of choosing modern lighting fuel increases with a female household head and with improvements in income, wealth, and education. Female-headed households have shown a preference for modern fuels over traditional ones, primarily due to the decision-making power women hold over cooking fuel choices.

Despite these advancements, the specific energy needs, uses, and challenges women face often go unaddressed, limiting the opportunities for them to benefit equally from electricity access. Certain patriarchal norms in regions like North India encourage the preservation of gas and women's work associated with the use of solid fuels. The introduction of renewable energy technologies, such as biogas digesters, energy-saving biomass stoves, and solar energy cookers, has had positive impacts. Not only do these technologies reduce time spent on cooking and collecting fuelwood and solid biofuels, but they also enhance women's health by reducing exposure to indoor smoke pollution. Financial savings from energy conservation have enabled women to make discretionary purchases, further highlighting the empowerment potential of the energy transition.

In a broader context, education and renewable energy consumption have been found to reduce CO2 emissions. However, land enclosures for energy projects, like solar parks, can displace women from their traditional access to resources such as firewood and grazing lands.

In the end, the transition to modern energy has been both a challenge and a boon for women. It has led to significant positive changes, including empowering women through skills training and enabling them to earn additional income.

The analysis of the selected publications also highlighted several research gaps that need to be assessed by future research. Among other technologies, biogas has emerged as a successful model of renewable energy, but only a few studies have explored its correlation with gender equality. This indicates a research gap, suggesting a need for more comprehensive investigations into the gender implications of technologies. Regarding residential ground-source heat pump (GSHP) systems, further research is needed to explore factors influencing their selection. Such studies can contribute to a better understanding of energy-efficient technologies for households. More in general the intersectional approach remains unexplored in understanding the social gap between public acceptance and local opposition to utility wind power. This indicates a research gap and calls for more inclusive investigations into gender and social dimensions of energy projects.

In terms of policy recommendation, the publications analyzed underscores the significance of economic diversification and subsidies as tools to empower rural communities, particularly women, in their transition away from traditional energy sources. The aim is to enhance their access to the national electric grid and diminish reliance on firewood. It advocates harnessing solar energy and adopting low-cost, energy-saving technologies to achieve these goals. Empowering women's access to energy services is highlighted as a crucial factor contributing to the broader objective of Sustainable Energy for All and subsidies can play a pivotal role in enabling women to access energy resources.

Moreover, available publications identify the potential for entrepreneurial opportunities and new markets, especially for women-led micro, small, and medium-sized enterprises, through clean energy access. They suggest that financial mechanisms should be implemented to help poorer households to afford electricity connections, resulting in benefits for women-headed households and overall connection rates. The integration of clean energy connections into rural households is proposed to alleviate energy poverty. The research highlights the importance of pairing electricity use introduction with education and appropriate technologies to promote energy efficiency. Additionally, strategies like introducing woodlots for firewood supply and engaging women in entrepreneurial and forestry activities are advocated to build resilience to climate change and reduce dependence on natural resources.

The importance of democratizing energy access and management at the local level, particularly for marginalized communities, is emphasized to ensure equitable benefits from new energy systems. Policies should prioritize clean fuel use over infrastructure development, considering societal norms and gender dynamics that influence energy-related decisions. Furthermore, strategies should be implemented to promote clean energy awareness and adoption, including using social media to target younger generations, engaging users as promoters, and raising public awareness through media campaigns and educational initiatives.

Table 6 summarizes the results of the Transition to modern energy cluster.

Table 6.: Aggregation matrix summarizing the results of the Transition to modern energy cluster

Modern energy sources too expensive	*The transition to modern energy sources significantly influences women's lives in several ways in developing countries. This transition process is marked by challenges, particularly financial ones, where women struggle with consistent payments for electricity or the cost of connection. For this reason, it has been noted that often women prefer to use gas stove only once firewood is depleted since gas is more expensive. There's also a cultural preference for cheaper traditional fuels, such as firewood, over modern fuels like gas stoves, even though the procurement of firewood has associated health risks and financial costs.*
Modern energy can empower women	However, the transition to modern energy also presents opportunities. Utilizing biogas, for instance, saves women time from collecting firewood, thereby allowing them to engage in other productive activities such as education and social involvement. For instance, several studies pointed out how the reduction in workload for women and children is one of the most significant benefits of switching to biogas. The introduction of renewable energy technologies, such as biogas digesters, energy-saving biomass stoves, and solar energy cookers, has had positive impacts. Not only do these technologies reduce time spent on cooking and collecting fuelwood and solid biofuels, but they also enhance women's health by reducing exposure to indoor smoke pollution.
Differences in acceptance of modern energy	There are gender differences in perceptions and acceptance of modern energy solutions, with men often showing more willingness to adopt technologies like biodigesters. Factors like gender, experience, and family size significantly influence the adoption of such technologies. This could be due to men having more spare time for training as women are typically more burdened with household chores.
Education & women's bargaining power for clean energy	The level of education and intra-household bargaining power of women significantly influences the transition away from traditional fuels. With higher educated women with higher levels of bargaining power, households are more likely to use modern fuels, signifying that women's empowerment within the household can influence energy choices.
Female-headed households prefer modern fuels over traditional ones	The energy ladder hypothesis has also been validated, with evidence showing that the likelihood of choosing modern lighting fuel increases with a female household head and with improvements in income, wealth, and education. Female-headed households have shown a preference for modern fuels over traditional ones, primarily due to the decision-making power women hold over cooking fuel choices.

Access to resources	Land enclosures for energy projects, like solar parks, can displace women from their traditional access to resources such as firewood and grazing lands.
Future Research	• more comprehensive investigations into the gender implications of technologies (e.g., exploration of correlations between biogas and gender equality). • more inclusive investigations into gender and social dimensions of energy projects (e.g., understanding the social gap between public acceptance and local opposition to utilize wind power)
Policy recommendations	• Empowerment of rural communities in their transition away from traditional energy sources through economic diversification and subsidies. The aim is to enhance their access to the national electric grid and diminish reliance on firewood. • Prioritization of clean fuel use over infrastructure development, considering societal norms and gender dynamics that influence energy-related decisions. • Strategies should be implemented to promote clean energy awareness and adoption, including using social media to target younger generations, engaging users as promoters, and raising public awareness through media campaigns and educational initiatives.

Source: Authors' elaboration

Cluster 5 – Knowledge/Awareness

The research cluster regarding "Knowledge/Awareness" explores gender differences in the understanding and awareness of renewable energy (RE) sources, and other energy transition-related topics. It unveils a complex narrative that intertwines aspects of gender, societal roles, education, and environmental consciousness.

Most cited articles in Knowledge/Awareness

Residential energy consumption in Greece is largely based on fossil fuels, with heating, cooling, and Domestic Hot Water (DHW) production being significant contributors. Ground Source Heat Pump (GSHP) systems are a solution for reducing fossil fuel use and its negative effects. A questionnaire survey was conducted to examine awareness and adoption intention issues concerning this technology in Greece. Factors affecting the subjects under investigation are gender, age, education level, environmentally friendly behavior and awareness, as well as having an occupation, studies, or interests related to the environment, technology, or engineering.

Karytsas, S. (2018). An Empirical analysis on awareness and intention adoption of residential ground source heat pump systems in Greece. *Energy Policy*, 123, 167–179.

This study analyzes people's knowledge and concerns about energy sustainability and the role of gender in this context. The study surveyed 100,956 respondents across 37 countries and found that males report having more knowledge about energy sustainability than females, while females are more concerned about the importance of energy sustainability than males. These results are consistent with the evidence that males are stronger regarding cause-effect logic and females are stronger in holistic associations.

Arachchi, J. I. & Managi, S. (2021). Preferences for Energy Sustainability: Different effects of gender on knowledge and importance. *Renewable & Sustainable Energy Reviews*, 141, 110767.

In the academic and professional world, men generally exhibit higher awareness and understanding of RE. This is particularly apparent within disciplines like biomass, geothermal, ocean thermal, tidal, and wave energy. However, it is important to note that this is not a universal trend. For instance, in a study conducted among Palestinian students, there is no substantial gender difference found in the overall knowledge of RE, though nuanced differences do emerge concerning awareness of specific facets like the Palestinian use of solar energy.

Interestingly, female teachers and lecturers demonstrate superior comprehension of governmental policies related to RE support and implementation, providing a counterpoint to the trend seen in hard sciences. This points to the complexity of the gender-energy nexus, indicating it might not be merely about inherent knowledge and awareness but perhaps also about the domains and contexts in which knowledge is applied or valued.

Environmental consciousness also features in this narrative, with women exhibiting greater awareness and concern for the environment. Young females appear to be more acquainted with RE than young males. Female students appear to be more aware of the nature of fossil fuel sources and nuclear energy than males. Nevertheless, this heightened concern does not necessarily translate into a willingness to pay more for green energy, indicating that attitudes and actions towards RE can be influenced by a multitude of factors beyond just awareness or concern.

Socioeconomic contexts further complicate this picture. The advantage of urban students over their rural counterparts in RE knowledge is a stark reminder that access to information and quality education can significantly affect awareness. Similarly, the disadvantages women in low-empowerment households face in terms of access to and awareness about energy services underscore the intricate interplay of gender and socioeconomic status in shaping energy behaviors. Women within low-empowerment households seem to be significantly less likely to be aware about energy services. Such a gap in awareness displays differences in satisfaction. Women in higher-empowerment households appear more unsatisfied with the energy services, such as home and community lighting, compared with their husbands.

Implications for education are also profound. A gendered pattern emerges for instance in rural India, where the use of household solid fuel significantly hampers girls' educational outcomes more than boys' one. This vividly illustrates how energy choices can disproportionately impact women and girls, exacerbating gender inequities.

Despite these hurdles, there are beacons of hope. One study indicates that integrating a gender perspective into the curriculum can encourage inclusivity, diversity, and contribute to sustainable energy practices in line with Sustainable Development Goal 7. Furthermore, there is evidence that women exhibit higher levels of awareness, readiness, and action than men in the context of smart energy systems.

The analysis of the selected publications also revealed important gaps that future research should try to assess. One significant gap is represented by the limited knowledge about the long-term social development outcomes of electricity access, particularly from the deployment of renewable energy technologies. While the focus on expanding electricity access is crucial, understanding its broader social implications is equally important. The analysed publications emphasize the importance of considering multidimensional poverty aspects and increasing policies that promote clean energy development to reduce poverty. Further research on the need to raise awareness and education is suggested. Future studies should explore how concerns for the natural environment and climate change influence women's education, training, and career choices in renewable energy. By understanding the link between environmental awareness and women's engagement in the energy sector, targeted educational programs can be developed to promote sustainable practices and foster gender inclusivity. Limited knowledge about renewable energy sources among students is possibly influenced by socio-cultural factors. Thus, the need for more robust teaching models is suggested to enhance environmental awareness. There is a clear made for systematic integrated analyses of impacts, comparing them with fossil or nuclear-fired power plants. Such comprehensive assessments are essential to make sustainability recommendations for different energy systems.

In terms of policy recommendations, according to the publications analysed, knowledge concerning renewable energy can be enhanced by integrating RE-

related topics and projects into university and school curricula. The level of awareness can be increased through various channels and by presenting the information in different and appealing formats (e.g., movies). The topics addressed in the curricula should also be adapted based on the trends in industry and requirements of the region and regularly updated to include the latest technology. Vocational training should include learning by doing methods. In addition to school curricula, awareness raising can be realized through educational and outreach campaigns aimed at the large public and by combining traditional mass media channels such as newspaper, television, radio with community-based initiatives. However, it is underscored that energy saving campaigns should be coupled with incentives for businesses and users that decide to adopt RE in order to create the conducive environment for the uptake of these new energy sources. With a specific reference to female users, other policy recommendations include the following: (1) Target women to increase awareness and participation in smart energy initiatives; (2) Implement campaigns and education to promote positive attitudes towards smart energy, particularly among those with higher education. (3) Design policies emphasizing the economic benefits of smart energy for lower-income groups; (4) Focus on younger population with short-term actions, awareness campaigns, training, and incentives; (5) Empower and support younger Eastern Europeans to contribute to the energy transition; (6) Encourage community energy initiatives and share best practices.7) Emphasize environmental action among younger people in Western Europe: (8) Collaborate with industries to foster support for smart energy systems: (9) Support businesses with incentives and training for energy-saving initiatives.

Table 7 summarizes the results of the Knowledge/Awareness cluster.

Table 7. Aggregation matrix summarizing the results of the Knowledge/Awareness cluster

Men tend to exhibit a higher awareness and understanding of RE	*In the academic and professional world, men generally exhibit higher awareness and understanding of RE. This is particularly apparent within disciplines like biomass, geothermal, ocean thermal, tidal, and wave energy. However, it is important to note that this is not a universal trend.*
Different contexts in which knowledge is present	Interestingly, female teachers and lecturers demonstrate superior comprehension of governmental policies related to RE support and implementation, providing a counterpoint to the trend seen in hard sciences. This points to the complexity of the gender-energy nexus, indicating it might not be merely about inherent knowledge and awareness but perhaps also about the domains and contexts in which knowledge is applied or valued.
Women have higher environmental consciousness	Environmental consciousness also features in this narrative, with women exhibiting greater awareness and concern for the environment. Young females appear to be more acquainted with RE than young males. Female students appear to be more aware of the nature of fossil fuel sources and nuclear energy than males. Nevertheless, this heightened concern does not necessarily translate into a willingness to pay more for green energy,

	indicating that attitudes and actions towards RE can be influenced by a multitude of factors beyond just awareness or concern.
Sociocultural context matters for information access, awareness, and behavior	Socioeconomic contexts further complicate this picture. The advantage of urban students over their rural counterparts in RE knowledge is a stark reminder that access to information and quality education can significantly affect awareness. Similarly, the disadvantages women in low-empowerment households face in terms of access to and awareness about energy services underscore the intricate interplay of gender and socioeconomic status in shaping energy behaviors. Women within low-empowerment households seems to be significantly less likely to be aware about energy services. There are differences satisfaction: women in higher-empowerment households appear more unsatisfied with the energy services, such as home and community lighting, compared with their husbands.
Future research	• Consideration of multidimensional poverty aspects and promotion of clean energy development to reduce poverty. • By understanding the link between environmental awareness and women's engagement in the energy sector, targeted educational programs can be developed to promote sustainable practices and foster gender inclusivity.
Policy recommendations	• Integrating RE-related topics and projects into university and school curricula to enhance knowledge concerning renewable energy. • Awareness can be increased through various channels and by presenting the information in different and appealing formats (e.g., movies). • Awareness raising can be realized through educational and outreach campaigns aimed at the large public and by combining traditional mass media channels such as newspaper, television, radio with community-based initiatives.

Source: Authors' elaboration

Cluster 6 – Perception

The results of the publications examined cover a range of perceptions related to gender and energy transition/transformation. On the one hand, there is a clear indication that physical and psychological perceptions related to energy usage and comfort differ between genders. For instance, a study found that males and females have different thermal comfort preferences, with males feeling colder and more affected by drafts than females. Clothing adjustments appear as a strategy for both genders to achieve their desired thermal comfort levels, which might be seen as an indirect way to save energy consumption. In another example, the Pee Power toilet technology, which generates light from human urine, is perceived positively, especially among female students. The safety and convenience provided by the lighting enhanced their experience and indirectly improved educational outcomes and social empowerment.

Most cited articles in Perception

The study investigates the perceptions of Grade 8 teachers in Qatar on Education for Sustainable Development (ESD) integration, as well as the challenges they face for such endeavor. The findings reveal a need for a more holistic and integrated embedding of sustainability values that do not contradict with the local ones, and that move beyond subjects' compartmentalization. The study proposes a preliminary framework for a transdisciplinary and holistic integration of sustainability values within K-12 curricula to empower teachers as the critically important agents of change.

Zguir, M. F., Dubis, S. & Кочкодан, В. (2022). Integrating sustainability into curricula: teachers' perceptions, preparation and practice in Qatar. *Journal of Cleaner Production*, 371, 133167.

Energy communities are important for sustainable energy systems that engage many people, but social and economic factors, including gender, influence participation in desirable energy activities and decision-making. The article explores how energy communities allow for broader participation and how gender influences engagement with collective solar ownership models. The study revealed that energy communities can raise justice concerns in terms of inequities concerning access, capacity, and opportunity to engage in decision-making. Integrating gender into the analysis will provide insights into possible measures to remedy limitations and accelerate the renewable energy transition.

Lazoroska, D., Palm, J. & Bergek, A. (2021). Perceptions of participation and the role of gender for the engagement in solar energy communities in Sweden. *Energy, Sustainability and Society*, 11(1).

Contrasts in energy source preferences and perceptions of environmental impacts were also found. Women tend to value emission reductions more than men. However, both genders seem to prefer electricity as the primary energy source for domestic needs, with men showing a greater reliance on purchased energy, while women lean towards freely available traditional sources like fuelwood. Interestingly, there is a mutual failure to associate pollution with the use of fuelwood.

Perceptions also diverge when it comes to renewable energy's potential impacts. While male respondents see renewable energy as safer and inclusive, some female respondents express concerns about serious environmental issues arising from its use in the future. On the other hand, males appear more concerned about the effects of global warming, while women tend to have a lower preference for nuclear energy than men, and this is because women perceive a higher risk.

The selected studies also explore how gender perceptions affect attitudes towards science, technology, engineering, and mathematics (STEM) fields. There seems to be a prevailing stereotype associating masculine characteristics with science professionals, which is reflected in the belief that male students outperform female students in STEM disciplines.

With respect to the research gaps to be assessed by future research, available publications highlight the importance of considering gender perspectives to gain a comprehensive understanding of the dynamics within renewable energy projects. It would help identify measures to tackle limitations and accelerate the renewable energy transition, thus creating more inclusive and sustainable energy solutions. Moreover, they call attention to the need to explore perceptions of renewable energy among educators and students.

In terms of policy recommendations, institutions and energy developers can improve public perceptions regarding RE with the adoption of locally embedded approaches. This implies creating partnerships with local people and private sector developers for the delivery of local community energy projects. In addition to this, educational and training programmes can be designed, and mass education workshops can be realised so that households are better equipped for managing energy consumption. Similarly, to the health cluster, it is recommended to combine these interventions with initiatives aimed at poverty alleviation and skills development.

Table 8 summarizes the results of the Perception cluster.

Table 8. Aggregation matrix summarizing the results of the Perception cluster

Physical and psychological differences	*There is a clear indication that physical and psychological perceptions related to energy usage and comfort differ between genders. For instance, a study found that males and females have different thermal comfort preferences, with males feeling colder and more affected by drafts than females.*
Energy technologies can foster women's bodily integrity	In another example, the Pee Power toilet technology, which generates light from human urine, is perceived positively, especially among female students. The safety and convenience provided by the lighting enhanced their experience and indirectly improved educational outcomes and social empowerment.
Differences in perception regarding concerns	Perceptions also diverge when it comes to renewable energy's potential impacts. While male respondents see renewable energy as safer and inclusive, some female respondents express concerns about serious environmental issues arising from its use in the future.

related to renewable energy	On the other hand, males appear more concerned about the effects of global warming, while women tend to have a lower preference for nuclear energy than men, and this is because women perceive a higher risk.
Stereotypes in STEM fields	The selected studies also explore how gender perceptions affect attitudes towards science, technology, engineering, and mathematics (STEM) fields. There seems to be a prevailing stereotype associating masculine characteristics with science professionals, which is reflected in the belief that male students outperform female students in STEM disciplines.
Commonalities between men and women	Both genders seem to prefer electricity as the primary energy source for domestic needs, with men showing a greater reliance on purchased energy, while women lean towards freely available traditional sources like fuelwood. Interestingly, there is a mutual failure to associate pollution with the use of fuelwood.
Future research	• Identification of measures to tackle limitations and accelerate the renewable energy transition by considering gender perspectives. • Exploration of perceptions of RE among educators and students
Policy recommendations	• Adoption of locally embedded approaches (e.g., create partnerships with local people and private sector developers for the delivery of local community energy projects). • Design educational and training programmes, so that households are better equipped for managing energy consumption. • Combination of these interventions with initiatives aimed at poverty alleviation and skills development.

Source: Authors' elaboration

Cluster 7 – Health

Gender differences play a pivotal role in determining the health outcomes associated with various energy sources, and therefore is a fundamental aspect to consider when assessing the relation between gender and energy transition/transformation.

Several studies showed how women, who are primarily involved in cooking tasks in many societies, bear the brunt of biomass combustion, which is still one of the main energy sources employed especially in rural areas of low- and middle-income countries. The toxic fumes they inhale lead to a range of health conditions, including chronic obstructive pulmonary disease, tracheal/bronchial/lung cancers, and even an increased risk of stillbirth during pregnancy. The examined reports pointed out how often awareness is insufficient regarding the associated non-communicable diseases, underlining the necessity for initiatives to educate about the adverse health effects of household air pollution, thereby fostering a transition towards cleaner fuels.

Most cited articles in Health

Around 2.5 billion people in low- and middle-income countries use solid fuels for cooking, which negatively affects their health and the environment. This review investigates the technologies and systems that are currently used to cook food, with a focus on low-income populations. It identifies key challenges that hinder a global transition to clean and sustainable cooking. Finally, it reflects on the recent success of Liquified Petroleum Gas (LPG) along with other fossil fuel-based cooking systems and discusses a potential transition to renewable energy-based cooking.

Wright, C., Sathre, R. & Buluswar, S. (2020). The global challenge of clean cooking systems. *Food Security*, 12(6), 1219–1240.

Another study investigated the impact of household cooking fuel choice on women's health from multiple dimensions. Switching from solid fuel to clean fuel improves women's self-rated and others-rated health. It has no significant impact on women's abilities of independence in daily activities. The health effect on women aged 46 and above is more significant than that on women aged 45 and below. There are significant differences between urban and rural areas in the impact of household cooking fuel switching on women's health. Uneducated women benefit more than educated women from clean cooking fuel switching.

Wu, S. (2021). The health impact of household cooking fuel choice on women: Evidence from China. *Sustainability*, 13(21), 12080.

Moreover, the implementation of new energy facilities, such as biogas, solar stoves, and biomass stoves, brings tangible benefits for women's health. For instance, Tibetan women reported a significant decrease in disease incidence after the introduction of cleaner and more efficient energy stoves, which also relieved them from the strenuous task of energy-sources collection. Studies demonstrated how women engaged in cooking with traditional wood stoves noticed an improvement in their quality of life when shifting to biodigesters fed by waste, yielding not only environmental advantages but also time savings and reduced energy costs.

Yet, it is crucial to consider that household air pollution disproportionately impacts women and children, who typically spend more time in cooking and food preparation. This exposure discrepancy exacerbates the adverse health effects in these groups, which can also vary considerably between regions. Further, the opportunity costs for women and children engaged in fuelwood collection are considerable, hindering opportunities for schooling, work, and increasing the risk of injuries or attacks. Therefore, the transition to cleaner fuels, such as shifting from solid fuel to clean fuel for cooking, is not only an environmental concern but a pressing health and gender issue. Indeed, such a switch has been shown to improve women's self-rated health, though it does not significantly affect their daily activity independence. Therefore, broader structural changes are required to fully address the health and gender implications of energy use.

The examined studies highlight how more evidence-based research on the gender-energy-poor urban nexus in Africa is needed to achieve universal access to energy for all, and to consider health aspects. A reference to more data on health and indoor air pollution is underlined in different studies. Few studies underline that research has primarily focused on ecological environmental health, neglecting the human health implications such as Indoor Air Pollution (IAP). This points to a research gap, urging further investigation into the health impacts of energy transitions.

Consequently, in terms of policy recommendations the publications considered claim the need for the development of IAP standards that are sometimes lacking. More generally, it is important that the energy policies meet the needs of the women; to this end Women community organizations can be formed to advocate for these requests and bolster mutual help regarding energy use, housework, education, and healthcare. Good outcomes in terms of improved physical and mental health among women can be achieved by enabling affordability, supply and reliability of clean fuels among low-income households through subsidies and improving electrification and energy infrastructures networks in the rural and remote areas and villages. Furthermore, it has been demonstrated that knowledge about the adverse impacts of solid fuel on the health and the environment can drive energy choices toward the use of RE; thus, energy policies should support such education campaigns. Overall, these energy policies should go hand in hand with policies for poverty alleviation if they want to improve health outcomes. Indeed, poverty often forces women and households into the use of solid fuels (e.g., fuelwood).

Table 9 summarizes the results of the health cluster.

Table 9. Aggregation matrix summarizing the results of the health cluster

Health issues disproportionately affect women	*Several studies showed how women, who are primarily involved in cooking tasks in many societies, bear the brunt of biomass combustion, which is still one of the main energy sources employed especially in rural areas of low- and middle-income countries. The toxic fumes they inhale lead to a range of health conditions, including chronic obstructive pulmonary disease, tracheal/bronchial/lung cancers, and even an increased risk of stillbirth during pregnancy. The examined studies point out how often awareness is insufficient regarding the associated non-communicable diseases.*
Cleaner energy facilities can improve life quality	The implementation of new energy facilities, such as biogas, solar stoves, and biomass stoves, brings tangible benefits for women's health. Studies demonstrated how women engaged in cooking with traditional wood stoves noticed an improvement in their quality of life when shifting to biodigesters fed by waste, yielding not only environmental advantages but also time savings and reduced energy costs.
Current energy sources hinder women's and girl's opportunities	Further, the opportunity costs for women and children engaged in fuelwood collection are considerable, hindering opportunities for schooling, work, and increasing the risk of injuries or attacks.
Future Research	• Further investigation of human health impacts of energy transitions, such as Indoor Air Pollution (IAP).
Policy recommendations	• Development of IAP standards. • Enabling affordability, supply, and reliability of clean fuels among low-income households through subsidies and improving electrification and energy infrastructures networks in the rural and remote areas and villages. • Support for education campaigns about the adverse impacts of solid fuel on health and the environment.

Source: Authors' elaboration

3.3 Conclusions

Research on the nexus between gender and energy transition is a relatively new field of study that is gaining more and more attention in the last decade. In general terms, such nexus can be defined by different dimensions that could be summarized by the following macro-research questions.

1. If, how, and to what extent the energy transition is experienced and affects women and men differently and if and how it reinforces existing inequalities from a gender and intersectional perspective?
2. How do women contribute to the development of the energy transition in terms of knowledge production and workforce?

3. Do the decision-making processes and the policies concerning the energy transition incorporate a gender dimension?

It is worthy to consider that the research on the nexus between gender and energy transition is very heterogeneous and that the above-mentioned research questions have been investigated through diverse perspectives, methodologies and approaches spanning several different disciplines. The outcomes of the related research are therefore very diverse.

Thus, the SLR here performed allowed us to make sense of a fragmented and variegated corpus of knowledge and to derive from its analysis several interesting insights. To do so, we clustered the publications analysed by macro-themes. The clustering exercise allowed us to identify seven clusters: 1. Transition to modern energy; 2. Employment/work; 3. Knowledge/awareness; 4. Perception; 5. Attitudes/behavior; 6. Health; 7. Empowerment.

In this section, we will discuss the results that appeared transversally through several macro-themes or that appeared to affect different clusters simultaneously.

First and foremost, the analysis of the results highlighted *the lack of gender disaggregated data*. This lack of data is pointed out by many publications and make it difficult to analyse the nexus between gender and energy transition. The lack of data is evident in many disciplines and characterizes all the components of the nexus, as well as the different geographical location. Most of the publications analysed, therefore, call for increasing the efforts directed at data collection and claim the fundamental need to collect and systematize gender disaggregated data.

The SLR also points out that most of the gender issues in the energy transition are strongly *dependent on context-specific cultural factors and norms and on established social roles*. For instance, issues as the low participation of women in the energy sector workforce and their low participation in education and training in the energy sector is context-dependent and it is highly influenced by the beliefs concerning the overall role of the women within each society as well as by the gender stereotypes that derive from these beliefs.

Besides, the analysis highlights that there are many aspects of the nexus between gender and energy transition that, until now, have received little to no attention and therefore need to be investigated in order to fully understand the phenomenon. For instance, it is essential to *understand the intersectionality of gender with other social dimensions, such as race, ethnicity, age, education, and economic status*. By considering these multiple dimensions, researchers can better grasp the specific benefits or challenges faced by different groups in accessing and benefiting from renewable energy resources. Also, further research needs to focus on the economic benefits of closing the gender gap in renewable energy by quantifying the potential job creation and economic growth associated with gender equality in the sector.

At the same time, many of the publications claim for the need for more comprehensive investigations into the gender implications of the technologies used for the transition. Many questions remain still unanswered, and future research should dig into these questions in order to disentangle the benefits, opportunities and hindering factors that are intrinsic to the energy transition.

Another emergent result is related to the effects of the energy transition on women. Several publications, in fact, point out that the *transition to renewable energy can be, in various world regions, a double-edged sword for women.* This may happen because, on the one side, the transition can undoubtedly bring about socio-economic benefits such as increased levels of education, health, employment and ultimately empowerment. But on the other side, it can disrupt traditional livelihood activities such as gazing livestock and collecting biomass, making those women that did not directly benefit from new employment opportunities opened by renewable energy power plants even more vulnerable.

Lastly, strictly connected with the previous point, most of the publications analysed highlighted how the energy transition process is not neutral and lend itself to a market-driven logic that will inevitably create winners and losers, likely affecting in a negative way the weakest and most marginalised segments of the population groups, including the women. For this reason, research deems of outmost importance that the process is driven and regulated through appropriate policies. According to the research analysed, in fact, policymakers need to intervene to forecast and avoid the negative consequences of the transition whenever possible, or, when neutralising these consequences is not possible, to envisage actions for their mitigation. The great majority of the publications considered, therefore, agree on the fact that policymaking is essential to drive energy transition toward just and fair outcomes.

4. GREY LITERATURE REVIEW

This grey literature review is conducted within the gEneSys project and is a part of T1.1. It aims at exploring how the gendered innovation approach is embedded in the energy transition domain, and specifically at mapping the interrelations between gender and energy transition and exploring how the gender dimension is framed and analysed within the political, economic, socio-ecological, and technological subsystems. In particular, the Grey Literature Review aims at answering the following research questions:

RQ1. How do have non-governmental organizations and policy initiatives frame the energy-gender nexus in Europe and beyond?

RQ2. Which parts of the world, including regions, countries, and inner-country areas, are of special interest to analysed policy-oriented organizations?

RQ3. How are different technologies and resources intertwined with the frames of the energy-gender nexus?

RQ4. How is the gender-energy nexus discussed at different levels of analysis, such as the household and structural levels?

RQ5 What are the primary areas of intervention recommended for addressing the gender-energy nexus in policies?

RQ6, Lastly, to what extent does grey literature contribute to mainstreaming gender within the energy sector?

The review covers the publications of international and regional organisations having focus on energy transition and/or gender. It supplements the systematic literature review covering peer-reviewed journal articles. Together with the systematic literature review, it will facilitate the design of analytical framework for policy review (T1.4).

The project members agreed to include grey literature in the review of existing research on gender-energy nexus to have a complete, comprehensive picture of the available evidence. In comparison to scientific articles which may concentrate on particular countries or regions, the publications issued by international organisations often provide a global perspective on the analysed issues. The analysis of grey literature allows for capturing the most recent initiatives and policies addressing the gender gaps in the energy transition, which may be missing in the research articles. Additionally, as grey literature is more accessible and relevant to a wider range of readers than the scientific papers, it is an important source of knowledge and therefore it is worth to analyse how the gender aspects of energy transitions are depicted and interpreted in these publications. Finally, as grey literature is often practice-oriented, its' analysis can provide concrete solutions, measures, and best practices for effectively addressing gender gaps and injustices in the energy processes.

There are few grey literature reviews that focus on the selected gendered aspects of energy, energy transition or just transformation. Paula Carroll (2022) performed – together with a systematic review of academic papers – a critical review of the grey literature using the EU reports and policy documents on gender equality and the energy transition to identify how the gender equality objectives in the European Research Area - gender equality in scientific careers; gender balance in decision making; and integration of the gender dimension into the content of research and innovation - have been, or may be, used to mainstream gender into the EU energy transition. The review of grey literature showed an insufficient connection between EU gender equality and clean energy plans and that gender had not been fully mainstreamed into the EU energy transition. A literature review prepared as part of the H2020 project DIALOGUES (2022) included both peer-reviewed articles and grey literature and aimed at informing project participants on the relevant gender aspects of energy. It showed that they were clustered along nine topics. The energy poverty cluster was represented by papers focusing on how women are more affected by energy poverty. The gender roles & technology cluster included papers focusing on roles of gender in the context of prosumerism and renewable energies. The papers in the gendered energy consumption cluster focused on gender as a determinant of domestic energy use (laundry, cooking, cleaning etc.). The gender-responsive energy policy cluster was represented by papers focusing on tools, methods and solutions to make energy policies gender-responsive. The intersectionality cluster included papers analysing intersectional aspects of the energy sector and energy transition. The just transition cluster referred to analyses on how just transition for the energy sector needs to look like, with a gender focus. The representation in renewable energy cooperatives cluster concentrated on the (under)representation of women, lesbians, inter, non-binary, trans, agender people in renewable energy cooperatives, local energy initiatives and community-based energy. Finally, the data on gender cluster was represented by papers that use gender as a variable or cite findings of different papers.

Pueyo and Maestre (2019) performed a review of literature linking energy access, gender and poverty, which included both peer-reviewed articles and grey literature. The aim of this review was to verify whether there were gender differences in obtaining benefits from the Productive Use of Electricity (PUE) and which interventions worked to achieve gender equity in the PUE? The authors found that PUE literature had so far considered gender mainly at the household level, by looking at the labour supply effects of access to electricity. The analysis also allowed to identify the constraints that explain performance differentials between male and female led enterprises.

Other literature reviews on the gender-energy nexus do not include insights from the grey literature as it requires time consuming manual searching of individual web sites (Johnson et al., 2020) and as it "mostly reflects the normative approaches of non-governmental organisations and funding agencies to gender mainstreaming in energy policy (...) [and it] often lacks methodological soundness and transparency, and such publications are often not peer-reviewed" (Feenstra & Özerol, 2021: 5). The report first presents the research objectives and the methodology of the grey literature review. It then provides general statistics describing the pool of analysed publications.

This is followed by in-depth analysis of selected issues emerging from the review: 1. the specificity of discussing gender/energy nexus in relation to different technologies (renewable, traditional), 2. the specificity of discussing gender/energy nexus discussed according to world regions and the level of analysis (e.g. household level vs. structural analysis), and 3. the main areas of intervention at the gender-energy nexus according to grey literature policy recommendations.

The general objective of this grey literature review was to explore how the gendered innovation approach is embedded in the energy transition domain. In particular, we aimed at mapping the interrelations between gender and energy transition in the grey literature as well as exploring how the gender dimension is framed and analysed within the political, economic, socio-ecological, and technological subsystems.

The report first presents the methodology of the study. It then quantitively describes the main results of the grey literature review. This is followed by qualitative analysis of the selected publications aiming at better understanding the interrelations between gender and energy transition.

4.1. Methodology

4.1.1 The logic of sample design

The Grey Literature Review aims to reconstruct how the energy-gender nexus is framed by different types of organisations active in the field of policy-making in the context of sustainable transition. This analysis is intended to complement the systematic review of the academic literature (SLR).

Given the wide variety of publications produced by different bodies, we decided to use a purposive sampling design, based on non-probability sampling techniques, in which units are selected because they have characteristics that we defined as useful for the project objectives.

We then decided to search the archives of the most important organisations, based on the expert judgement of researchers.

As a **first step**, we decided to include two types of organisations:

1) organisations specialised in energy policy

2) organisations active in the field of gender policy

The rationale for this choice was to capture how organisations focusing on energy issues use the gender perspective, gender-oriented organisations problematise energy policy issues. Additionally, how global organisations working with general problems but experienced with analysing gender issues frame the energy-gender nexus.

In a **second step**, both types of organisations were subdivided into categories that differ in their scope and area of activity. Thus, we distinguished between global organisations and organisations with a focus on European affairs, those associated with the EU through research or technological development (European Commission Research Programmes, ETIPS, The EU Energy Initiatives) and those not associated but actively collaborating with EU bodies in policy making (energy and gender NGOs). As a result, we constructed the matrix of organisations of different types, scope of activities and interests (Tab.1)

Table 1. Matrix of types and focus of included organisations

Types of organisations:	***Worldwide and African organisations***		***Orgnisations associated with the EU***		***Organisation collaborating with the EU in policy making***	
Organisational focus:	General focus	Energy focus	Research team realizing EU's R&I programme	EU Energy initiatives and agendas	Gender Focus	Energy focus

In the next step, six groups of researchers were assigned to search and analyse the publications according to their expertise, one group for each category. The work was coordinated by the research team from the Jagiellonian University. Each research group searched the archives of the organisations available online with defined keywords (gender & energy, women & energy, female & energy, "girls & energy). Due to specificality of resources in each group, different strategies of searching the archives were applied. Identification of projects conducted under the EU's research and innovation programme and potentially analysing the nexus of energy and gender required searching Cordis (https://cordis.europa.eu/) database and screening project websites for the deliverables/reports. The search for the publications related to the EU Energy Initiatives was preceded by Google search and then narrowed down to the screening of publications on the EU Directorate-General for Energy website.

During the task, the team met three times to discuss the selection of the organisations, discuss and modify the criteria for inclusion and exclusion of publications, and finally to discuss and modify the descriptive categories and to exchange information about the archives and the work in progress.

Despite these meetings, we could not avoid different interpretations of the agreed categories, resulting in different ways of description. For this reason, the entire database was checked independently by three scholars from Jagiellonian University to verify the relevance of the documents. The documents not referring to gender issues or energy transformation at all or in which gender was mentioned only sporadically, as one of several other variables without any further consideration, or only as part of a socio-demographic description, were considered irrelevant and excluded from the database. In this way, the initial number of 232 datasets was eventually reduced to 138.

4.1.2 Inclusion criteria

From the entire corpus of texts identified with keywords and phrases, we decided to include only reports, working papers, policy briefs, white papers, recommendations and strategies published in the timeframe 2018-2023 for further analysis.

4.1.3 Exclusion Criteria

We excluded newsletters, conference proceedings and presentations, theses, event agendas. This decision was motivated by the intention to reconstruct the position of organisations as institutional actors (rather than individual authors), their deliberate and authorised contribution to the public sphere.

4.1.4 Publication Analysis and Data Extraction

Table 2. Categories included for the extraction of the information

Category	**Explanation**
Does the publication actually assess the nexus between gender and energy transition/transformation (Yes/No)	to assess whether the publication relates to our the gender-energy nexus and to exclude those publications that even passing the abstract screening does not match with the scope of the GLR
Does the publication's focus is on gender issues (gender as main topic, gender as subtopic, gender as a variable, without deeper consideration)	to assess whether the publication relates to our gender dimensions and to exclude publications that do not consider gender issues.
Subsystems: political economic socio-ecological technological (Bell et al. 2020)	to assess the subsystem or subsystems considered, based on the four subsystems proposed by Bell et al., 2020
Research Findings	to report the gender related results of the publication
Types of gender issue(s) addressed	to assess the type of gender issue addressed by the publication, based on the EIGE index: 1) Work; 2) Knowledge; 3) Time; 4) Health; 5) Power; 6) Safety and Trust; 7) Quality; 8) Other
Mentioned Technologies, Infrastructures and Material Systems	to assess the technology mentioned in the publication, for instance, wind, solar, hydro, coal, etc.
Which country/ies are analysed?	to assess which country or countries are assessed by the publication

Theoretical contribution	to assess how the publication contributes to the state-of - the art of gender- energy nexus.
Spatial Context	to assess the spatial context of the analysis: international, national, inner-country, peri-urban, rural
Research method	to assess the nature of the research method employed: qualitative, quantitative, mixed, theoretical
Level of analysis	to assess on what level the analysis were conducted (individual, household, institutions, sector)
Type of analysis	to assess what kind of analysis the publication provides (casual relations, comparative, descriptive)
Sample Size (n) total	to assess the sample size of the analysis
Policy Recommendations given	to assess the presence of policy recommendations and their types.
Gender Injustices identified? (Yes/No)	to assess the presence of gender injustice within the analysis
Other Social / Vulnerability Categories interacting with Gender (Intersectional Approach)	to assess the presence of an intersectional analysis and what characteristics are included
Pathways	to assess the presence of a pathways analysis within the publication

Data codification: All documents were coded between 07.2023 and 09.2023.

For the sake of analysability, some of the categorical variables have been re-coded. In particular:

- The variable "type of organisation" has been re-coded by creating 2 additional categories: African of general focus and African of energy focus to better capture the variety of organisations, whose publications were included into the review of grey literature. The categories are therefore the following: Worldwide of general focus, Worldwide of energy focus, African of general focus, African of energy focus, EU energy initiatives, EU project consortia, Policymaking in Europe of gender focus, Policymaking in Europe of energy focus
- The variable "name of organisation" has been expanded into two variables "name of organisation" and "name of EU project"
- The variable "type of publication" has been re-coded by aggregating several similar types of publication into one category and adding a new category "other" for the types of publications that were single. The category "organisational reports" captures reports, annual reports and technical reports produced by regional and global organisations, the category "project reports" refers to the documents produced by EU project consortia, the category

"others" includes a bulletin, a compact, a factsheet, a management response, a white paper, a strategy, submission of views, and a summary.

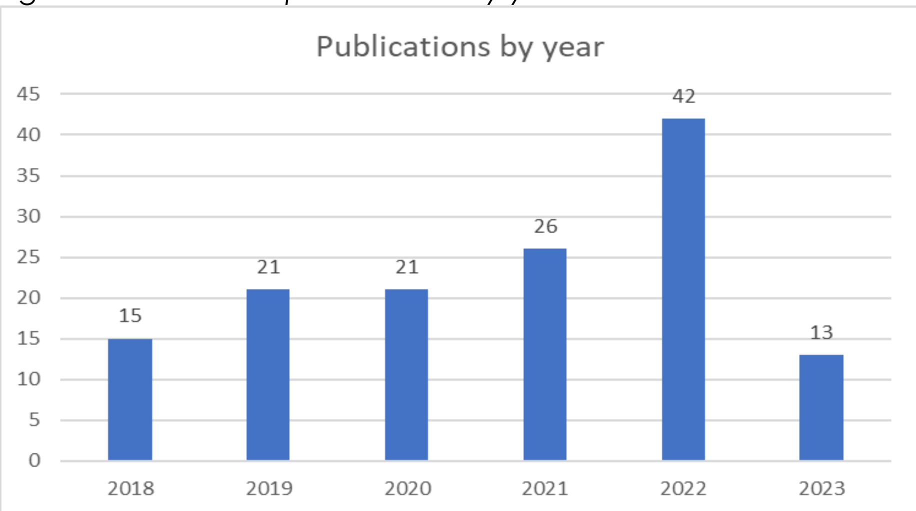
- The variable "technology" was recoded into two variables: "mentioned sources of energy" and "mentioned technologies".
- The variable "country" was recoded into three variables: "single country", "multiple countries" and "region (EU/Africa); a list of countries listed as "single country" was created.
- The category related to methods were split into two categories: one describing the type of presented analysis, and another one describing the particular methods and techniques referred to in the documents.

4.2. The Quantitative Analysis – Descriptive Statistics

As it was stated above, the initial number of 232 records, after removing duplicates, publications from before 2018, publications that did not refer to gender issues or energy transformation at all or mentioned them only sporadically with no further reference, was reduced to the final 138 unique publications.

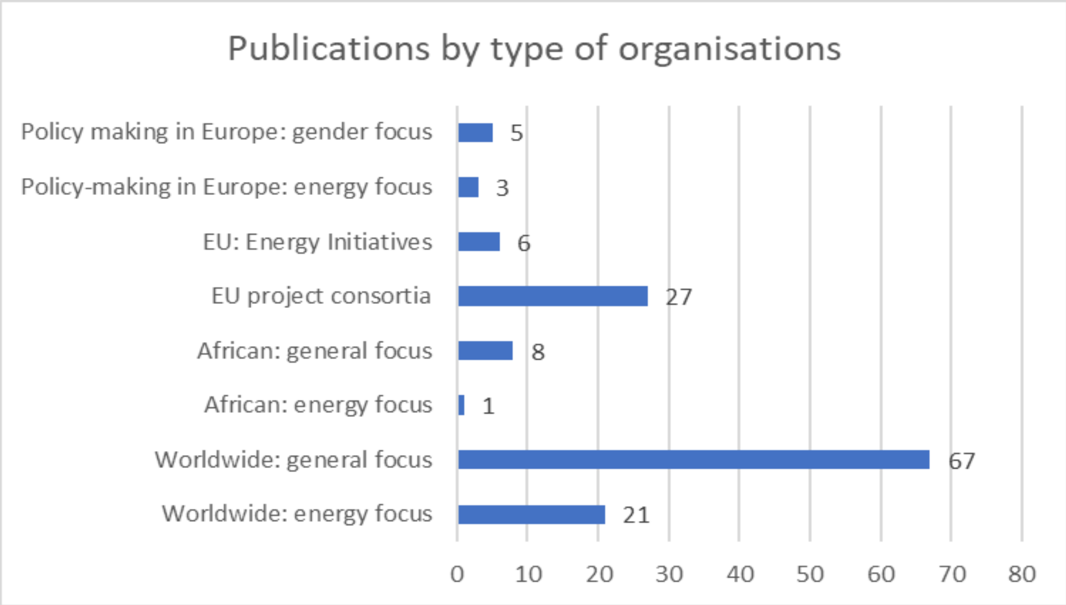
Most of them were published in 2022, which might suggest a growing interest in the gendered aspects of energy transformation among the organisations covered in the analysis (the record for 2023 is incomplete as the analysis took place in summer 2023) (see Fig. 1).

Figure 1. Number of publications by year



The largest number of records are documents of worldwide organisations with general focus (such as World Bank and United Nations). They are followed by publications delivered by interorganisational consortia carrying out European projects that focus on energy transition and by worldwide organisations specifically focusing on energy. Publications by regional organisations, operating in Europe or in Africa, are less frequent (see Fig. 2).

Figure 2. Number of publications by type of organisations



Out of 138 publications, 111 were released by organisations of global or regional reach, 27 - by EU project consortia operating in the Research & Innovation sector. Among the 111 organisational publications, 97 were released by single organisations, and 14 documents were the results of collaborations between two or more organisations. Most publications were released by the World Bank, followed by the United Nations and the International Renewable Energy Agency. Table 1 presents all organisations designated as responsible for analysed publications.

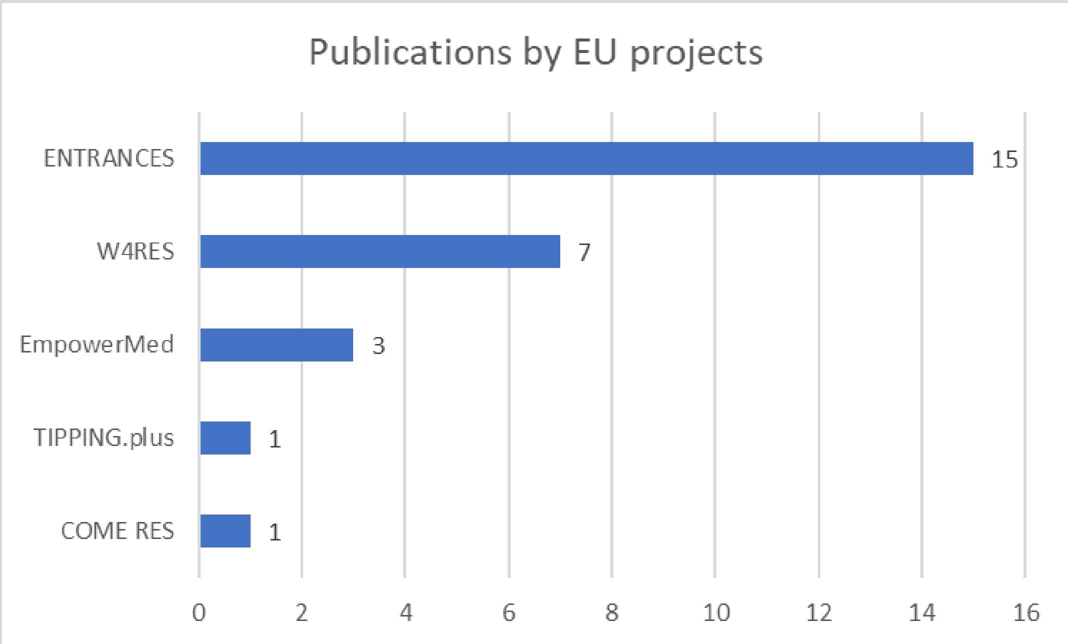
Table 3. Number of publications by organization

Organisation	**No of publications**
WB	*34*
UN	*26*
IRENA	*10*
AFDB	*9*
IEA	*8*
ILO	*7*
WHO	*6*
EC	*4*
SE4ALL	*4*
WECF	*4*
GWNET	*3*
European Parliament	*2*
Women in Energy	*2*
GWEC	*1*
FES Just Climate, Friedrich-Ebert-Stiftung	*1*
COBENEFITS	*1*
Fraunhofer Institute for Systems and Innovation Research	*1*
Zelena energetska zadruga	*1*
European Environmental Bureau	*1*

Centre for Renewable Energy and Energy Efficiency of the The Economic Community of West African States	*1*
New Partnership for Africa's Development (NEPAD) Infrastructure Project Preparatory Facility (IPPF) Special Fund	*1*

Note: The number of publications does not sum up to 111 as a few of them were released by 2 or more organisations

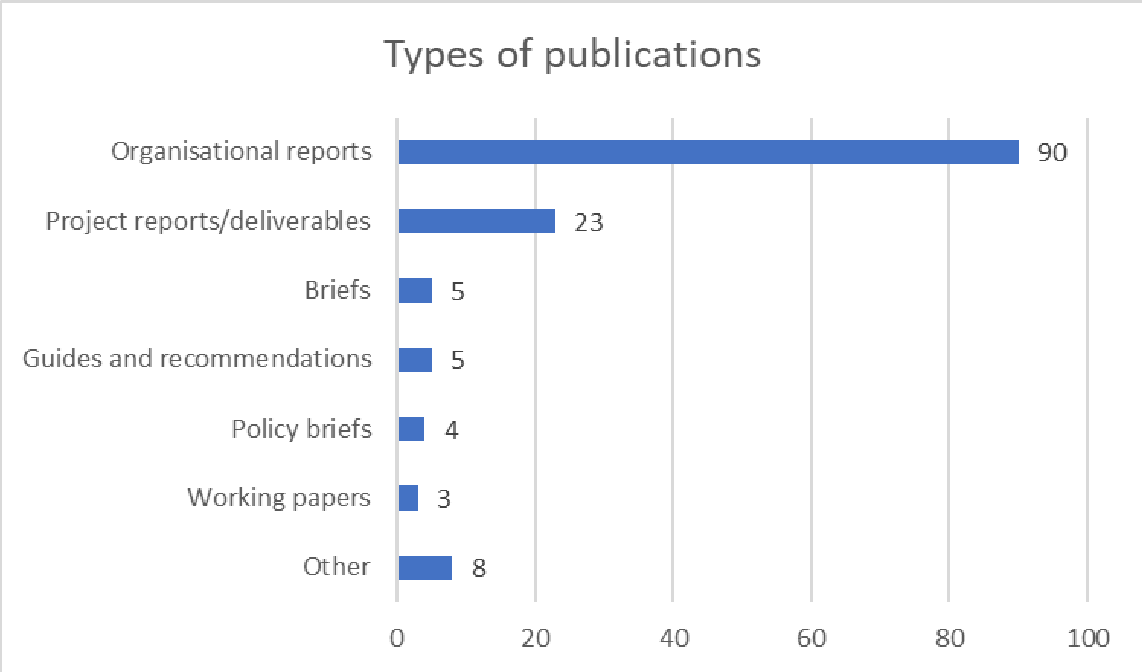
Figure 3. Number of publications by EU project



As for the EU project consortia, the analysed reports were published by the Horizon 2020 projects: ENTRANCES (ENergy TRANsitions from Coal and carbon: Effects on Societies), W4RES (Women for Market Uptake of Renewable Heating and Cooling), EmpowerMed (Empowering women to take action against energy poverty in the Mediterranean), TIPPING.plus (Enabling Positive Tipping Points towards clean-energy transitions in Coal and Carbon Intensive Regions) and COME RES (Community Energy for the uptake of RES in the electricity sector. Connecting long-term visions with short-term actions).

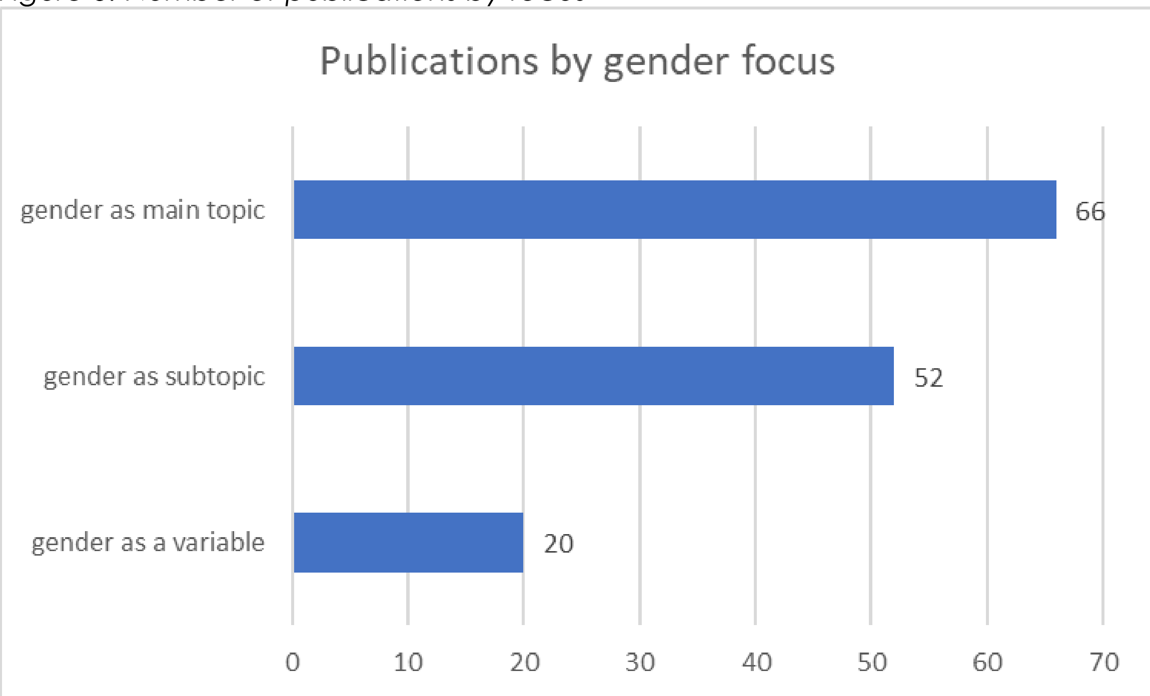
Most of the analysed publications were in the form of an organisational or a project report. There were also a few briefs, guides, policy briefs and working papers and other documents (Fig. 4).

Figure 4. Number of publications by type of publication



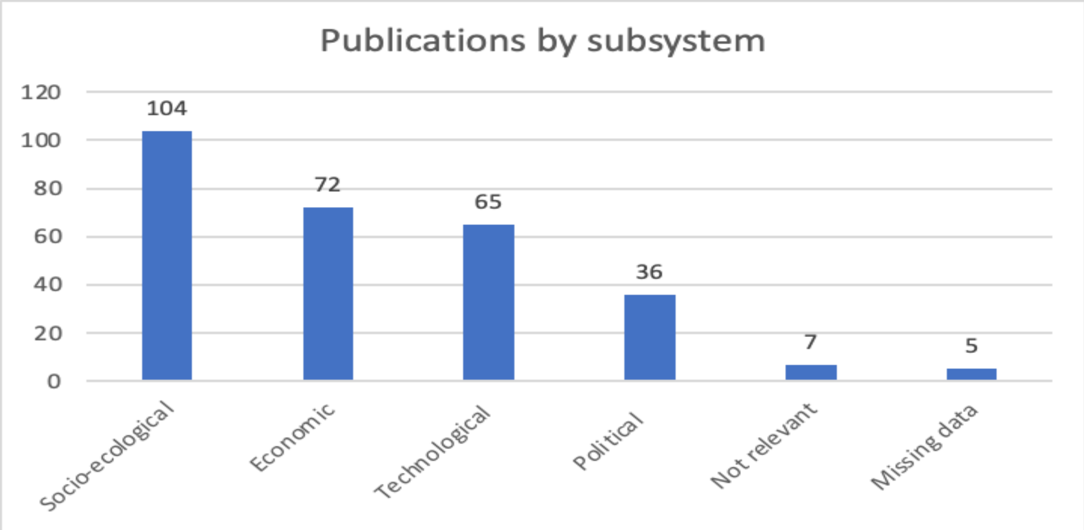
The majority of the publications concentrated on gender issues or gender dimension as the main topic of the analysis. They were followed by documents in which gender issues were still widely discussed, but they constituted one of a few addressed topics. The smallest category were the publications where gender was introduced as an important variable but was not further analysed (comp. Fig. 5).

Figure 5. Number of publications by focus



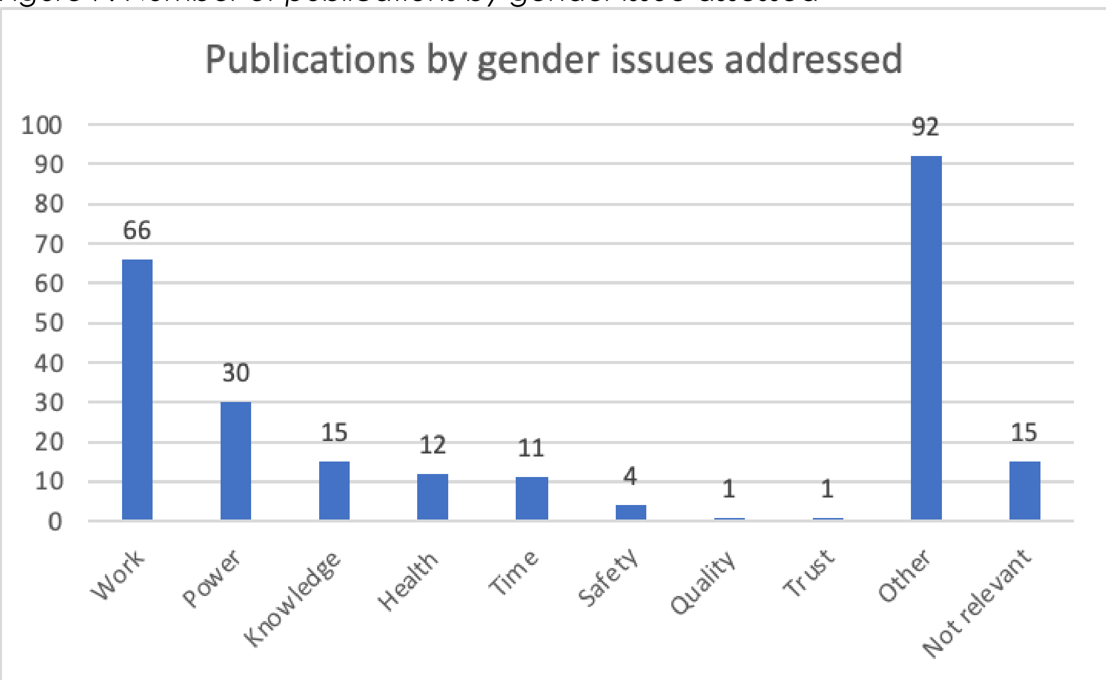
Among the 66 publications that focused on gender as the main topic, most of them (51) analysed the nexus between gender and energy transition, energy sector or energy poverty or between gender and climate issues, where energy transition was depicted as an important aspect (7). The rest of publications (8) discussed gender aspects in various sectors, including energy.

Figure 6. Number of publications by subsystem



Out of 138 publications, only 47 applied as a framework one of the subsystems, while 79 mentioned at least two subsystems (in different configurations). The most frequently mentioned subsystem was the socio-ecological one. Almost half of the publications referred to economic (72) and technological (65) subsystems, while only a few studies discussed the results in relation to the political subsystem.

Figure 7. Number of publications by gender issue assessed



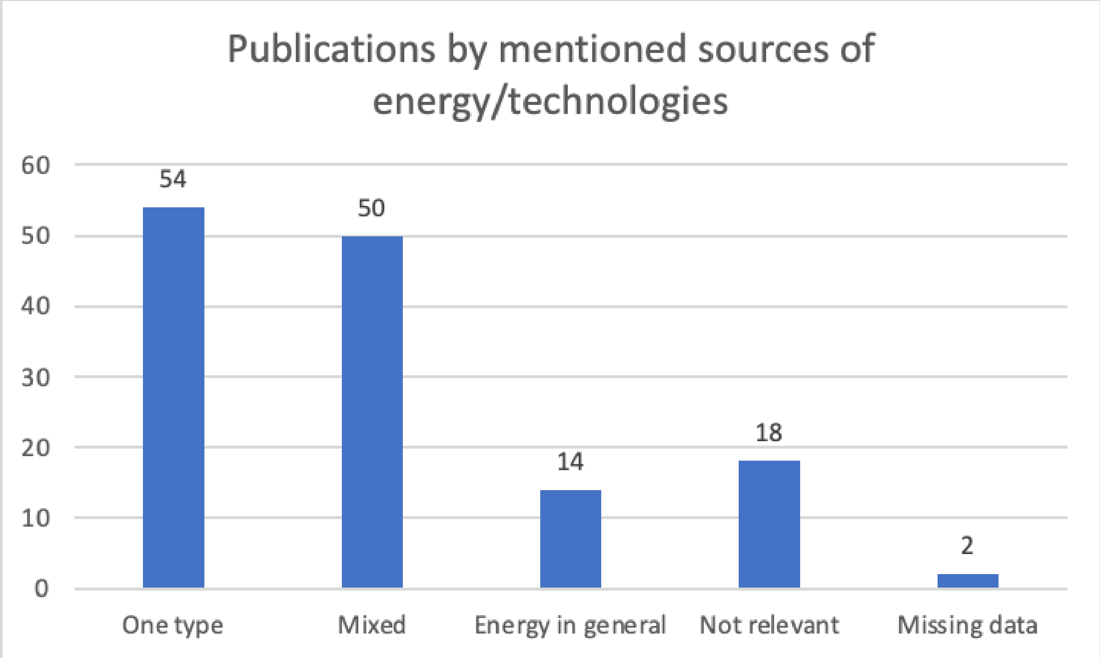
Out of the 8 gender issues searched in the publications, work appeared to be the most frequently occurring topic (66 times in all documents). It was followed by the issues linked to "power "but the latter was mentioned twice as rarely as "work". Three other dimensions: knowledge, health and time were even less likely to be discussed from the gender perspective, while safety, quality and trust were almost absent in the analysed papers.

Table 4. Number of mentioned "Other" gender issue assessed

Gender issues addressed – Other	***Number***
Energy access	*35*
Economic inequalities	*11*
Gender norms	*8*
Gender mainstreaming	*6*
Monitoring	*5*
Energy poverty	*3*
Gender inequalities	*3*
Mobility	*3*
Social	*3*
Empowerment	*2*
Women's roles	*2*
Other (with no specific issue)	*1*
Acceptance	*1*
Access to land	*1*
Access to new opportunity	*1*
Access to public service	*1*
Care	*1*
Digital gender gap	*1*
Ecology & climate	*1*
Gender impact on energy transition	*1*
Transport	*1*
Vulnerability	*1*
Total	***92***

Many of the publications pointed out other topics related to the nexus of gender and energy, including access to energy (mentioned 35 times), economic and financial inequalities (11 times), gender norms and expectations (8 times). Gender mainstreaming and monitoring were also mentioned few times.

Figure 8. Number of publications by mentioned technologies/sources of energy



The majority of publications referred either to specific source of energy or type of technology or mentioned "energy in general". Almost the same number of reports pointed a single and mixed (at least two) source(s) of energy/technology(ies). 14 - out of 138 reports - discussed energy in general, without pointing out a specific source of energy or technology. Only 18 publications did not report information on this category - they did not see it as an important component of the analysis.

Figure 9. Number of mentioned sources of energy

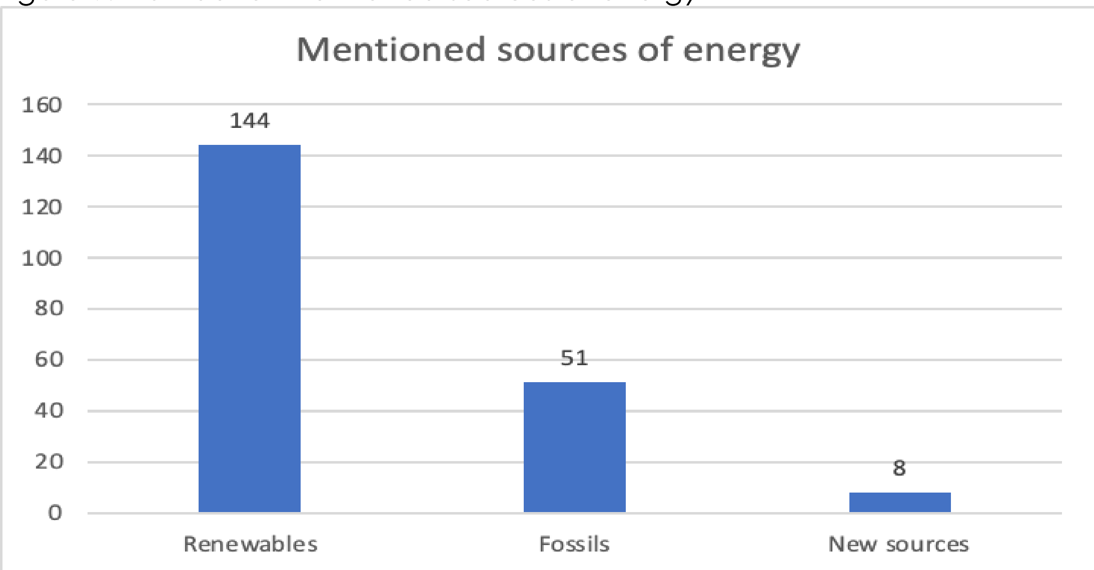
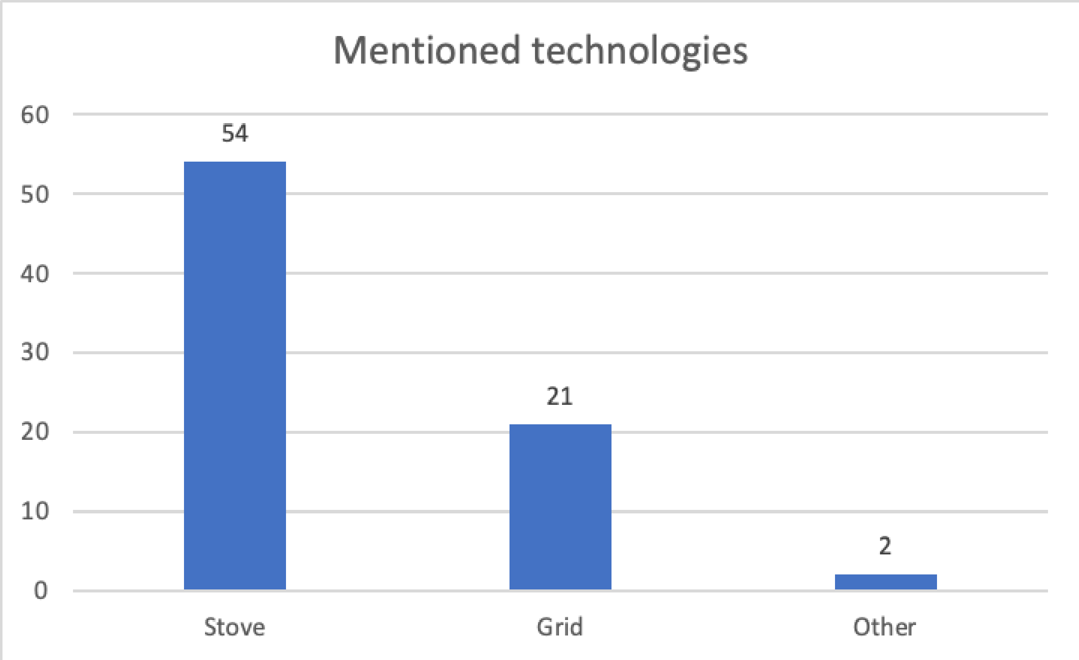
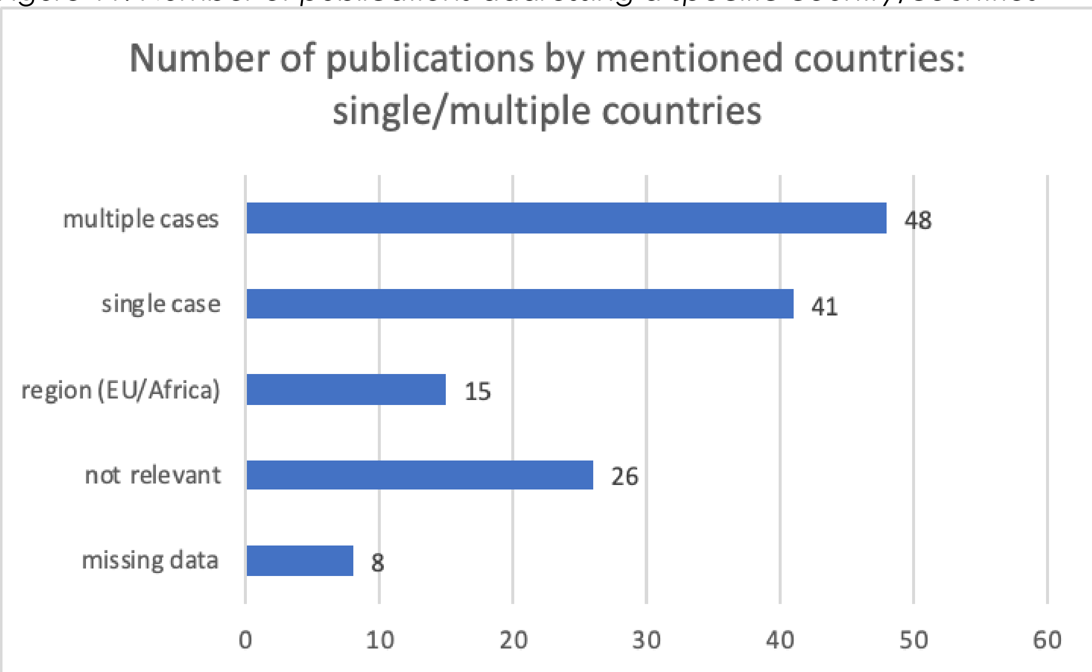


Figure 10. Number of publications by mentioned technology



In the publications that provided information about the sources of energy, renewables are mentioned almost three times as often as fossils. In case of technologies, stoves were mentioned in 54 documents while grids were reported in 21 publications.

Figure 11. Number of publications addressing a specific country/countries



Most publications focused on specific county(ies) (89 in total), but some of the reports presented a broader perspective and referred to continent (Africa) or its regions and entities such as the EU. Among documents discussing the nexus of gender and energy in specific country(ies), similar number referred to a single country (41 cases) and multiple countries (48 cases). Interestingly, the reports do not cover countries typically considered as important for energy sector, such as Iran, Iraq, Saudi Arabia, United Arab Emirates, Kuwait or Israel.

Table 5. Countries mentioned in the publications

Country	**Number of occurance**
Germany	12
Italy	9
Bulgaria	6
India	6
Norway	6
Poland	6
Slovakia	6
Spain	6
Ukraine	6
Bangladesh	5
Serbia	5
Belgium	4
Croatia	4
Denmark	4
France	4
Greece	4
Kenya	4
Romania	4
Albania	3
Austria	3
Ethiopia	3
Georgia	3
Ghana	3
Lebanon	3
Nepal	3
Slovenia	3
Uganda	3
UK	3
Afghanistan	2
Bosnia and Herzegovina	2
Czech Republic	2
Hungary	2
Indonesia	2
Marocco	2
Moldova	2
Myanmar	2

Nigeria	2
Pakistan	2
Portugal	2
Senegal	2
Tunisia	2
Turkey	2
VietNam	2
Zambia	2
Armenia	1
Belarus	1
Bhutan	1
Burkina Faso	1
Cambodia	1
Canada	1
Cote d'Ivoire	1
Egypt	1
Haiti	1
Iraq	1
Japan	1
Kosovo	1
Kyrgyzstan	1
Maldives	1
Montenegro	1
Niger	1
North Macedonia	1
Philippines	1
Republic of Yemen	1
Rwanda	1
São Tomé and Princip	1
Saudi Arabia	1
Somalia	1
Sri Lanka	1
Tanzania	1
USA	1
Uzbeskistan	1
West Bank and Gaza	1
Total	191

The database included both reports from the EU projects and worldwide organizations, which is translated into the specific countries. Germany and Italy are most common countries mentioned in the reports (respectively 12 and 9 occurrences), followed by

Bulgaria, India, Norway, Poland, Slovakia, Spain and Ukraine. A detailed list of countries mentioned in the reports are presented in Table 5.

In many of the documents analysed, the spatial context was not specified (in most of these cases, the analysis referred to the general situation in the energy sector). Where it is specified, it often refers to the country level, to regions within countries, but also to regions in the sense of geographical areas such as sub-Saharan Africa or East Asia. Some of the analyses focus on urban and rural areas, and few on the global picture of gender-related energy issues. There is also a group of reports that look at multiple levels (country, regions or country, rural-urban).

Figure 12. Number of publications by spatial context

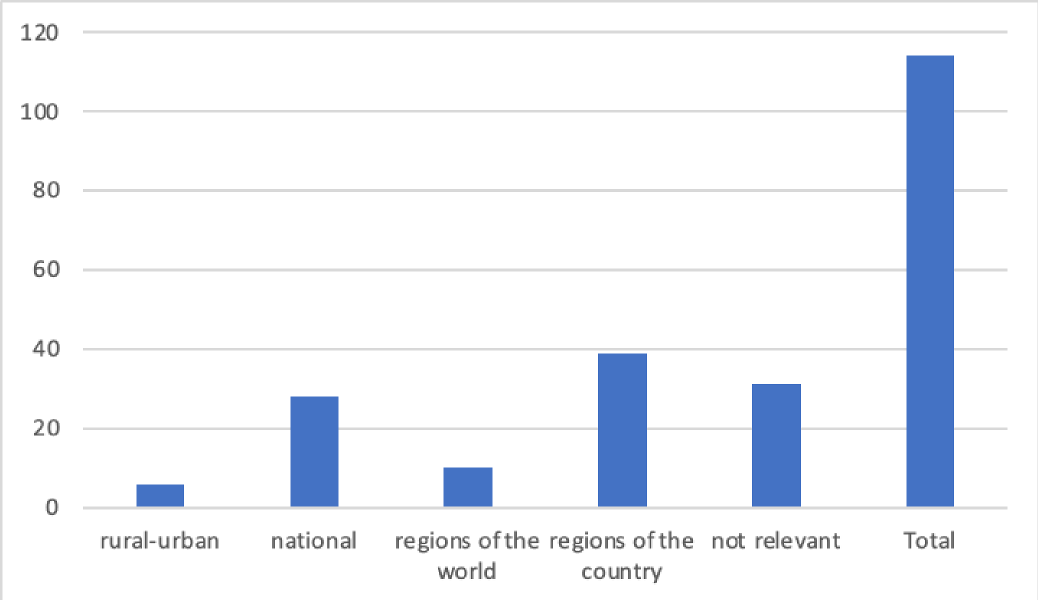
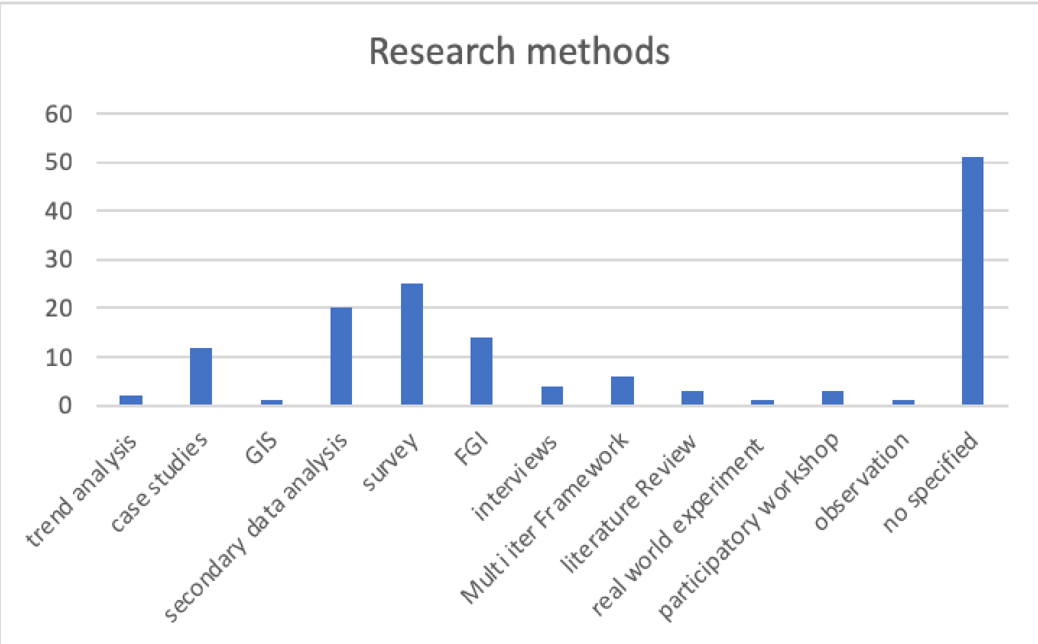
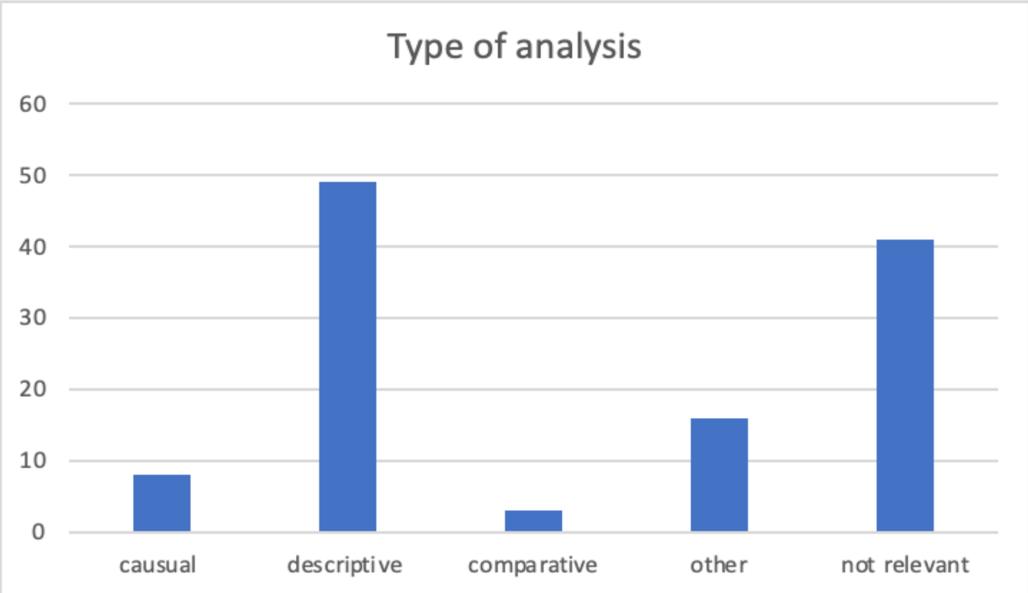


Figure 13. Number of publications by research method



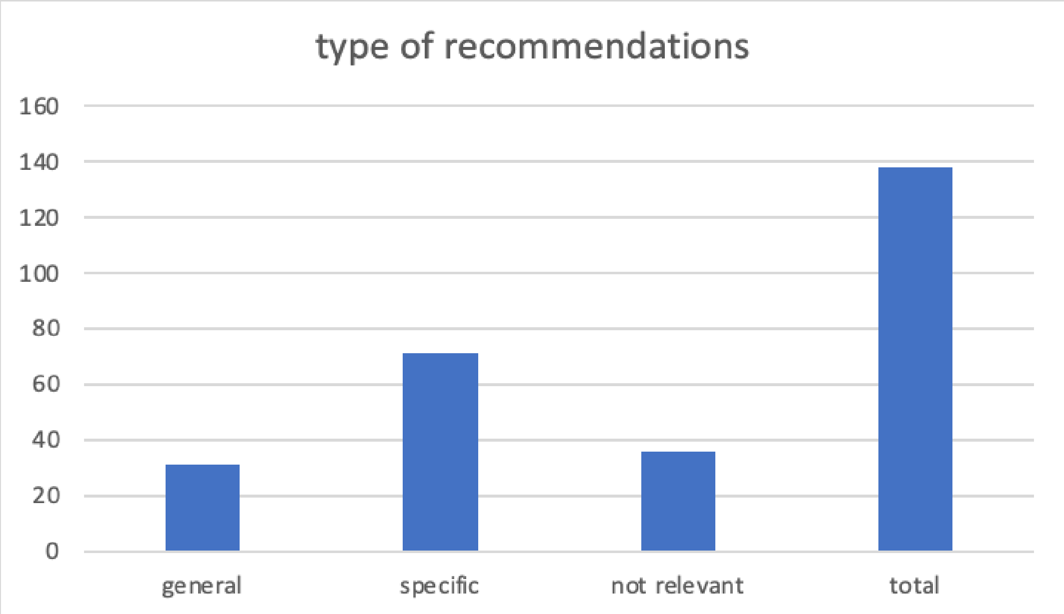
Looking at the type of analysis, we coded the data as those that focused on providing a description of the current situation in the chosen area, causal analysis - considering the relationships between the data provided and proposing an in-depth explanation in terms of causality, and those that proposed a comparative lens. It should be noted, however, that many of the documents do not contain an analytical part, but rather focus on making recommendations or discussing the problem or solution in rather general terms and normative way.

Figure 14. Number of publications by the type of analysis



Most of the documents analysed make policy recommendations, although they vary in scope and type. We have recorded the data to mark those that do not refer to specific gender issues, but refer more generally to energy transition, climate change mitigation or adaptation. This group includes some general recommendations that do refer to gender issues, but are formulated in a general way and express a more normative position, such as 'gender equality should be taken into account' or 'energy transition needs better consideration of gender issues'. The second group are specific recommendations related to gender policy - they are addressed to different types of policy makers (governmental and non-governmental bodies, local authorities, international organisations) or to industry, often discussing specific solutions and policy instruments.

Figure 15: Number of publications by the type of policy recommendations



4.3 The Qualitative Analysis – Gender dimension in the energy transition

In this part of the report, we answer the research questions on the basis of the qualitative analysis of documents that had been selected in the review. Firstly, we look into how gender-energy nexus appears in the reports and how it is discussed in relation to different technologies. Then, we investigated how the gender-energy nexus is discussed according to the level of analysis. Last, we reconstruct the main areas of intervention at the gender-energy nexus according to policy recommendations.

4.3.1 Gender-energy nexus and different technologies

The technological subsystem is defined by the focus on technological innovation. It is concerned with materiality, which defines what can be achieved now or in the near future, and by what means. Technological thinking usually narrows the perspective to the most likely or desired scenario (Luhmann, 1976) and is often linked to conditions of economic viability and political regulation. In the analysed data, the relevance of technology is twofold: it can refer to energy sources or to the technology of energy production or distribution. Thus, the documents consider old systems as those based on fossil fuels (coal, oil, gas) or new systems as those based on renewable energy sources (water, wind, solar, geothermal).

In the other dimension, we categorise the technologies of extraction and production mentioned by the documents like mining, coal-fired power stations, gas-fired power stations, oil refineries, coal-fired power stations, etc.; but also the technologies of distribution, such as networks, pipelines, or even those related to a particular way of using energy, such as cooking or heating technologies. Nuclear energy or hydrogen - perceived as technologically advanced ways to achieve carbon neutrality - do not fall into the above categories: they are based on limited resources (uranium, platinum), require advanced technologies and are perceived as socially controversial due to the high risks involved (Hienuki et al., 2020). Nevertheless, like all other technologies, they are not gender neutral (Bowen et al., 2023). Looking at the initial data through the lens of the technology under consideration leads to the first observation that many energy reports are gender blind or use gender categories only as descriptive socio-demographic variables without any deeper consideration.

In those documents that have provided insight into gender issues, the energy technology gender nexus is defined in different ways. The first observation relates to the use of gender as a sensitising category when analysing access to different types of energy services, such as clean cooking technologies (SE4All, 2018; AFDB, 2020), cooling services or transport (EEB, 2021). Traditional gender roles made women more vulnerable to the harmful pollution associated with old-fashioned cooking technology. Lack of access to electricity made daily work much more difficult and time consuming (World Bank, 2021; Dubey et al., 2020; Brutinel et al., 2020). In the energy production system based on fossil fuels, women occupy lower paid positions and are more exposed to the different types of inequalities (IEA, 2022; SE4 ALL, 2019). It should be noted that reports on the extraction of rare minerals and metals (necessary for the development of renewable and digitalised energy systems) reproduce old problems and social inequalities in developing countries (RAID, 2021).

Gender is proposed also as a lens to analyse the gender impact of energy solutions like energy efficiency in buildings. Observed differences between female and male workers related to different metabolism, dress practices and, in consequences, different patterns of experiencing thermal comfort or discomfort shed new light on the energy consumption in winter-summer periods in the office (Canpolat & Casabonne, 2021). Generally, the impact on gender is observable on the patterns of energy consumption. Women are also generally more concerned about the environmental and climate issues and more eager to change their everyday practices.

Another key area of the gender-energy nexus is employment and the labour market. The grey literature review shows that the new energy system based on renewable resources is more gender sensitive than the old systems based on fossil fuels. Gender equality is more often monitored and reported. The policy recommendations related to the RES technologies more often propose the gender equity defined in terms of equal access to managerial and engineering positions in the employment structures (World Bank, 2020; SE4 All, 2018). This issue remains insufficiently addressed in reports related to nuclear energy or the European Technology or Innovation Platform.

In summary, gender is discussed in relation to energy technologies and resources as 1) a factor influencing energy consumption patterns in households, workplaces and public spaces, 2) as a dimension of injustice in terms of unequal access to energy services, exposure to harmful effects of pollution and risks related to old fuels, 3) injustice conceptualised as a systemic feature of unequal access to STEM education, pay gap, unprivileged position of women's work in the labour market 4) in the context of talent gap and untapped potential of marginalised groups in the energy sectors. The few reports however, elaborate this kind of gender- energy analysis as leading to conceptualise the pathway for carbon neutral societies including gender equal social order (AFDB, UNWomen, 2021). Gender impacts on energy transitions, however recognised, remain under-theorised. They are rarely incorporated into technological development nor translated into specific policy tools.

4.3.2 Gender-energy nexus and levels of analysis

The understanding of gender-energy nexus requires applying on a context-sensitive lens, as it is proven in the existing grey literature. While all analysed reports refer to gender as an important axis of analysis, there are some differences in how gender is included and utilized. One of the aspects highlighted in these studies is that gender can be integrated at various level: either at the individual or household level, illustrating the relation of gender and energy at microlevel (e.g. UNWomen, 2021; WHO Housing and health guidelines, 2018), or at structural level (e.g. World Bank, 2022; IRENA, 2020), showing how broader cultural, political or economic - just to name few – factors impact this relation. The analysed reports proved that at the individual level gender is often included as a variable and rarely as the main topic (Just transition, 2022). It is used to provide sex-disaggregated data, to examine the progress towards achieving SDGs or indicate potential gaps and inequality issues pertaining to energy. While they provide an important basis for better understanding of the gender-energy nexus, it seems that they rather use the category “sex” than “gender”, pointing out the differences between men and women in relation to various aspects of energy system. While moving to the more complex level of analysis, the reports articulate more gender perspective, focusing on gender either as both main and subtopic (at country or regional level) or only main topic (at global level).

The change of perspective is further related in discussed issues and how they are addressed as the reports clearly recognized the cultural and structural barriers leading to gender inequalities in energy system. The reports focusing on the individual level examine the gender-energy nexus in relation to work, emphasising problems such as developing female business/entrepreneurship (ECREEE, 2021) or process of strengthening skills and abilities (capacity building) (Just Transition in a Renewable Energy Rich Environment, 2022). They apply individual perspective, perceiving the analysed situation though individual, specific experiences. While work is still an important field of analysis at other levels, other topics also occur. For example, many reports analysing the gender aspect of energy at the household level also refer to health (e.g. COP24 Special Report, 2018), while at the country and regional level power (e.g. Clancy et al., 2022), education (e.g. Tracking SDG7, 2021) as well as access and control of energy (e.g. Report on energy transition in Asia and the Pacific, 2018) are pinpointed. The reports focusing on these levels shows how fluid and context-dependant the concept of gender is and how diverse impact it can have on energy system.

Although there is a consensus on cultural and social barriers of gender roles on energy system, its impact is varied in terms of education opportunities, labour market practices, power relations or mobility. Not surprisingly, the global perspective introduces an overall view, with a more general discussion focusing mostly on work-related problems such as access to labour market in energy system, career development and supportive measures/mechanisms or pay gap (e.g., IRENA, 2019; IRENA, 2020; Beck & Panczel, 2018). Therefore, economic subsystem clearly prevails in the reports discussing the global perspective, followed by political subsystems and rarely socio-ecological and technological ones. What is interesting in these reports is that they tend to focus only on one of the subsystems and the intersection of few of them is rather rare. The opposite situation is presented in the reports focusing on a regional and country level as most of them discuss at least two dimensions, and in case of country level very often all four dimensions are mentioned.

The number of subsystems mentioned in the reports also matters. At the region level, if only one subsystem is mentioned, it is in most cases the socio-ecological one, whereas in case of discussing several subsystems, economic and technological areas are more often discussed. At the country level, only the reports from ENTRANCES projects (Malafaia, 2022; Singh, 2022) focus on one subsystem (socio-ecological) while other reports look at least 2 subsystems, with political system being the most often examined. Therefore, we can observe that the more general is the level discussed, the more the analysis is focused on one subsystems while at the micro (individual) and meso (household / country / region) level the intersection of several subsystems is provided. Importantly, regardless of the level of analysis, if gender is discussed, it is directly related to energy transitions. Such tendency occurs at the micro-, meso- and macrolevel (except for household level). However, while at the global level social justice is linked with a general problem of male and female access to energy and gender gap in energy system, at regional / country and individual level refers to areas such as education, employment or health. For example, some reports indicate how lack of access to energy increases the mortality of pregnant women or how the involvement of girls and women prevents them from schooling, employment and pose danger to their health.

Importantly, the reports discuss gender justice in the energy sector as being hindered by the cultural gender roles (e.g., United Nations Environment Programme, 2020; regional Initiative, IRENA Coalition for Action, 2021). Due to gender stereotypes and norms, women are trapped in vicious circle: due to cultural expectation women and girls spend more time on cooking and household duties and therefore not only put in a greater risk of health problems but also kept away from education. Moreover, discriminatory practices in secondary and tertiary science, technology, engineering, and mathematics education prevent women away from attaining high-quality jobs in energy system and pushes them to unpaid care and domestic work. Therefore, the analysed reports show how gender justice in energy system is intertwined with gender cultural norms and roles.

4.3.3 Main areas of intervention according to policy recommendations

A preliminary analysis has shown that not all grey publications that have been included into this review contain policy recommendations referring to the gender-energy nexus (see Fig. 15). Among the publications that have them, general recommendations – often formulated in a normative way – are interspersed with practical instructions addressed to specific stakeholders. The reports generally emphasize the urgent need for redefining the energy transition in such a way that it includes not only technical applications and economic profit but also includes social aspects, needs and practices of all citizens (EEB, WECF, 2021), including women. The need for accelerating the integration of gender equity into energy transition pathways is highlighted (UN, 2021). It is more specifically recommended to include fully both women and men in shaping the territorial transitional trajectories in coal and carbon intensive regions to enable pursuing an effective energy transition (ENTRANCES, 2022) and to ensure that their needs and contributions are addressed in the expansion of energy access (Pearl-Martinez, 2018). General recommendations further suggest that to advance gender equity it is necessary to work towards increasing the number of women in the talent pool, to advance opportunities for them in the renewable energy workforce and to increasing the participation of women-owned and women-led companies (AFDB, UNWomen, 2021; World Bank, 2022a; EA, IRENA, UNSD, World Bank, WHO, 2023).

The analysis of the more practical, specific recommendations helps identify the gender gaps in the energy sector and energy transition that need intervention from policy makers and other stakeholders. These include employment, energy access, knowledge, social norms & gender stereotypes.

As many of the analysed publications concentrate on the issue of **work** (see Fig. 7), they also accordingly formulate recommendations referring to the aim of increasing women's employment in the energy sector as such (Orlando et al., 2018; World Bank, 2022a), and specifically in the area of renewable energy (Angelou & Roy, 2019; Clancy & Feenstra, 2019). The proposed policy implications that contribute to gender equality in non-traditional occupations in energy infrastructure include setting quotas for women in construction and maintenance jobs, encouraging the establishment of women's recruitment bureaus, ensuring separate washroom and toilet facilities for women and men at work sites, and enhancing women's safety as well as design and provision of vocational training in the communities affected by the energy infrastructure projects (Orlando et al., 2018). It is noticed that the perceptions of the energy sector as male-dominated needs to be changed through targeted communications that promote women's roles and that showcase female role models and success stories as well as through enhancing working conditions with introducing various measures for work-life balance (Ahmad et al., 2019).

Much attention is paid as well to the problem of **access to safe energy**, which is seen as strongly associated with women's economic empowerment (EA, IRENA, UNSD, World Bank, WHO, 2023; Orlando et al., 2018). In the context of African countries some specific financial mechanisms to enhance access to energy – including renewable energy such as off-grid solar systems – are being recommended. They include pro-poor targeting actions, whereby female-headed households (that often have lower ability to pay) may be automatically eligible, credit schemes allowing payment of connection fees in affordable instalments, combination of a reduced connection fee and longer repayment time, subsidized connection costs, and lifeline tariffs (Luzi et al., 2019; Dubey et al., 2020; Brutinel et al., 2020; Koo et al., 2018). Similarly, integrating gender dimensions into energy interventions in such countries as Afghanistan and Uzbekistan is argued to require establishing female-friendly microfinance facilities for low-income households and providing grants, subsidies, revolving funds or interest-free credit, loans or staggered payment structures to women and other vulnerable populations to cover the upfront costs (Angelou & Roy, 2019; World Bank, 2019). In the European context the projects addressing gender poverty are additionally advised to emphasize women's role as active agents of change, who purchase and operate energy-saving technologies and may be innovators of energy efficient solutions, through actively recruiting women-led households (Habersbrunner & Martschew, 2020). Additionally, to enhance participation in the clean energy transformation one stop-shops are suggested to be established, providing technical assistance on renewable energy installations. Similarly (Gender) Energy Ambassadors could function in local communities and visit low-income households, inform about Do-It-Yourself measures or inform about and install smart meters in the households (Clancy, & Mohlakoana, 2020; Groneweg et al., 2023).

Another identified area of intervention is **knowledge** seen as a prerequisite for both equitable workforce participation and access to clean renewable energy. Therefore, much attention is paid to enhancing female access to education and training programs, as well as targeted scholarships (World Bank, 2022a). Interventions are advised to be implemented at the pre-tertiary education level including the integration of counselling programs targeting female students in secondary schools to expose them to options of STEM programs during their study at university (Brutinel et al., 2019; Brutinel et al., 2020; UN, 2020a). In the African context it is also recommended to carry out campaigns to raise awareness among both women and men on the benefits of clean and efficient cooking solutions (Brutinel et al., 2019; Brutinel et al., 2020), incentivize them to switch to stoves with lower emissions and to change their everyday practices, e.g. separate cooking areas from sleeping areas, minimizing time in the cooking area and improve ventilation to limit household members' exposure to harmful pollutants (Padam et al., 2018).

In the context of exposure to pollutants the need to pay special attention to the differential **health impacts** at the gender-energy poverty nexus has been emphasised in a few reports (Dubey et al., 2020; Orlando et al., 2018).

Addressing **cultural norms** and **gender bias** is less frequent and often comes to general recommendation that the national governments should address underlying social norms that create additional barriers for women and disadvantaged group (Federal Ministry for Economic Affairs and Climate Action, 2022; World Bank, 2022a). Providing gender and inclusiveness trainings for men to explain how a more inclusive approach will also benefit them and therefore to reduce their resistance to gender transformative interventions has been suggested to renewable energy communities operating in Europe (Clancy et al., 2020).

Irrespective of the area of intervention many publications conclude that the implementation of gender-responsive policies and approaches and tracking their progress are hindered by the lack of data. Therefore, the need for further research and collecting **sex-disaggregated and gender relevant data** – both quantitative and qualitative – are repeatedly recommended. The data is necessary to be able to visualize gaps and benchmark future progress in skill and workforce equality (World Bank, 2022a), to identify women's needs and possible ways to overcome barriers to energy access (Brutinel et al., 2019), to assess the gendered impact of the energy infrastructure projects in the affected communities (Orlando et al., 2018; UN, 2020b), and to measure gender inequalities and energy poverty (Habersbrunner & Martschew, 2020; Clancy, & Mohlakoana, 2020; Groneweg et al., 2023). Data is almost unanimously seen as "a driver to unlock policymaking" (GWEC, 2021) Therefore, gender-disaggregated data and indicators should be subject to continuous monitoring and periodic publishing, including in the annual national gender reports (UN, 2020b).

The analysed recommendations are directed to different types of stakeholders. The reports on the gender-energy nexus in Europe emphasize the prominent role of the **EU institutions** in giving guidance to member states and national governments on how to implement gender dimension (Habersbrunner & Martschew, 2020). For example, it is advised that the European Commission's Directorate-General (DG) Energy should develop a gender action plan for addressing energy poverty that would set a benchmark for Member States and other energy sector organisations to follow. Similarly, the European Statistical Office (Eurostat) should start collecting sex-disaggregated data from member states to better address climate crisis and introduce new policy measures to help bring about the transformative change (Clancy et al., 2022). Likewise, it is argued that establishing an advisory board on gender inclusivity and energy transition by the European Commission would foster a gender approach in all policies (Groneweg et al., 2023). In the European context the critical role of **renewable energy communities** in addressing energy poverty is also emphasised (Groneweg et al., 2023). It is also advised that they transform themselves to become inclusive, through setting up gender targets in their statutes, creating an inclusive working environment, and making a gender, intersectional analysis of the communities they operate in (Clancy et al., 2020).

The reports on energy transition in global perspective or focussing on regions other than Europe indicate the role of **financial institutions**, e.g., to provide microfinance (UN, 2020b) and to simplify procedures and provide trainings on financial literacy (United Nations Environment Programme, 2020) as well as **energy utility companies** and their teams implementing energy infrastructure projects (Orlando et al. 2018) and **women's business associations** (World Bank, 2022a). Additionally, irrespective of the regional focus **national governments** (United Nations Environment Programme, 2020; World Bank, 2022a; Habersbrunner & Martschew, 2020; Clancy, & Mohlakoana, 2020; ESMAP, 2020) and **civil society** (Kuschan et al., 2022; UN, 2020b; Clancy et al., 2022) become an important addressee of recommendations. It is also underlined that effective policy planning and implementation requires cooperation between a range of actors dealing with policy making (including public authorities and local governments), urban planning, housing and energy companies (Clancy & Feenstra, 2019; Clancy et al., 2020).

Among the specific solutions **targets and gender quotas** are widely recommended to be introduced, both to enhance the participation of women in the energy workforce and to achieve equality in the organisational boardrooms (EEB, WECF, 2021; Federal Ministry for Economic Affairs and Climate Action, 2022; IRENA, 2019; IRENA, ILO, 2021; Orlando et al., 2018; World Bank, 2022a). Similarly, **engaging men** in designed interventions is seen as an important factor enhancing their effectiveness, since they are often the key decision-makers in their households and communities (Brutinel et al., 2019; Brutinel et al., 2020; Dubey et al., 2020; World Bank, 2022b). The need for incorporating an **intersectional perspective** is present only in a few publications. It is generally advised that the governments should include an intersectional perspective in their energy policies (Kuschan et al., 2022), similarly as teams implementing energy projects should consider from an intersectional perspective across all activities in order to understand in its full complexity when designing and implementing activities and interventions (Clancy & Feenstra, 2019; Habersbrunner & Martschew, 2020). More specifically, the recommendations focus on collecting data disaggregated not only by gender, but also by ethnicity, age, gender identity, sexual orientation, ability, class, and geographic location (World Bank, 2022a; see also: EEB, WECF, 2021) and to present them in an intersectional way e.g., to present a typology of energy users at the household level (Clancy & Feenstra, 2019).

4.4. Conclusions

Most of the analysed publications are in the form of reports issued by international organisations with a general focus and global perspective, such as World Bank and the United Nations. The vast majority of selected documents have gender either as the main topic of consideration or as one of few subtopics.

In recent years, there has been an increase in the number of publications addressing the energy-gender nexus. The visibility of the gender gap is also increasing. The gender-energy nexus is a multifaceted and complex issue that intersects with various aspects of energy systems.

Looking at the energy-gender relations through technology lens reveals several significant observations and implications. The focus on technology in the energy sector plays a pivotal role in shaping the present and future possibilities of energy production and distribution. This focus is deeply intertwined with economic viability and political regulation. It categorizes energy systems into old fossil fuel-based and new renewable energy-based systems, with emerging technologies like nuclear and hydrogen standing apart due to their resource limitations and social controversies.

First, traditional gender roles have had a significant impact on access to different energy services, particularly affecting women who were more vulnerable to pollution from outdated cooking technologies and the lack of access to electricity.

Second, gender becomes a lens through which to analyse the gender impact of energy solutions, such as energy efficiency in buildings. Differences in metabolism, dress practices, and thermal comfort preferences between genders influence energy consumption patterns in workplaces.

Third, employment and the labour market within the energy sector show distinctions between old fossil fuel-based systems and new renewable energy-based systems. Renewable energy systems tend to be more gender-sensitive, with greater emphasis on monitoring and promoting gender equality, including equal access to managerial and engineering positions.

Fourth, gender-related issues extend beyond immediate energy consumption to encompass systemic gender inequalities, including unequal access to STEM education, pay gaps, and the underprivileged position of women's work in the labour market. The reports also highlight the untapped potential of marginalized groups in the energy sector.

The grey literature examines gender-energy nexus at all levels: from individual and household level, through country and regional level to global level. In most of the reports, gender is considered as either a main topic or a subtopic of the study. This literature shows the importance of applying gender-analytical approaches. The gender-energy system is often described as complex, broad and varied, which is reflected in the scope of the analysis provided in the grey literature. As a result, gender is examined in a variety of contexts, with economic and socio-ecological dimensions prevailing in the analysed reports. Yet, regardless of the subdomains in which gender is examined, it is often defined through the lens of gender justice, revealing gender inequalities in the energy system.

While almost all publications present recommendations for policy and practical interventions in the energy sector and processes, in almost one third of documents those recommendations do not refer to gender gaps. While some of the gender-relevant recommendations are of a general nature and are formulated in a normative way, there is a lot of practical instructions targeted at specific stakeholders and domains. Most of the proposed measures and activities are directed at occupational gender equality, resulting in gender balanced workforce and leadership in the energy sector, both traditional and renewable. Only a few recommendations address the cultural norms and roles, which is surprising taking into account that the latter are presented in the reports as one of the main barriers preventing women and girls from being recognised as equally important actors in energy systems.

Another important area is energy access seen as strongly associated with women's economic empowerment and gender equality and most often discussed as gender unjust and needing intervention, especially in the African context. A further sphere of intervention that is widely discussed and provided with specific solutions include energy knowledge as a prerequisite for both equitable workforce participation and access to clean renewable energy. However, irrespective of the addressed area, producing evidence and collecting sex-disaggregated data are seen as an urgent need and as a necessary condition for any intervention.

The recommendations are directed at a variety of stakeholders, including national governments, civil society including women's groupings and renewable energy communities, financial institutions, and – in the European context – EU institutions. As the specific solutions are concerned, introducing targets and gender quotas as well as involvement of men in policy interventions are underlined. The need for implementing intersectional perspective is highlighted in only in few reports.

Many of the reports analysed lack a clear methodological section, and there are very few evaluations of interventions. The Grey Literature Reviews conclude that the practical and organisational knowledge, while relevant, is fragmented and difficult to compare with other data. There are some regions in Europe or Africa that are more frequently analysed and monitored than others, such as Australia, Asian or Arctic countries being beyond the scope of analysis. The gap in gender - energy reflection is in Arab countries, which are strongly associated with the oil industry.

The global gendered impacts of war and military crisis, noticed by the worldwide organization (UN women, 2022) in Ukrainian context, needs further analysis and continuous attention.

The overall conclusion of the Grey Literature review confirms recognising that addressing gender inequalities and integrating gender perspectives into energy-related policies and technological development is essential for creating sustainable and equitable energy systems for the future. However, the technology reports related to energy issues, in majority remains gender blind. Gender perspective is rarely integrated into technological development. The potential for gender to play a crucial role in shaping a path towards carbon-neutral societies with gender-equal social orders is recognized but remains largely unrealized.

5. GENERAL CONCLUSIONS

The length and complexity of the analyses described in each section makes it visible the multifaced nature of the gender-energy transition nexus. This should not come as a surprise given that two constructs in this nexus are inherently multi-dimensional and require a network-based approach to be analysed. This complexity is not always reflected in research outputs. For example, the Energy system ontology (ESO) described in this deliverable is one of the firsts to incorporate a multi-disciplinary prospective and to graphically display the multiple interconnections among the sub-systems of the energy transition.

Against this background, the scientific research and the grey literature looking at the interplay between energy transition and gender is on the rise. However, precisely due to the complexity of the phenomenon at stake, it remains very heterogenous and rarely provides clearly-cut responses. Gender and energy transition intersect with other variables that, in turn, influence the way in which the nexus between the two plays out.

To begin with, the lack of gender-disaggregated data in the energy sector hamper a full comprehension of the phenomenon. When this type of data is collected, they evidence that gender inequalities are pervasive and span from access to energy sources to participation in the processes of production of knowledge and technology for the energy transition as well as in many other dimensions such as decision and policy making. Thus, there is the need for breakthrough and systemic solutions that disrupt the status quo. In order to do so, as highlighted in the grey literature's conclusions, gender has to become a lens of analysis for all the processes involved in the energy transition. With this intent, Task 5.2 of the gEneSys project (*Integrating gender perspectives into Energy SHIFTS*) will aim at systematically incorporate a gender lens into the 400 SSH questions of the SHIFT project by the application of the gender innovation approach. The lack of disaggregated data is due to the gender blindness of the energy sector that prevailed until a few years ago. The current push towards sustainability in the energy sector has also brought along the emergence of the issue of social justice and gender equality inherent in the notion of sustainability, but the path ahead is still long and uncertain.

Among the several issues affecting the nexus between gender and energy transition, cultural roles and gender norms are particularly difficult to tackle as they are entrenched into the mechanisms that regulate the functioning of a society and refer to how the individual perceive itself within its community and the world in general. This reinforces the idea that gender is a socially and culturally constructed characteristic. Although repetitively highlighted, the research collected in this deliverable does not provide specific directions about how to modify these patterns.

It is worth mentioning a possible bias of this work which in turn opens the way for future, more comprehensive efforts. For both the literature review and the creation of the ESO, only literature published in English was taken into account, excluding the valuable corpus of publications in other languages. These analyses reflect other spatial locations of research and case studies, but also epistemological positions in the Global South, where the connection between different elements of socio-ecological systems is currently being analysed in depth, including the gender-energy transition nexus.

The way forward for the energy transition to incorporate a gender and intersectional perspective can be identified through an inclusive integration of different type of knowledge (scientific and grey literature), disciplines (interdisciplinary), but also giving greater resonance to the insights and innovations coming from the Global South.

Finally, the research evidence emerging from this deliverable certainly points at the paramount role of policy interventions. Appropriate policies can target multiple dimensions of a phenomenon and undermine existing mechanisms underpinning the perpetuation of gender inequalities. However, these policies need to be data-driven and backed by ex-ante and ex-post evaluations to define pre-intervention assumptions and goals and gauge the effectiveness of post-intervention outcomes. Without this, policies' effects risk to be short-lived.

In the near future, knowledge products such as the ESO could be used for the assessment of the sustainability and social impact of new policies. This can be enabled by establishing connections with pertinent data sources, including information related to local energy infrastructures and societal data. However, if we are to realise pathways toward just energy transition, gender equity concerns will need to be tacked at each node.

In the meantime, however, the results of the analyses produced in this deliverable will be used as a basis for future project's activities. In particular, the ESO and the related definitions will be used in WP1 for mapping out the energy knowledge communities (T1.3) and in WP5 to support the identification of the criteria for sustainable pathways (T 5.1). The results of the SLR and the grey literature review will offer a solid basis for the development of the cross-country survey in WP2, but also for the gender-based energy policy analysis and survey to R&I workforce in the energy sector envisaged in WP1 (task 1.4 and 1.5).

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