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An Open Digital Platform to Support Interdisciplinary Energy Research and Practice—Conceptualization

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Abstract: Energy research itself is changing due to digitalization and the trend to open science. While this change enables new research, it also increases the amount of, and need for, available data and models. Therefore, a platform for open digital energy research and development is required to support researchers and practitioners with their new needs and to enable FAIR (findable, accessible, interoperable and reusable) research data management in energy research. We present a functional and technological concept for such a platform based on six elements: *Competence* to enable researchers and practitioners to find suitable partners for their projects, *Methods* to give an overview on the diverse possible research methods within energy research, *Repository* to support finding data and models for simulation of energy systems, *Simulation* to couple these models and data to create user-defined simulation scenarios, *Transparency* to publish results and other content relevant for the different stakeholder in energy research, and *Core* to interconnect all elements and to offer a unified entry point. We discuss the envisioned use of the outlined platform with use cases addressing three relevant stakeholder groups.

Keywords: energy research; digital platform; research data management

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1. Introduction

Energy research is facing multiple challenges for practitioners and researchers. The energy systems' transition requires the integration of more decentralized renewable energy, increasing the complexity of energy systems [1]. The digitalization toward cyber–physical energy systems (CPES) addresses this issue by enabling a new level of automation. As a consequence, the complexity of simulations increases further, and their development requires additional technical skills and theoretical background [2]. Keeping results from simulations reproducible presents an additional challenge.

Due to the political, societal, and economic relevance of the energy systems' transition, energy research has received extensive funding from federal and state governments. These funds can be more efficiently used by opening models and data, as proposed by Open Science [3]. In this way, obstacles in interdisciplinary research can be overcome by providing a fundamental basis of freely accessible knowledge and tools. This change should be accompanied with making data more findable, accessible, interoperable, and reusable (FAIR) for humans and machines by applying the FAIR criteria [4]. This reduces barriers for participation in energy research and helps to produce new results and data more quickly.

Werth et al. introduced an open digital energy research and development (R&D) platform to enable FAIR energy research. The platform should help to improve energy research based on open science and the FAIR criteria with five key services for researchers and practitioners. These key services are *Competence* to enable researchers and developers to find suitable partners for their research and practice projects, *Best Practices* to deliver ideas to structure cooperative open energy research, *Repository* to help in finding available data and frameworks for energy systems' simulation and optimizations, *Simulation* to couple frameworks and models, and *Transparency* to publish results and contents from the energy community to reach various interested stakeholders [5].

Werth et al. performed a requirements analysis for the introduced platform idea based on semi-structured interviews with different stakeholders, e.g., energy researcher, energy providers, and grid operators, in [5]. The results showed the need for a clear added value for the users of the platform. Relevant profiles can be useful to find partners as long as they can be easily maintained. Especially for beginners in academia, an overview of best methodological practices in open energy research can be helpful when its quality is ensured. Tailored data and model descriptions were evaluated as practical for the different stakeholders, of which some also favored a provision of data on request. In particular, users with a scientific background state that they would use a platform to configure simulations. A stakeholder-specific presentation of research results was desired by multiple stakeholders who also saw a need for an exchange platform. However, their examination lacks in an articulation of a detailed concept toward an implementation with regard to the technicality and functionality of the detailed platform [5].

Based on the requirements analysis and an additional extensive review of existing platforms, we developed a detailed concept for an open digital energy R&D platform which we present in this work. Hence, our contributions to theory and practice are as follows:

- First, we provide an overview about work on similar platforms in the energy and other domains in Section 2.
- Then, we present a detailed platform concept based on the detailed requirements and related work in Section 3.
- We discuss the usability of the proposed platform based on the use cases in Section 4.

Finally, we present conclusions in Section 5.

2. Materials and Methods

There are multiple platforms addressing some of the requirements identified by Werth et al. [5]. In contrast to the related work of Werth et al. [5], we also introduce existing platform outside the energy domain besides the ones focusing on the energy domain. To obtain insights into already existing functionalities, we reviewed these existing platforms, tools and frameworks by exploratory searches in various databases (e.g., Google Scholar (https://scholar.google.com/, accessed 23 August 2022), Scopus (https://www.scopus.com/home.uri, accessed 23 August 2022)) or by our own knowledge. We present an overview in Table 1. There are several reasons why the body of research on research platforms is surprisingly small in the scientific literature: First of all, the design of research platforms is an upcoming topic where we believe more scientific work will emerge due to the various activities (e.g., European open science cloud (EOSC)). Additionally, the design of research platform is often considered only a support for research, but not research in itself, thus the approaches are not automatically science based. While this review does not claim as to be complete, it gives a useful overview of existing approaches. All presented platforms only deliver parts of the required services, though they are still a valuable foundation to build an open energy R&D platform covering all relevant identified areas. First, we give an overview on platforms from non-energy domains in Section 2.1. Then, we outline some platforms from the energy context in Section 2.2. For both presentations, we follow the five services *competence*, *best practice*, *repository*, *simulation* and *transparency* as introduced by Werth et al. [5].

2.1. Non-Energy Domains

Edecy (https://edecy.de/, accessed on 11 January 2022) is a commercial tool offering an automated matching of research partners for research projects. The underlying overview of research institutes is not openly available.

Table 1. Overview of related platforms.

		Competence	*Best Practices*	*Repository*	*Simulation*	*Transparency*
Non-energy domains	edecy	✓				
	TIB VIVO	✓				
	Open Science Framework		✓			✓
	bio.tools			✓		
	Zenodo			✓		
	Bayern Innovativ					✓
Energy domain	Energy Research Center of Lower Saxony	✓				
	openmod		✓	✓		
	OEP			✓		
	OpenEI			✓		
	FfE Open Data Portal			✓		
	oemof				✓	
	Co-Simulation Model Catalog [6]			✓	✓	
	enArgus	✓				✓
	Energiesystemforschung					✓

The TIB (Leibniz Information Centre for Science and Technology) offers the TIB VIVO (https://vivo.tib.eu/fis/, accessed on 15 January 2022). This platform provides a search engine to discover research among scholars of all disciplines at the TIB (https://blogs.tib.eu/wp/tib/2013/07/15/tib-open-science-lab-vivo/, accessed on 29 March 2022). It includes people, departments, courses, grants, and publications at TIB. Moreover, key research areas are displayed on the landing page to directly attract new visitors. Unfortunately, the accessible information is limited to one institution. The TIB platform is based on the open-source framework VIVO (https://vivo.lyrasis.org/, accessed on 23 March 2022) currently used by 149 academic institutions (status as of 23 March 2022).

The Open Science Framework (https://osf.io/, accessed on 11 January 2022) tries to support the complete research process in a domain-independent way. They offer to privately store different files, such as research data and preprints, but also allow to share them publicly. They integrate different tools, such as GitHub, and identifiers, such as ORCID and digital object identifier (DOI).

Bio.tools (https://bio.tools/, accessed on 7 January 2022) provides an overview of software tools in the field of life science. All software artifacts are provided with extensive metadata, based on a common metadata schema called biotoolsXSD. A lot of metadata are ontology based for improved search functionalities. The information on the tools is presented in a comprehensive way. The tools themselves are not stored on the platform but instead link to common repositories, such as GitHub or GitLab [7].

Zenodo (https://zenodo.org, accessed on 11 January 2022) is a data repository created by CERN and OpenAIRE. It accepts any file format and assigns DOI to all content, which makes it easily citable. General metadata are collected for all content and are publicly available via an OAI-PMH interface. In 2017, Zenodo was mainly used to store figures, conference papers, journal articles, and software. Additionally, datasets can be found on Zotero [8].

Bayern Innovativ (https://www.bayern-innovativ.de, accessed on 11 January 2022) is a state-supported company that processes research results from Bavaria and presents them clearly on the site. The target group are interested citizens and companies.

Overall, there exist multiple relevant platform with overlapping features. Some of them are already well accepted in their domain and can act as a role model for our approach, e.g., bio.tools.

2.2. Energy Domain

On its website, the Energy Research Center of Lower Saxony (EFZN) (https://www.efzn.de/de/forschung/efzn-standorte, accessed on 7 January 2022) lists various professors in Lower Saxony clustered in broad subject areas. Unfortunately, the website misses further information on the chairs and their research focus. Furthermore, this page lacks a search and filter function.

The open energy modeling initiative (openmod) (https://openmod-initiative.org/, accessed on 7 January 2022) aims to promote open energy modeling in Europe. It includes a mailing list, a discussion forum, and a wiki. The wiki contains information on how research can be conducted more openly, e.g., information on different licenses [9]. In this way, openmod provides parts of the best methodological practices service without linking them to concrete projects or persons. The wiki lists different models with links to source code [10], while it only has a limited search functionality. The whole platform addresses researchers as the main user group.

Another platform is the Open Energy Platform (OEP) (https://openenergy-platform.org/, accessed on 7 January 2022). It aims to improve transparency, reproducibility, and quality in energy research. The platform includes a database on different frameworks (model factsheets), scenario descriptions (scenario factsheets), and data. All information is searchable and filters can be applied [11]. The OEP offers repository services, e.g., by using an application programming interface (API). An ontology is provided to better describe the energy data. However, the onology is yet not included in the metadata of data and frameworks [12]. A presentation of the results to recipients other than researchers is out of scope of the OEP [11].

OpenEI (https://openei.org/wiki/Main_Page, accessed on 11 January 2022) provides a lot of data and partly software in the field of energy. The site offers a search function which is not very detailed. The site is based on a semantic wiki and operated by the US Department of Energy [13].

The FfE (Forschungsstelle für Energiewirtschaft) data platform (http://opendata.ffe.de/, accessed on 11 January 2022) makes data from FfE research projects openly available. These data are searchable and filterable. There is metadata for all datasets, but the scope is limited.

Multiple frameworks exist to build large-scale energy simulations: The Open Energy Modeling Framework (oemof) (https://oemof.org/, accessed on 7 January 2022) [14] provides a toolbox that can be used to build comprehensive energy system models. The different parts of the framework can be combined in various ways to perform offline simulation.

Co-simulation tools, such as mosaik (https://mosaik.offis.de/, accessed on 7 January 2022) [15] can also be used as modeling frameworks [16]. Multiple open-source models are already offered for mosaik. A semi-automated tool for scenario configuration for mosaik is available in the midas project (https://gitlab.com/midas-mosaik/midas, accessed on 22 March 2022) also providing a collection of mosaik simulators for smart grid co-simulation. Schwarz et al. [6] present a framework to assist in the planning of co-simulation based on semantic knowledge representation. These tools and frameworks address the simulation service idea but only link a few projects using them without referring to their results.

enArgus (https://www.enargus.de/, accessed on 7 January 2022) is the central information system for energy research in Germany. It presents an overview of all recent and ongoing energy research projects in Germany. The website provides a search functionality based on a light ontology [17]. While the website gives basic information on research projects, it misses information on the outcomes of the projects, such as projects reports, publications, or information on the used software and scenarios.

Energiesystemforschung (https://www.energiesystem-forschung.de/, accessed on 7 January 2022), presents research results in an understandable way for multiple stakeholders and, therefore, provides a transparency service. For further details, the website references to enArgus, which only contains management information and misses technical details.

Overall, it can be seen that there exist different platforms in the energy domain with different scopes. While none of them cover all requirements, some already present a well-developed solution to certain issues, e.g., the OEP for research data in the energy domain.

3. Results

We developed a concept for an open digital energy R&D platform based on the requirements analysis [5] and the related work presented in Section 2. Besides the five different key services introduced by Werth et al. [5], we added a sixth central key service containing functionalities required by all other key services: *Core*. Since the naming of the key service *Best Practices* led to several misunderstanding during the requirements analysis [5], we renamed the key service to *Methods*. Figure 1 gives an overview on these six key services. This section describes all key services, their goals, and functionalities.

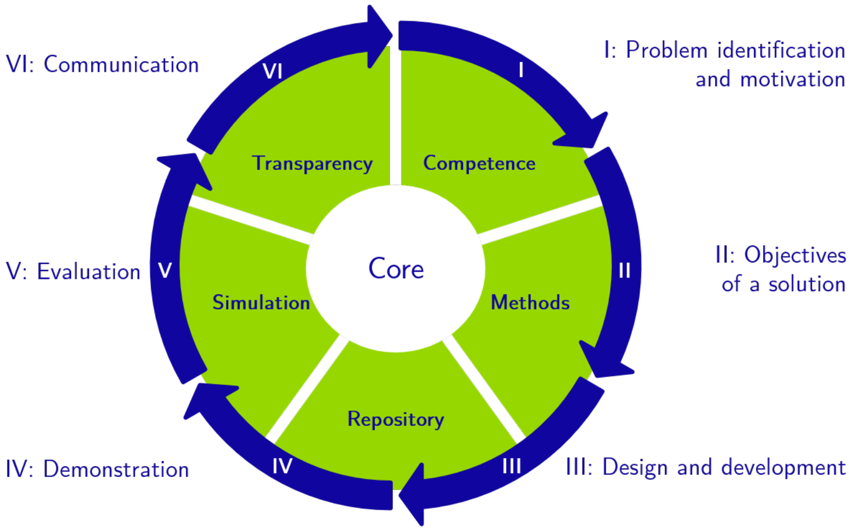

Figure 1. New key services of the open energy R&D platform extending the work of [5].

3.1. Core

The goal of *Core* is to support the other key services with basic functionalities not specific for the energy domain.

Work flows for the continuing development of the platform are defined based on a *Technical Infrastructure* and are usable for all key services. *General Pages*, including *"About us"* and *"Privacy policy"*, give an overview about the history, last developments, the involved institutions of the platform, and the privacy policy of the platform.

User Management provides central authentication, login, and registration for user accounts for all key services as well as linking to user accounts on other platforms, e.g., to ORCID (https://orcid.org/, accessed on 7 January 2022) or Gitlab (https://about.gitlab.com/, accessed on 7 January 2022).

Federated Search enables searching over the whole R&D platform. A search API is defined such that all key services can be accessed the same way and filters from the different key service can be used.

PID Service allows to create PIDs via an API for different entities on the platform, such as data description in *Repository*, institution profiles in *Competence*, or project descriptions in *Transparency*. These PIDs will not change over time and, therefore, allow persistent linking between the key services so that an institution in *Competence* can be used as responsible institution in the data description in *Repository*.

Ontology Service provides an access point to ontologies in the energy domain for all services, such as the Open Energy Ontology [12], the common information model [18], and others. By using common ontologies for the description of artifacts, such as data, software, or for the information stored in *Transparency* or *Competence*, the same words are used for the same things, improving the interoperability and search functionality of the platform.

3.2. Competence

The goal of *Competence* is to demonstrate multi-layered competences on the presented open digital energy R&D Platform. It also includes a presentation of its underlying research network considering subject-specific and user-oriented presentation, as well as easy and multi-sided access to competences. *Competence* enables information transfer via an API.

Competence consists of multiple functions to adequately present the competences and proficiencies of registered users and entities on the open digital energy R&D platform. Figure 2 shows an overview of the different functionalities of *Competence*.

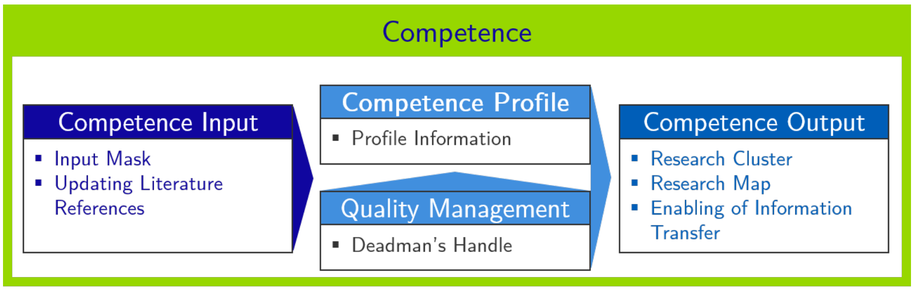

Figure 2. Overview of the grouped functionalities of *Competence*.

The central function of *Competence* is the *competence profile*, allowing a proper presentation of the registered entities' proficiencies. A clear representation of competences and research interests are requirements for this element identified by Werth et al. [5]. Figure 3 shows a mockup of the *Competence Profile*. The level of detail respectively identification for each profile will be the workgroup-level (e.g., workgroup "Energy Systems" at elenia Institute for High Voltage Technologies and Power Systems (https://tu-braunschweig.de/elenia/team/wimi, accessed on 16 March 2022)). Higher level of detail or person-specific profiles are not intended, as they will drastically increase the amount of needed profiles and therefore. maintenance effort. *Competence* uses *Core*'s *PID Service* and *Federated Search* to enable a persistent linking and finding of competences over all platform key services.

Profile Information includes all necessary content to describe a *Competence Profile*. It consists of basic information about the stakeholder, a representative, and a contact person (see Figure 3). The contact person should also be in charge of maintaining the profile. Moreover, the research focus, research projects, and current publications (including papers, data, and simulation models) but also open matching processes (see *Competence Matching*) are listed together with memberships in other research networks. The implementation of *Profile Information* may be following TIB VIVO but reducing the personal dissolution to the described workgroup level. Potential user-created and/or used *Methods*, data or models (both from *Repository*) are linked and listed in the *Profile Information* (see Figure 3). Generated or used scenarios from *Simulation* are included in the *Profile Information*. Activities in the *Public Forum* of *Transparency* and other shared information from *Transparency* are also directly displayed in the *Profile Information*. In this way, *Transparency* works as a communication channel for the provision and spread of information. All of the *Profile Information* is accessible by *Core*'s *Federated Search*.

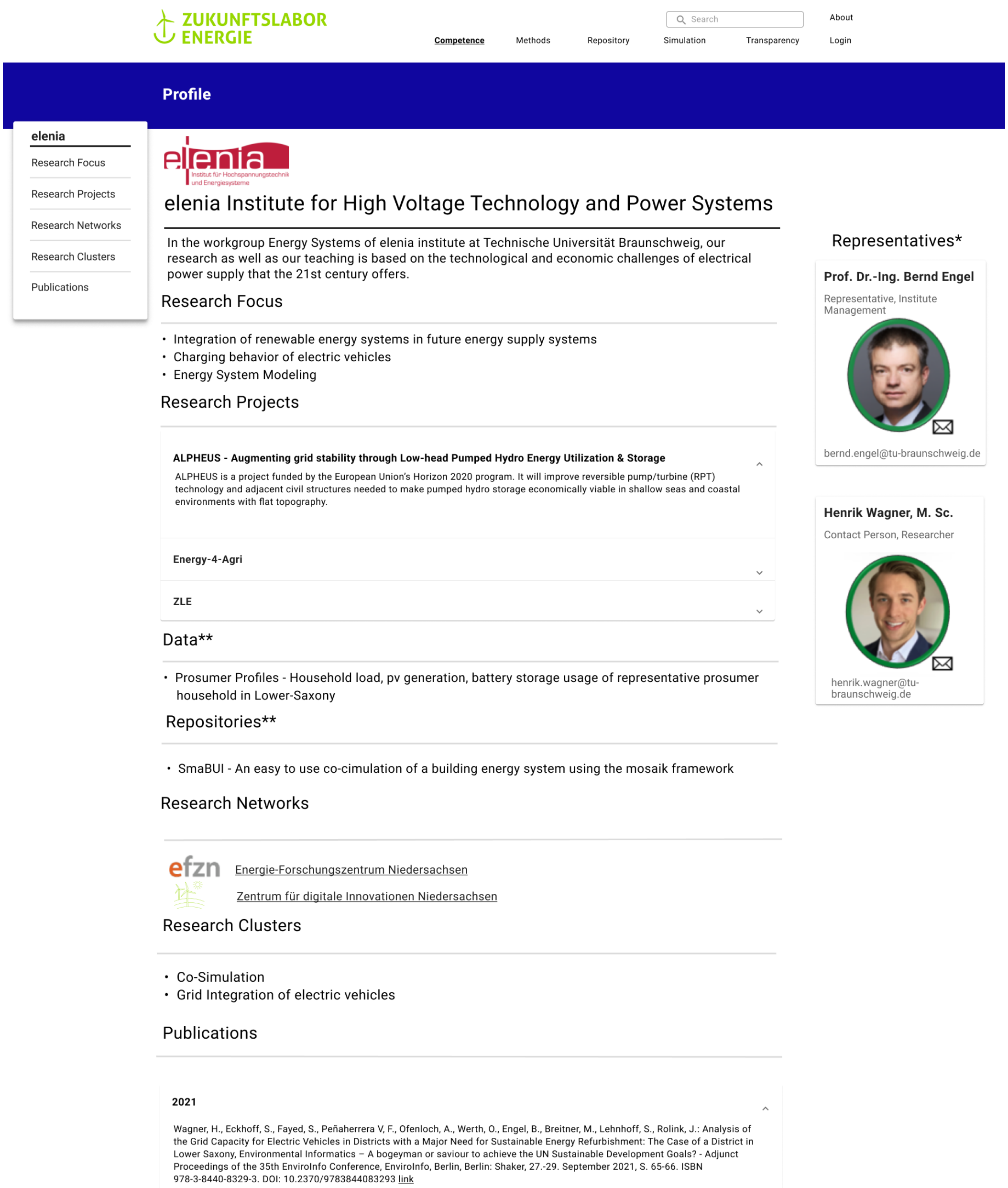

Figure 3. Mockup of the *Competence Profile*; * derived from *Core* and ** derived from *Repository*.

Input Mask provides two different ways of entering information for the Profile creation. First, the questionnaire uses an interview-based format which leads through the profile creation process by questioning the needed information (e.g., "What is the shortcut of your research institute?"—elenia). The questions follow one after another and include useful hints as well as examples. This provides an interactive way which may reduce terminations of the profile creation process. Second, as another way to create a *Competence Profile*, the *Input Mask* provides prescribed answer boxes. For adequate search results, the *Competence Taxonomy* simplifies filling out the profile.

Updating Publications refreshes the profile's literature reference by uploading and processing BibTex files, vastly reducing handling time. The publications can also be updated automatically by crawling listed publications (e.g., using the name of the profile representative) of a profile from Google Scholar.

Dead Man's Switch flags profiles as inactive when they do not update their information (e.g., literature references) nor log in for a set amount of time (see Figure 3 green circle around representatives pictures). In this way, up-to-date profiles are guaranteed, identified as a requirement [5] . This increases the incentive to maintain the profiles and shows the active participation in the community of the research platform.

Research Clusters allow the grouping of competences based on a common research focus, e.g., co-simulation of energy, or membership, e.g., of a local research society, as it is done by the Energy Research Center of Lower Saxony. The clustering helps to synthesize groups of researchers which may not belong to the same institution or project but still focus on the same research topic. Moreover, it also provides a connecting point for new researchers. Additionally, displaying research clusters in the form of a word cloud (e.g., in the style of Mentimeter (https://www.mentimeter.com/, accessed on 16 March 2022)) provides inspiration and arouses the curiosity of new users.

Competence Taxonomy unifies and simplifies filling out the entries in the profiles. This enables describing the same competences with the same definition, reducing less precise descriptions and enabling the formation of competence clusters and displaying them as described in the *Research Clusters*. *Competence Taxonomy* is derived from the *Energy Ontology* of *Core*.

All registered profiles are displayed on an interactive map (e.g., in the style of ZDIN's resarch map (https://www.zdin.de/digitales-niedersachsen/forschungslandkarte, accessed on 29 March 2022)) within the *Research Map*. It includes filter functions (e.g., based on address or perimeter). Additionally, a network representation of *Research Clusters* can be selected showing the geographical spread of in terms of *Research Clusters* connected profiles.

Competence Matching helps to form new research consortia and alliances similar to Edecy. Each platform profile can initiate a new matching process (e.g., based an a current research proposal) and define the needed competences. Then, the matching algorithm identifies relevant registered profiles and invites them to participate in the matching process. Therefore, new research consortia and alliances can be formed as a result of the matching process.

3.3. Methods

The goal of *Methods* is to provide an overview of scientific methodologies in energy research, both general and platform-specific, during the different stages of research. It presents methods for conducting open energy research gathered from successful experiences and current research practices. Methods and standards for cooperative project development, scenario modeling, and data management are required to deliver ideas to structure and execute cooperative research. Additionally, *Methods* provides an introduction for the use of the different services of the platform, also showing how the key services can be used during the general methods. Therefore, it helps users to learn how to use our platform efficiently in their work.

The requirement analysis identified that this key service is mostly interesting for the research community, from beginners to experts, potentially interested in methodologies for open energy research [5]. Therefore, this service is designed with these stakeholders in mind. Some functionalities of this key service may also be developed with different users under consideration (e.g., industrial partners, decision-makers, and citizens). Similar to openmod, *Methods* is designed like a wiki, allowing to create, edit, search, and present content while also including connections to other key services, especially to *Core* (*User Management*, and *Federated Search*). Figure 4 gives a broad overview of the different parts of the *Methods* element.

First, *General Methods for Open Energy Research* provides an overview of experiences from research projects for different stages of the research cycle. The content entries include examples from project and application formulation linked to more information in *Transparency*. The methods include, but are not limited to, the following: scientific project management and scientific research methods; modeling in energy research; information and examples on data management and analysis (data base management, licenses, FAIR data principles [4]); and guidelines for publications and listing (or links) to themed conferences or journals. A first view of what is desired may be partially reflected in existing initiatives and communities for energy system modeling and simulation platforms, such as openmod or Open Science Framework. The structuring should use defined words from *Core*'s *Ontology Service* when possible. Additionally, it is desired that any registered platform user is able to create and edit content (via *User Management*), with the rights to approve, revert, and delete content reserved for platform administrators.

Second, *Platform Methods* is linked thematically with the other platform key services. Guidelines for their use are introduced and linked to the *General Methods for Open Energy Research*. Introductory explanations are showcased with demonstrative examples under consideration of user profiles and degree of expertise providing explanations and coding templates for use of the platform. Examples for proper use of the online *Simulation* tool, *Competence* search functionalities, and *Transparency* services are to be showcased. The creation and change of this content is restricted to platform developers.

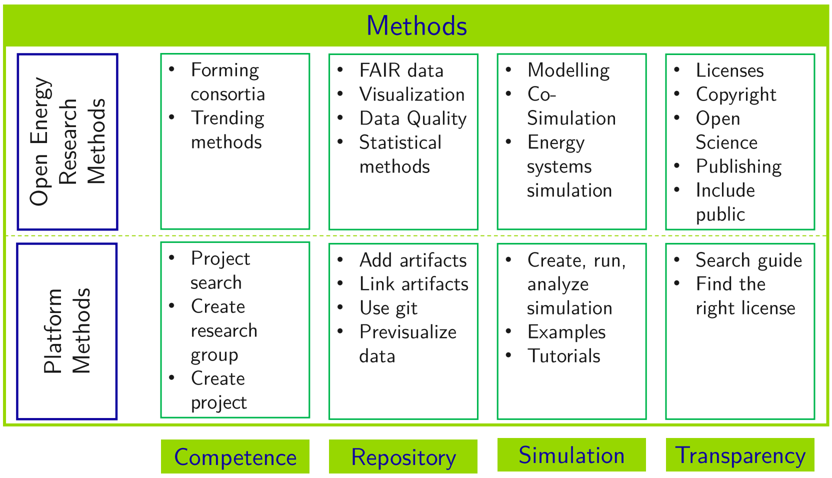

Figure 4. Overview of *Methods*.

3.4. Repository

The goal of *Repository* is to make data, models, and scenarios in the energy domain more FAIR. A metadata database is introduced to make these artifacts findable. Werth et al. identified the need to included not openly available artifacts [5]. Therefore, *Repository* includes information on openly and not openly available artifacts. Werth et al. identified a great potential for common harmonized interfaces [5]. Therefore, they are supported by labeling and describing them and, therefore, increasing their visibility to improve the overall interoperability and reusability. Based on these standardized interfaces, data and models can be used within scenarios in *Simulation*.

Figure 5 gives a brief overview of the main functionalities of *Repository* focusing on three main classes of artifacts: data, models, and scenarios. These are described with metadata based on standardized *Metadata Schemas*, so their description can be better compared and integrated into other key services like *Simulation*. The metadata and data are stored in *Databases*. Users can access *Repository* via three functionalities: *Artifact Add*, *Artifact Search*, and *Artifact View*.

Artifact Add enables users to add new artifacts with their description and, if possible, with their data. The addition of data is left optional, so data that are accessible only on request can be added as well, which was identified as a requirement by Werth et al. [5]. An interactive form is provided to add the required information with questions based on the according metadata schema. Relevant information is automatically collected from a provided link to the artifact, e.g., from gitlab. *Artifact Add* supports users to add links to entities in other key services, e.g., *Research Projects* in *Transparency*, predefined ontologies from *Core*, or other semantic web resources by presenting suggestions when input is typed.

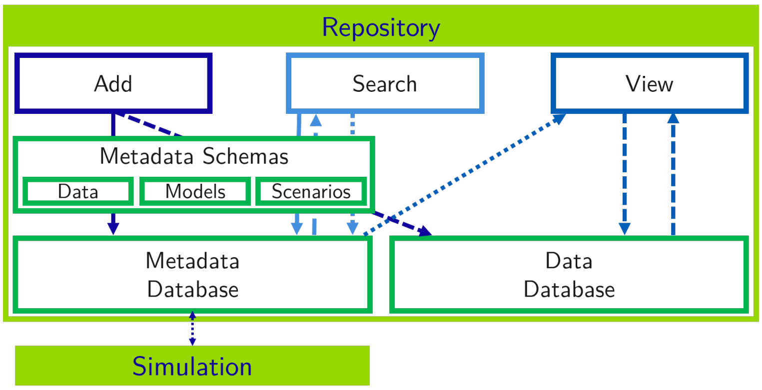

Figure 5. Basic functionalities of *Repository* and their interaction.

Artifact Search should be developed in accordance with the API of *Core*'s *Federated Search*. All *Databases* should be searched for relevant entries, and the results can be filtered according to different elements of the *Metadata Schemas*.

Artifact View defines an artifact overview page for all artifacts presenting the most important information from the related metadata and links to other relevant resources. A preview and a graphical visualization for data are included into the page, similar to Kaggle (https://www.kaggle.com/datasets, accessed on 7 January 2022). Additionally, the services offer to download data in different formats and time resolutions. For scenarios, it is possible to directly import them into *Simulation* as shown in Figure 6. Additionally, a comparison page enables to compare different artifacts.

Metadata Schemas are required to describe the artifacts in a standardized and machine-readable way. They are used to predefine the different elements needed to describe and categorize a certain artifact. For each element, the schema defines if a free value is allowed or if the use of a controlled vocabulary is required, e.g., domain-specific ontologies provided by *Core*, to increase the interoperability of the metadata [19]. Bio.tools shows how a well developed metadata schema can be the base for a registry for research software and, therefore, inspires the use of metadata schemas for this service.

The *Metadata Schemas* for data, models, and scenarios can share some common elements while some elements will differ, similar to the way these different artifacts are described on the OEP. In general, the *Metadata Schemas* include links to papers, projects, other relevant artifacts, and their description, e.g., in *Transparency*; information about who is allowed to access the artifact (based on *Core*'s *User Management*); quality of the artifact, e.g., origin of the data, if they are reviewed and tested, and how often they are already reused in other studies; and the authors and others which can be partly inherited from DCAT (https://www.w3.org/TR/vocab-dcat-2/, accessed on 7 January 2022) and a PID created by *Core*'s *PID Service*. To date, no common standard for metadata schemas exists in the energy domain [20]. *Repository* builds on and extends different existing metadata schemas to increase interoperability, such as the metadata schemas for datasets of the Open Energy Platform and CodeMeta (https://codemeta.github.io/, accessed on 7 January 2022) as metadata schema for research software. The metadata schema for scenarios, also used for *Simulation*, requires the use of semantic web technologies [6] to support automated scenario creation. Reder et al. collected requirements for the description of scenarios in energy research [21]. These requirements will be used for the development of a metadata schema for scenarios as well.

Two types of *Databases* are required for *Repository*. For all artifacts, *Repository* needs to store the metadata based on the defined schemas. For data, *Repository* stores the data and allows access via an API which can be limited to specified user groups (as result of the requirements analysis, see [5]). For all data, metadata are also required and stored in the according database. Artifacts from the *Databases* can also be linked and displayed in *Competence*'s *Profile Information*.

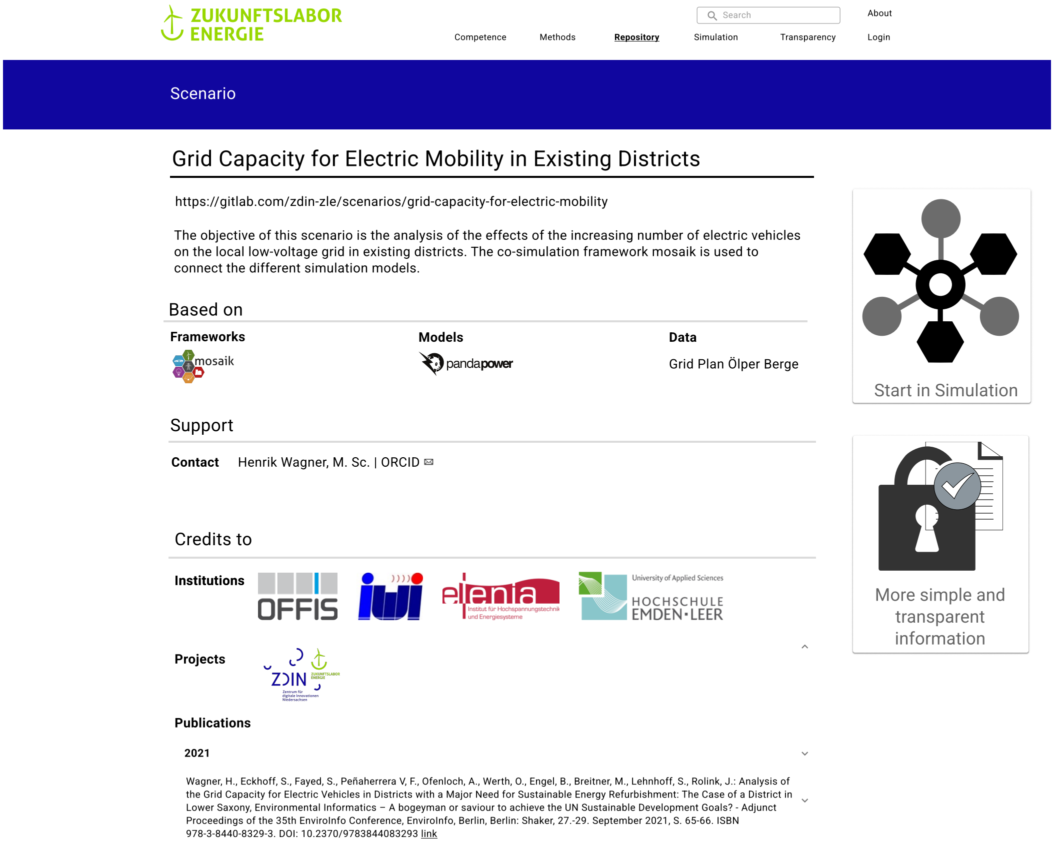

Figure 6. Mockup of an *Artifact View* page for a scenario with links to *Competence* in the credits to part and links to *Simulation* and *Transparency* on the right.

3.5. Simulation

The goal of *Simulation* is to provide an online co-simulation platform to couple different tools and models. Thus, *Simulation* supports the reusability of different simulation tools and models to enable co-simulation of various scenarios by addressing typical use cases in interdisciplinary energy research. This key service extends co-simulation frameworks like mosaik by adding assistance to build complex scenarios based on the artifacts from *Repository*. The focus lies on the combination of different domain-specific simulation tools and models into the co-simulation [16]. Since the models and data are mainly derived from *Repository*, the semantic-web based *Metadata Schemas* for data, models, and scenarios are required and used as a foundation for *Simulation* to list and connect compatible artifacts within the co-simulation platform.

Figure 7 gives a brief overview of the main functionalities of the co-simulation platform and consists of three parts: *Simulation Create* allows to extend scenarios from *Repository* and to create user-defined scenarios. *Simulation Run* includes the execution of the scenario and visualization during runtime. *Simulation Analyze* enables to view and explore the simulation results including data visualization.

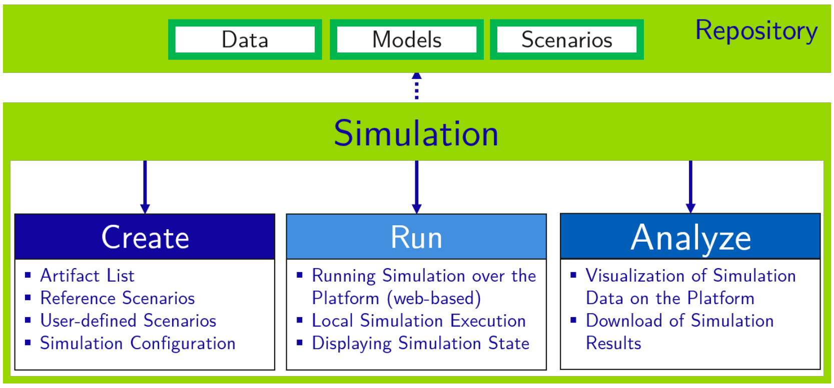

Figure 7. Basic functionalities of *Simulation* and their interaction.

Simulation Create allows the users to customize predefined scenarios and to create new ones with a user-friendly web interface, such as the *open_plan* tool (https://open-plan.rl-institut.de/de/, accessed on 17 March 2022). In particular, the user-friendliness was identified as a requirement by Werth et al. [5]. In addition, the *Maverig* tool from mosaik (https://gitlab.com/mosaik/tools/maverig, accessed on 17 March 2022), a graphical user interface for creating and visualizing smart grid simulations, can be used as a reference for the co-simulation platform. The scenarios are based on models and data with common interfaces, which are stored and labeled in *Repository*. In this regard, an approach presented by Schwarz et. al [6] can be used to assist in the planning of co-simulation based on semantic knowledge representation. It will be aligned with the *Energy Ontologies* provided by *Core*.

Simulation Run initializes and runs the simulation directly over the platform and locally. The co-simulation platform has a user-friendly interface for a simple run configuration. In addition, a node diagram with color-coded nodes for violations and failures (e.g., voltage levels, bottlenecks) are added to display the current grid state. An automated generated scenario script or configuration file (ontology-based) is provided for local execution via the platform. This file enables the automated creation and execution of scenarios within a co-simulation environment, such as mosaik.

Simulation Analyze includes the analysis of the simulation results. Therefore, the simulation results are displayed via a dashboard (e.g., via Grafana (https://grafana.com/, accessed on 7 January 2022)) when the simulation is finished. This includes the presentation of selected parameters, key performance indicators (KPIs), and optimized results (e.g., primary and secondary energy, energy production from renewable energy sources, and local consumption). Furthermore, a benchmark comparison of scenarios is included to compare relevant characteristics. The *User Management* of *Core* is needed to save scenarios and simulation data within the user profile and to access them at any time. In addition, user-defined scenarios and simulation results can be directly saved into *Repository*.

3.6. Transparency

The goal of *Transparency* is to process, publish, and communicate the research and development content to promote a broader and interdisciplinary discussion among all respected types of stakeholders. It serves as a foundation to use these processed results in research-oriented teaching and education and enables a communication channel for distributing relevant information in the energy sector. We visualize the functionalities of *Transparency* in Figure 8.

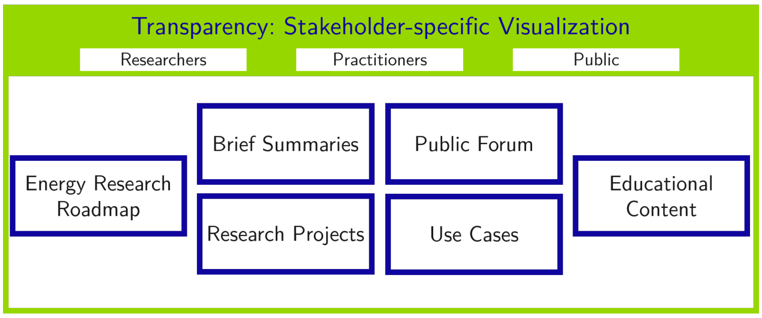

Figure 8. Basic functionalities of *Transparency* and their interaction.

The stakeholders of the platform, e.g., researchers, practitioners with different backgrounds, or citizens, are distinguishable in terms of characteristics, such as their knowledge base and intended purpose to use the platform. Hence, it is vital for the success of this key service to offer the content presented on the platform and their delivery channel in a stakeholder specific manner, as identified as requirement by Werth et al. [5]. For this reason, the content of this key service is processed in multiple ways, e.g., advanced content and easy-to-understand content. From a technical perspective, the *User Management* of *Core* is required for *Transparency* in terms of user-generated content, such as partners sharing information about projects. Furthermore, *Transparency* uses profile information from the users already included in *Competence*. *Transparency* also benefits from the *Federated Search* in terms of supporting users in finding and filtering for information they want to retrieve. *Transparency* consists of several services to reach the above stated goals. For all functionalities, the quality, correctness, and neutrality of the content has to be ensured. Energiesystemforschung can serve as an orientation for this. The platform should be promoted toward the (mass) media and local authorities for reaching a broader part of the society.

An *Energy Research Roadmap*, including a trend cloud, can be established to gain a comprehensive overview over the past and future research in the energy sector. Here, on one hand, a scientific presentation can be beneficial. On the other hand, there should be a less complicated presentation for citizens and practitioners that are less experienced, but interested in the energy domain. A quick overview over trending topics in the energy sector can also be provided by implementing a word cloud.

While scientific papers are likely comprehensible for more experienced stakeholders in their published form, they can be processed into *Brief Summaries* to promote the tangibility and clarity of energy research for less experienced stakeholders. If existent, recordings of conference speeches can be published for the same reasons. Additionally, the social media content of researchers can be embedded on the platform. This information should be connected to the user profiles from *Competence*. Within the presentation of certain research topics, their practical relevance can be illustrated by realizing *Use Cases*. For example, certain simulations and their results can be demonstrated. The usage of anonymous profiles of energy communities, including their boundaries, can be linked. As another aspect of practical relevance, the presented content might contain implications for practical or private decisions. Artifacts from *Repository* used for the production of content, e.g., use cases, presented via *Transparency* can be linked.

Besides papers, *Research Projects* can also be briefly summarized to make the information more transparent for stakeholders. Here, the general information from enArgus can be included. Platform users are given the possibility to present their own *Research Projects*. Following this approach, the platform would work as a substitute for separate project websites. Research results and information about projects of partners from *Competence* can be processed and presented via *Transparency*. The *Competence* profiles of institutions involved as well as data and source code from *Repository* can be linked in the respective content presented in *Transparency*.

Educational Content, such as lecture slides, laboratory experiments, and lecture recordings, can be shared via the platform to be utilized for private educational purposes or for teaching in schools and universities. With this approach, a teaching and learning network, such as ATLANTIS (https://www.elan-ev.de/projekte_atlantis.php, accessed on 7 January 2022), can be established. Therefore, the results of workshops, e.g., from existing projects can also be employed. Practitioners might be more interested in application-oriented educational content, which can be provided by processing certain existing educational content. Public courses, lecture slides, etc., are also displayed in the linked *Profile Information* of *Competence*.

Public Forum can be implemented to promote a dialogue within the platform's community and the communication between researchers and other stakeholders, particularly citizens. The potential to develop into a place for citizen dialog was identified by Werth et al. [5]. In this forum, users can direct questions toward researchers or discuss certain topics publicly, e.g., regulatory content. It remains to be evaluated to what extent a registration of users is reasonable or necessary and if there should be a separate forum only accessible to researchers besides the public forum which has to be taken into account by the *User Management* of *Core*.

4. Discussion

In the following, we discuss the use of the open digital energy R&D platform based on three use cases. Section 4.1 focuses on a research project from a researchers perspective, while Section 4.2 includes industry participating in a research project as well. Section 4.3 gives an example how the platform can be used within university classes.

4.1. Research Use Case

The use case for a research perspective follows the six phases of the design science research methodology of Peffers et al. [22] as one example of how research can be conducted. Other research methodologies, e.g., the more domain-specific smart grid algorithm engineering (SGAE) process [2], are also supported by the platform services.

In the first phase, the research problem should be identified and motivated. Researchers can use the *Energy Research Roadmap* and the *Public Forum* to define and discuss research problems. Werth et al. [5] showed the need to include the public in this phase as an important requirement, which can be supported through opinions articulated in the *Public Forum*. Afterward, the *Competence Profiles* can be used to find suitable partners from industry and research to work on the research problem and to apply for (international) funding together.

In the second phase, the objectives for a solution should be defined. In this phase, *Methods* can support the research, e.g., by giving an overview on methods for requirements analysis. This is especially relevant for young researchers as pointed out by Werth et al. [5] and for researchers originally from a different discipline, which is common in interdisciplinary energy research.

In the third phase, the artifact should be designed and developed. Here, existing models and data in *Repository* can be reused as starting point. Researchers can use *Artifact Search* to look for relevant models and use *Artifact View* to get information on which models fit together based on common interfaces, as identified as a requirement by Werth et al. [5]. Additionally, the different models can be compared using *Artifact View* to find the best model. For multiple research questions it should be possible to just use a new combination of existing models or to only implement a few additional lines of code.

In the fourth phase, the artifact should be demonstrated. If all selected models are supported by *Simulation*, the whole simulation can be processed on the platform with *Simulation Run*.

In the fifth phase, the artifact needs to be evaluated. *Methods* can help in this phase by providing an overview on relevant methods while additional datasets for the analysis, e.g., anonymized load profiles, can be found within *Repository*.

In the sixth and last phase, communication of the results is required. Hevner et al. [23] emphasized that the results need to be communicated to two groups: the people which should use the results in their daily work life and researchers. For the first group, researchers can use *Transparency*, e.g., they can add to *Brief Summaries* and link them to their own *Research Projects*. Additionally, they can show the practical relevance by adding *Use Case*s. For the second group, the researchers, papers are typically written and published at conferences and journals. Researchers can also publish new simulation models, datasets, and scenarios to *Repository* by using *Artifact Add* to extend the knowledge base as emphasized by Hevner et al. [23]. With *Artifact Add*, the researchers can also include information about the interoperability of the new model making the new model easy to use to generate new knowledge.

4.2. Industry Use Case

While some research projects are initiated by researchers, some are also client-initiated research projects as Peffers et al. pointed out [22]. In this case, a company would identify a problem within their own field. They can use *Energy Research Roadmap* and *Brief Summaries* of *Transparency* to get additional information on their problem. If they decide to get in touch with researchers already working on similar problems they can search within the profiles of *Competence* and look into the relevant *Profile Information* giving clear and up-to-date information, identified as a requirement by Werth et al. [5]. The company can also look for local research partners by using the *Research Map* or the *Research Clusters*.

When the research partner and industrial partner agree on a common research project, the industrial partner can ask the research partner to build a small simulation use case to solve the problem of the industry. Therefore, the industry can provide data to the researchers. The researchers can register the data with *Artifact Add* to make their research comprehensive and to fulfill the FAIR criteria. The researchers can discuss with the industrial partner if the data can also be published (open data) or not.

The researchers can use *Simulation* (*Simulation Create*, *Simulation Run*, *Simulation Analyze*) to easily connect different simulation models and data from *Repository*. In this way, the industry partner can easily try to analyze additional configurations by itself.

4.3. Education Use Case

In the context of university teaching, the platform can offer support in two ways. First, new easy-to-understand material is provided by *Educational Content* in *Transparency*. Additionally, *Brief Summaries* and *Research Projects* can give information on research results and projects, which can be integrated into courses as well.

Second, *Simulation* in combination with models and data from *Repository* offers an easy entry to simulating energy systems enabling students to perform simple simulation of energy systems for better understanding, which was also identified as a use case during the requirements analysis of Werth et al. [5]. These models and data can be labeled "for training" to be better findable for this use case. In an introductory seminar, students can use predefined scenarios with *Simulation Run* and *Simulation Analyze*. Later on, the students can also create their own scenarios with *Simulation Create*.

5. Conclusions

Energy research is facing multiple challenges. On the one hand, the research subject changes rapidly due to the energy transition and the digitalization of energy systems. On the other hand, research itself changes due to digitalization, a higher demand for openness, and an increasing need for interdisciplinary research. To address these challenges, the idea of an open digital energy research and development platform and an extensive requirements analysis was presented by Werth et al. [5]. Based on that analysis, we developed a detailed, innovative concept for such a platform. The possible uses of the platform were formulated with three use cases from different potential stakeholders from the areas of fundamental research, industry-related research, and education. In this way, we showcased the benefits of such an artifact for the users. In further research, a use case based on social science in energy research should be added to reflect how this research can interact with the open digital energy research and development platform.

Over the whole platform, we see the challenge of motivating users to add content in the first place before the platform becomes usable for all stakeholder. Therefore, it will be critical to add as much information as possible in the initial phase of the platform development. In the context of *Methods*, it remains an open question as to how all relevant methods can be identified and if an overseeing instance is necessary for these methods. For *Repository*, it will be relevant to identify the right metadata which can improve search results. It should also be explored as to how industry data can be integrated in a good way to make the data FAIR. For *Simulation*, it remains open as to how an easy-to-use interface can be achieved while enabling complex simulation. As further research, the open digital energy R&D platform itself should be implemented for further evaluation of the concept and to work on these open questions. With the presented concept, we lay a good knowledge foundation for the implementation phase.

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