# Open Energy Data Server Used in Research Data Management

Florian Maurer[1,*] , Jonathan Sejdija[1] , and Volker Sander[1]

[1]University of Applied Sciences Aachen, Germany

*Correspondence: Florian Maurer, maurer@fh-aachen.de

**Abstract.** The integration of open data in energy informatics is increasingly crucial for the transformation towards a digital and decentralized energy system. However, challenges arise like licensing, accessibility as well as inconsistencies between source formats and desired formats, impeding efficient querying processes. To address these issues, the Open Energy Data Server has been developed, facilitating efficient usage of time series, geospatial and structural data in energy research, and applications in compliance with FAIR principles, despite limitations in the original sources. It features an administration frontend, dashboard visualizations and a REST API for application development. The included datasets contain information on power systems, weather, network frequency, as well as historic data on European energy and gas demands or generation.

**Keywords:** Open Data, Infrastructure, Fair Access

## 1. Motivation

In the field of energy system research, the imperative for open datasets to enhance parameterization, input data, and validation of training/simulation outputs cannot be overstated [1], [2]. However, the acquisition and management of such datasets poses significant challenges. The absence of a standardized repository for existing datasets and their curation steps often result in time-consuming processes being repeated several times by different researchers. While access to these datasets is typically free, registration and API keys are often prerequisites. Furthermore, datasets are available in diverse formats, often necessitating the use of proprietary software for visualization and editing, presenting a significant barrier to entry, especially for datasets that prohibit public redistribution [3], contravening the FAIR principles (Findable, Accessible, Interoperable, Reusable) [4].

Although many public organizations have understood the requirements for open data and may even be obligated to make information publicly available, their systems still frequently contain different data formats and barriers, preventing reusage of data [5]. Moreover, the dynamic nature of these datasets (predominantly time series), continuously updated with new values, underscores the necessity for real-time access without additional steps [6]. Existing research data management software primarily caters to dumping finite datasets, lacking support for continuous querying and extensions.

To address these issues, an institutional data management approach is preferred to reduce latency and accommodate the seamless integration of additional data sources. Using state-of-the-art technology the proposed open energy data server (OEDS) not only facilitates efficient data processing but also caters to diverse user needs through various interfaces such as REST APIs, interactive dashboards, and data export options. The creation of an open-source solution which can be hosted within an organization tackles this problem efficiently and allows for rapid prototyping of research ideas, and reusage of efforts in making data available for educational purposes.

## 2. Related Work

In the field of energy research data, various solutions to organize, structure and store data already exist. The importance of consistent data for simulations is shown in [7]. Frictionless data format, an option for static datasets is shown in [8], while an approach focusing on measurements of IoT devices based on FIWARE is shown in [9]. The SensorThings data model provides a generalized data model to store different sensor data [10], which is not suitable to store data with additional structural data.

Taking a broader view at data usage in research data management (RDM), one has to consider all activities related to research data [11]. Thus the OEDS contributes to RDM by providing an option to continuously store new model data next to existing data. To help with RDM tasks that can be very complex, there are a growing number of systems and platforms offering services to storing data results. On an interdisciplinary level, examples of such platforms are Zenodo[12], which offers structured storage and publication for papers and datasets, CKAN offering a self-hosted data-management platform for open-data sets and Coscine [13] offering a framework that supports proper use of RDM methods by giving structure for metadata and documentation around datasets. Specific for the energy research domain, a community driven open database for energy system models and datasets is available with the Open Energy Platform [14]. Many of these tools have the goal to help researchers organize and structure their data and results, in order to share them in a standardized manner. This leaves a gap in the tool landscape for a platform handling raw data provided by third party sources which can not be redistributed publically. The OEDS fills this gap by helping researchers to find and access such data by pulling and structuring data to a more uniform access, making it possible to rapidly integrate new datasets into a known strucutre with a standardized toolchain.

In computer science, the problem of storing historic data efficiently to analyze and query them has often been revisited in literature of data warehouses[15], [16], [17]. Core aspects of data warehouses include; OLAP (OnLine Analytical Processes) components as per [18], [19], ETL (Extract Transform Load) components as per [20], and may sometimes include distributed architectures for parallel analysis or extraction [21], [22]. Looking beyond data warehouses for a use case more similar to our own, data lakes can be used to store raw heterogeneous data sets [23]. OLAP components make use of a data cube model based around fact tables [18], however graph analysis methods are also becoming popular as they perform well on tasks such as page ranking or metadata analysis [19].

# 3. Realization

## 3.1 User requirements

Before implementing a software architecture, the resulting functionality should be derived from the user requirements. With regard to the diversity of content (structural, geospatial and temporal) in different data sources, and, their related data formats described in the last section, researchers need an architecture to handle these differences.

*Available datasources*

of the OEDS are shown in Table 1 including their containment of structural, geospatial or temporal identifiers. The datasets include the most relevant sources for modeling energy systems in Germany and can be extended to include other regions using the same pattern in the future.

**Table 1.** *Main data sources which can be selected, downloaded and updated through the OEDS*

| Name | Description | Type | Size (Estimated) |
|---|---|---|---|
| nuts | NUTS geographic data from EUROSTAT[24] | Temporal, Spatial | 30 MB |
| mastr | German power plant data from Markstammdatenregister [25] | Structural, Temporal, Spatial | 4.8 GB |
| weather | Weather Data from ECMWF [26] | Temporal, Spatial | 2863.9 GB |
| smard | Energy usage/generation data from SMARD [27] | Temporal | 70 MB |
| entsoe | Energy usage/generation data from ENTSO-E [28] | Temporal, Spatial | 19.2 GB |
| entsog | Gas usage/import data from ENTSO-G [29] | Temporal, Spatial | 15.3 GB |
| opsd | Power plants from Open-Power-System-Data [6] | Temporal, Spatial | 700 MB |
| jao | Cross Border Trading results from JAO [30] | Temporal, Spatial | 10.1 GB |
| gie | gas storage and LNG utilization from GIE [31], [32] | Temporal, Spatial | 686 MB |
| regelleistung | balancing power and auction results from German TSOs portal[33] | Temporal | 2561 MB |
| scigrid | Grid information from SciGrid [34] | Spatial | 800 kB |

In addition to supporting different data set hierarchies, accessibility, export functionalities, and visualizations are important. Especially noteworthy is the visualization option, as it also provides a simple and accessible plausibility check for data contents. As outlined before, another key missing feature of existing solutions is the possibility to update datasets from a source, and add datasets of research results next to the original source on the data server. Finally, due to a high turnover-rate of researchers in academic surroundings, the solution must have low maintenance footprint and should use well-known established software.

The requirements of the proposed data management tool can be summarized from the user's perspective:

1. Implementing structural, geospatial and temporal data
2. Continuous updating of dataset from their source
3. Efficient handling of large datasets
4. Allow extending data with research results
5. Developing configurable Visualizations
6. Supporting application development
7. Enable exporting of data subsets

## 3.2 Data technology stack

The actively developed relational database-management system PostgreSQL[1] suits the needs described in the previous section. Using PostgreSQL schemas instead of individual databases, joins between different datasets are possible, without relying on external data wrappers requiring additional configuration. To meet the requirements, open source extensions were used, which are described in the following. The creation of the OEDS is based on established and reliable technologies.
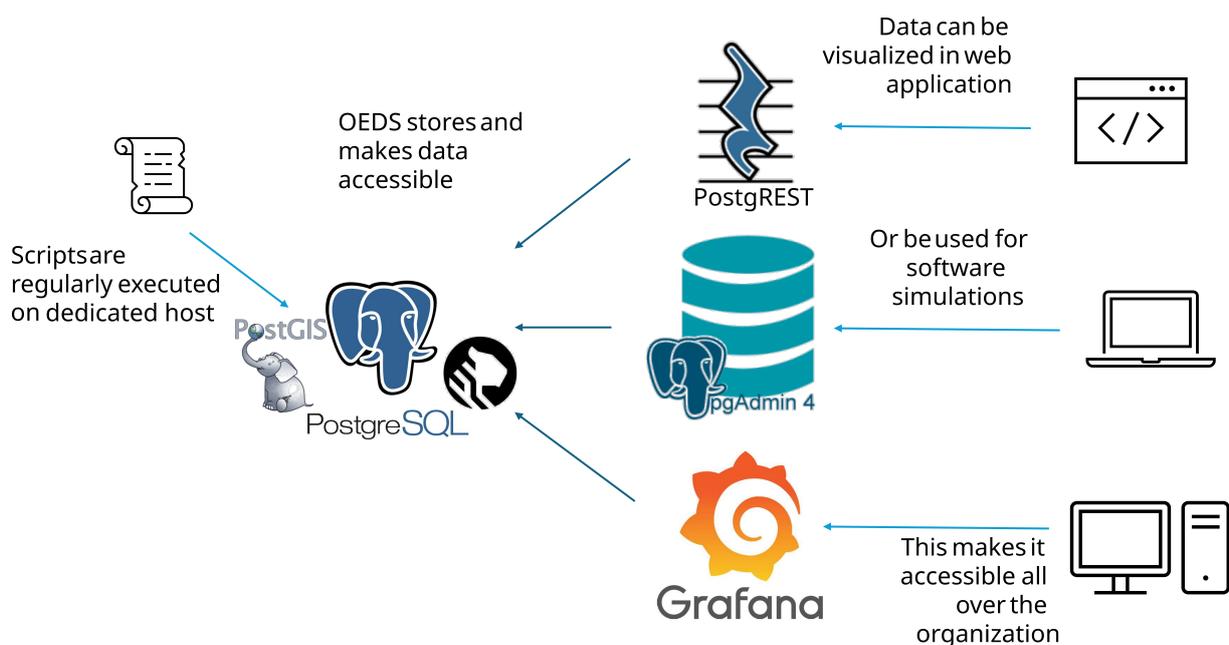


*Figure 1.* Architecture Open Energy Data Server

It should be noted, that accessibility to the public is not a requirement here, as the main focus is to make public data more easily accessible within an institution. The final tool set is open-source and available on GitHub[2]. The key components are visualized in Figure 1, which outlines the core system as well as the various methods with which to interact with the data.

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[1] https://www.postgresql.org/
[2] https://github.com/NOWUM/open-energy-data-server/

*Scheduled jobs*

regularly execute Python scripts which download latest data from publicly available APIs. The target of the project is to include various data sources, in a way which allows easy reanalysis and usage in research projects. As the database is hosted only inside the institute's network, data sources without public access can be integrated without violating usage agreements. The tool set which converts data into the structural database can be made available nonetheless, as it is the case for price data on the published repository.

*PostGIS*

is an extension for PostgreSQL which enables storage and processing of geospatial objects in relational data tables[35]. It extends PostgreSQL's capabilities, offering a wide range of functions for handling and analyzing geospatial data such as; points, lines and polygons; geospatial reference transformations. As PostGIS implements the OpenGIS "Simple Feature for SQL" standard [36], it provides a standardized method for efficient querying, such as finding objects within a specific area, calculating distances between points, or overlaying geometries. This standardization also ensures compatibility to other GIS software and data formats such as QGIS. To reduce redundancy of common data, the often referenced Nomenclature of Territorial Units for Statistics (NUTS) geometries are generally made available in the main public schema of the OEDS and reused in queries referencing NUTS regions.

*TimescaleDB*

improves the usage of PostgreSQL when querying tables which contain a time-referenced column. Beyond creating an index on the time column, it also shards a single table into multiple smaller tables, based on the time index [37]. This ensures that inserting data into the database stays performant without reindexing. When interacting with data, the usage of TimescaleDB makes it possible to group data into time buckets of averaged data, which is especially useful for continuous aggregations used in visualizations on a dashboard. In a more advanced setup, one can also use distributed hypertables to improve read and write performance across multiple nodes or to compress less often used data of tables with a time column.

### 3.3 Interaction tools

Besides the plain SQL connection, interaction with the OEDS is possible through three different interfaces, each of which serves a different use case.

The administration tool pgAdmin4[3] allows investigating and analyzing individual queries. The pgAdmin4 web interface can be accessed through a centrally hosted instance with a centralized login, reducing the required setup for researchers and new users using the database.

Visualizations can be created using Grafana[4] which includes a graphical user interface to configure parameters and graph details. The resulting graphs are created once and can be applied to any time range existing in the dataset.

Finally, to build small web applications on top of the database, we use PostgREST as a standardized HTTP access point to the data. This does not exhibit the full SQL

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[3]https://www.pgadmin.org
[4]https://grafana.com

standard and is limited to read-only access. PostgREST exposes a RESTful API with access to all datasets, without specific configuration needed when adding new data. This complies to the FAIR principles, as it increases the accessibility of the data in an uncomplicated manner. This also follows from the analysis Dunning et al. in [38], in which a simplified minimal guideline for achieving FAIR principles is laid out, one point being the recommendation to stick with HTTP requests as a protocol unless necessary. Simple queries can be sent directly using a purpose built URL, in which the HTTP query string is used to resemble SQL conditionals or operators. For example given the URL:
`https://monitor.nowum.fh-aachen.de/oeds/`
`cosmo?limit=10&country=eq.DE&temp_air=gte.303`
we are querying the Cosmo table, returning only the first 10 entries where the `country` column is equal to "DE" and the `temp_air` column is greater than 303. To execute this example successfully, one needs to issue the URL as a GET-Request with the `Accept-Profile` header set to: "weather", thus accessing the correct database schema. Complex queries can be made available in PostgREST through the usage of stored procedures. This makes it possible to publish access to a prepared PostGIS or TimescaleDB query through a REST endpoint. This is especially useful for services which are available outside the institution as interaction through HTTP(S) is often allowed where PostgreSQL connections are not due to security reasons.

The PostgREST server is configured to allow access to any schema in the database and new schemas are directly available after being created on the PostgreSQL server. To prevent accidental or malicious overloading of the REST endpoint, a rate limit on the web server configuration which prevents overloading of the PostgREST server is implemented.

### 3.4 Dataset storage

In total, the full OEDS deployment takes about 4 TB of data. The largest dataset is the weather dataset from ECMWF which contains various weather metrics for the whole of Europe in an hourly resolution of 4 km squares. It is possible to reduce this data to a single value per NUTS area in the data fetcher or to restrict it to weather in specific regions. Nevertheless, this also clarifies that the proposed solution scales well for multiple terabytes of research data, as it is being handled in a more performant format than the source format of the datasets.

Therefore, the third of our requirements is fulfilled by the OEDS. The other datasets and their size in gigabytes (GB) are shown in Figure 2, showing that most of the tables in the datasets have a temporal dimension. In the following, different use cases for visualizations, research process and usages in applications are presented, to showcase the utilization of the open data platform.

### 3.5 Integration of new datasets

To integrate new datasets, one must create a script which requests the latest data from a new data source. This script can then be added to a job scheduler like cron for execution. Of course, when the public API changes, such scripts have to be adjusted accordingly. The open source characteristic allows for other organizations to profit from adjustments which are implemented once in the OEDS repository.

Taking the example of simulating energy markets, a good practice is to save the simulation results and parameterization of the scenario, in order to adapt it to the actual data sets from the historic energy market, or to benchmark different market simulations
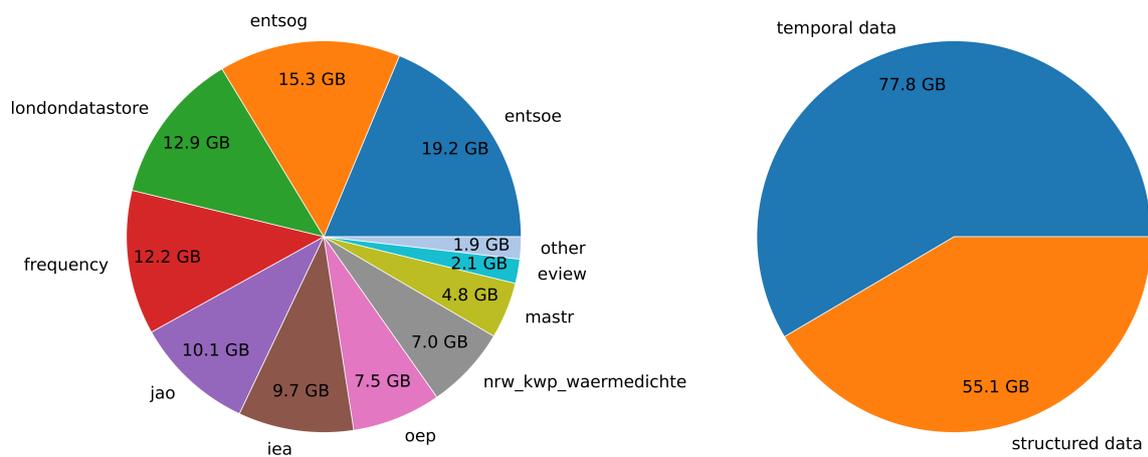
**Figure 2.** *Disk usage in GB by data source and data type, not including weather data due to its variable size depending on selected areas*

against it. This process can be improved when validation data for relevant scenarios is already present in the OEDS and only needs to be queried. An example figure of the market price comparison of two different open source energy market simulation tools is provided in Figure 3.
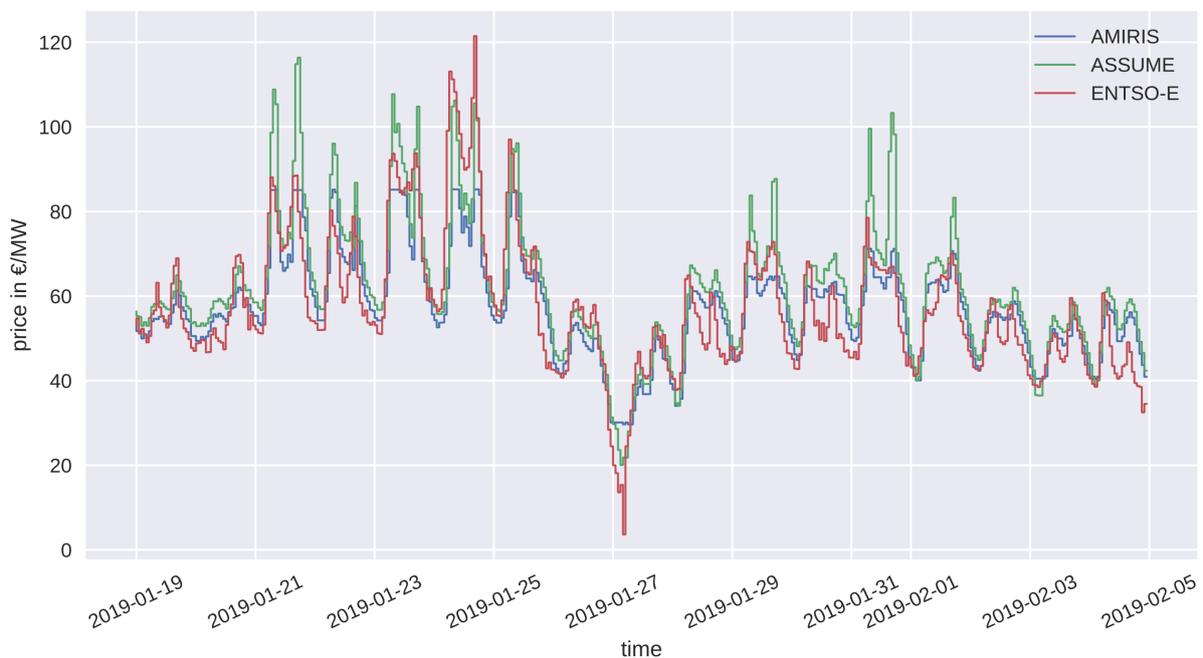


**Figure 3.** *Exemplary price time series from simulation comparison of energy market simulation*

For this simulation, both scenario runs are stored as additional datasets in the OEDS and are benchmarked according to the actual historic day-ahead market price of the ENTSO-E for the German market zone.

## 3.6 Access Management and Permissions

To integrate additional datasets, the data fetcher and dashboard has to be created only once - which is feasible in the constraints of a research project. Required steps are outlined in Figure 4, while the first step handles the data storing, while the second step provides useful visualizations for these datasets with a selectable timeframe.
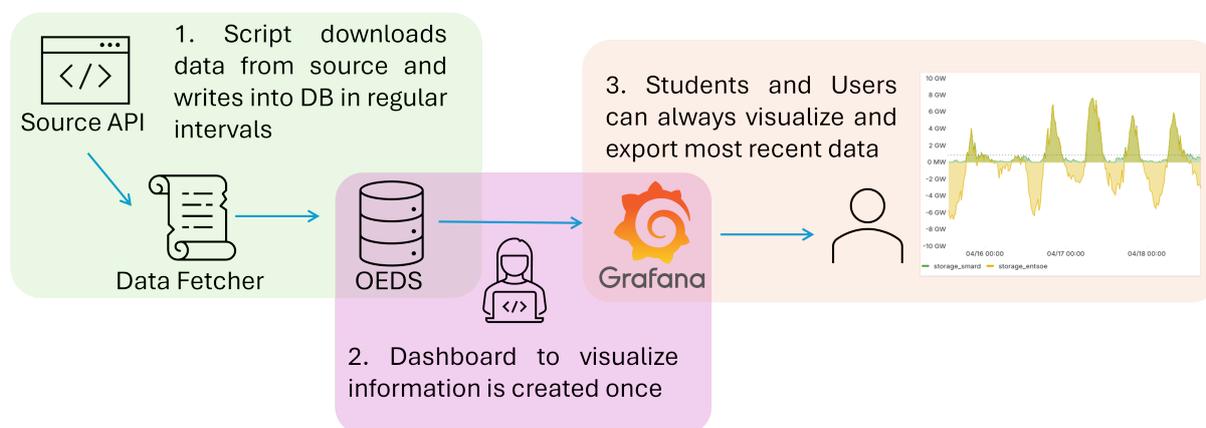


**Figure 4.** *Typical steps needed to add a dataset to the OEDS. Creating the Crawler and the dashboard is only needed once, while the resulting data can be utilized in many ways*

When interacting with data, it is often required to export a subset or the whole set in a given resolution to reuse or persist for RDM. The OEDS provides different ways to export data, which are shown in detail in the repository. For this, fine grained permissions can be set through the PostgreSQL permission model.

The data can either be accessed directly using the PostgreSQL connection with any programming language and save the result as CSV. Alternatively, the same can be accomplished using the public REST API call, which works without authentication. More interactively, one can download a query result as CSV directly from the pgAdmin interface or retrieve the exact source data of a given plot on a Grafana dashboard.

The resulting data can then be utilized through one of the different interactional tools, making it possible for users of different technical expertise to retrieve the required subset of data, enabling the last requirement.

# 4. Discussion & Conclusions

This study proposes a platform for accessing and visualizing continuously updated open datasets. Time-consuming curation processes are created from scratch due to the lack of a sustainable repository for existing datasets and their disparate methods of consumption. Furthermore, the variety of formats in which datasets are available, frequently calls for the need of proprietary software for editing and visualization. This poses an obstacle, particularly for datasets that do not meet open standards by forbidding public redistribution. To address these issues, an institutional data management approach is preferred to reduce latency and accommodate the seamless integration of additional data sources. The proposed tool set adheres to the outlined requirements, not only facilitating efficient data processing but also satisfying user needs through interfaces such as REST APIs, interactive dashboards, and query builders. The open-source solution can be used as a blueprint for usage within an organization to tackle this problem efficiently. This synergy does not only enhance the quality and reproducibility

of research but also facilitate greater collaboration and innovation in the field and makes datasets available for educational purposes.

The differences identified in the acquisition, management, and utilization of open datasets for energy system simulation highlight several avenues for further research and investigation. Further work is planned on the integration of automized checks on data completeness and consistency (e.g., of timezone usage), as well as a methodology to store metadata in a standardized format, making it possible to use information of available datasets in a LLM application for ease of use. Due to the rising size of the datasets, use of compression and down sampling of historic values is a future-proof way to raise efficiency beyond in the future. Through a community-based approach of collaborative work, additional datasets focusing on a broader international scope will be added, fostering a more inclusive and comprehensive understanding of energy systems worldwide.

## Data availability statement

The Open-Energy-Data-Server (OEDS) is publically available at https://github.com/open-energy-data-server/open-energy-data-server.

## Author contributions

FM: Conceptualization, Methodology, Writing - original draft; JS: Writing - review & editing, Software; VS: Conceptualization, Supervision, Writing - review & editing

## Competing interests

The authors declare that they have no competing interests.

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## References

[1] S. Pfenninger, J. DeCarolis, L. Hirth, S. Quoilin, and I. Staffell, "The importance of open data and software: Is energy research lagging behind?", *Energy Policy*, vol. 101, pp. 211–215, Feb. 1, 2017, ISSN: 0301-4215. DOI: 10.1016/j.enpol.2016.11.046. Accessed: Jul. 13, 2022. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0301421516306516.

[2] F. Bauer and M. Kaltenböck, "Linked Open Data: The Essentials", in 2017, ISBN: 978-3-902796-05-9.

[3] L. Hirth, "Open data for electricity modeling: Legal aspects", *Energy Strategy Reviews*, vol. 27, p. 100 433, Jan. 1, 2020, ISSN: 2211-467X. DOI: 10.1016/j.esr.2019.100433. Accessed: Jul. 13, 2022. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2211467X19301269.

[4] M. D. Wilkinson et al., "The FAIR Guiding Principles for scientific data management and stewardship", *Sci Data*, vol. 3, no. 1, p. 160 018, 1 Mar. 15, 2016, ISSN: 2052-4463. DOI: 10.1038/sdata.2016.18. Accessed: Oct. 27, 2023. [Online]. Available: https://www.nature.com/articles/sdata201618.

[5]   A. S. Kumar, I. Kouveliotis-Lysikatos, and L. Soder, "Comparison of Openly Available Power System Data for the Nordic Region", p. 6,

[6]   F. Wiese et al., "Open Power System Data – Frictionless data for electricity system modelling", *Applied Energy*, vol. 236, pp. 401–409, Feb. 2019, ISSN: 03062619. DOI: 10.1016/j.apenergy.2018.11.097. Accessed: Jul. 13, 2022. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0306261918318130.

[7]   J. DeCarolis et al., "Formalizing best practice for energy system optimization modelling", *Applied Energy*, vol. 194, pp. 184–198, May 15, 2017, ISSN: 0306-2619. DOI: 10.1016/j.apenergy.2017.03.001. Accessed: May 19, 2024. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0306261917302192.

[8]   D. Fowler, J. Barratt, and P. Walsh, "Frictionless Data: Making Research Data Quality Visible", *International Journal of Digital Curation*, vol. 12, no. 2, pp. 274–285, 2 2017, ISSN: 1746-8256. DOI: 10.2218/ijdc.v12i2.577. Accessed: May 19, 2024. [Online]. Available: https://ijdc.net/index.php/ijdc/article/view/577.

[9]   F. Terroso-Saenz, A. González-Vidal, A. P. Ramallo-González, and A. F. Skarmeta, "An open IoT platform for the management and analysis of energy data", *Future Generation Computer Systems*, vol. 92, pp. 1066–1079, Mar. 1, 2019, ISSN: 0167-739X. DOI: 10.1016/j.future.2017.08.046. Accessed: May 19, 2024. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0167739X17304181.

[10]  S. Liang et al., "OGC SensorThings API Part 1 : Sensing Version 1.1", Aug. 4, 2021. Accessed: May 19, 2024. [Online]. Available: https://brgm.hal.science/hal-04235851.

[11]  S. Netscher and A. Katsanidou, "Understanding and Implementing Research Data Management", in *Handbuch Methoden der Politikwissenschaft*, C. Wagemann, A. Goerres, and M. Siewert, Eds., Wiesbaden: Springer Fachmedien, 2018, pp. 1–18, ISBN: 978-3-658-16937-4. DOI: 10.1007/978-3-658-16937-4_4-1. Accessed: May 21, 2024. [Online]. Available: https://doi.org/10.1007/978-3-658-16937-4_4-1.

[12]  European Organization For Nuclear Research and OpenAIRE, "Zenodo", 2013. DOI: 10.25495/7GXK-RD71. Accessed: Jan. 25, 2024. [Online]. Available: https://zenodo.org/.

[13]  M. Politze, F. Claus, B. Brenger, M. A. Yazdi, B. Heinrichs, and A. Schwarz, "How to Manage IT Resources in Research Projects? Towards a Collaborative Scientific Integration Environment", *European Journal of Higher Eduction IT*, p. 8, May 15, 2020.

[14]  E. Kötter, B. Müller, L. Hülk, and M. Glauer (OvGU), "The OpenEnergy Platform (OEP) - A web-platform to improve transparency and reproducibility of energy system analyses", May 11, 2017. Accessed: Jan. 25, 2024. [Online]. Available: https://policycommons.net/artifacts/1554568/the-openenergy-platform-oep/2244377/.

[15]  A. Vaisman and E. Zimányi, *Data Warehouse Systems: Design and Implementation* (Data-Centric Systems and Applications). Berlin, Heidelberg: Springer, 2022, ISBN: 978-3-662-65167-4. DOI: 10.1007/978-3-662-65167-4. Accessed: May 20, 2024. [Online]. Available: https://link.springer.com/10.1007/978-3-662-65167-4.

[16]  Q. Yang, M. Ge, and M. Helfert, "Analysis of Data Warehouse Architectures: Modeling and Classification", presented at the 21st International Conference on Enterprise Information Systems, May 22, 2024, pp. 604–611, ISBN: 978-989-758-372-8. Accessed: May 22, 2024. [Online]. Available: https://www.scitepress.org/Link.aspx?doi=10.5220/0007728006040611.

[17]  K. Bakshi, "Considerations for big data: Architecture and approach", in *2012 IEEE Aerospace Conference*, Mar. 2012, pp. 1–7. DOI: 10.1109/AERO.2012.6187357. Accessed: May 22, 2024. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/6187357?casa_token=EAi1oV7QsPEAAAAA:iLL4Y3FyVn8of4PcdvWfIip29wCoHoDg-8Xt8Z_Wg5V_41AlibEkFMf_OxhiaHSvNXbK_lfNhg.

[18]  S. Chaudhuri and U. Dayal, "An overview of data warehousing and OLAP technology", *SIGMOD Rec.*, vol. 26, no. 1, pp. 65–74, Mar. 1997, ISSN: 0163-5808. DOI: 10.1145/2486

03.248616. Accessed: May 20, 2024. [Online]. Available: https://dl.acm.org/doi/10.1145/2 48603.248616.

[19] P. O. Queiroz-Sousa and A. C. Salgado, "A Review on OLAP Technologies Applied to Information Networks", *ACM Trans. Knowl. Discov. Data*, vol. 14, no. 1, 8:1–8:25, Dec. 13, 2019, ISSN: 1556-4681. DOI: 10.1145/3370912. Accessed: May 22, 2024. [Online]. Available: https://doi.org/10.1145/3370912.

[20] V. Goar, P. S. Sarangdevot, G. Tanwar, and D. A. Sharma, "Improve Performance of Extract, Transform and Load (ETL) in Data Warehouse", *International Journal on Computer Science and Engineering*, vol. 2, May 1, 2010.

[21] A. A. Yulianto, "Extract Transform Load (ETL) Process in Distributed Database Academic Data Warehouse", *Aptikom Journal on Computer Science and Information Technologies*, vol. 4, no. 2, pp. 61–68, 2 Jul. 1, 2019, ISSN: 2528-2425. DOI: 10.11591/APTIKOM.J.CSI T.36. Accessed: May 22, 2024. [Online]. Available: http://aptikomjournal.com/index.php /CSIT/article/view/36.

[22] K. Barker and A. Y. Noaman, "Distributed data warehouse architecture and design", 2000. Accessed: May 22, 2024. [Online]. Available: https://www.semanticscholar.org/paper/Distri buted-data-warehouse-architecture-and-design-Barker-Noaman/f32cc55a8ce440150bf b83ad374505c1865086a2.

[23] C. Mathis, "Data Lakes", *Datenbank Spektrum*, vol. 17, no. 3, pp. 289–293, Nov. 1, 2017, ISSN: 1610-1995. DOI: 10.1007/s13222-017-0272-7. Accessed: May 22, 2024. [Online]. Available: https://doi.org/10.1007/s13222-017-0272-7.

[24] Eurostat. "Territorial units for statistics (NUTS) - Eurostat", Accessed: May 22, 2024. [Online]. Available: https://ec.europa.eu/eurostat/web/gisco/geodata/statistical-units/terri torial-units-statistics.

[25] Bundesnetzagentur. "Marktstammdatenregister Datendownload", Accessed: Oct. 24, 2023. [Online]. Available: https://www.marktstammdatenregister.de/MaStR/Datendownload.

[26] copernicus. "Climate reanalysis — ECMWF", Accessed: Oct. 24, 2023. [Online]. Available: https://climate.copernicus.eu/climate-reanalysis.

[27] Bundesnetzagentur. "SMARD — Marktdaten", Accessed: Jan. 5, 2024. [Online]. Available: https://www.smard.de/home/downloadcenter/download-marktdaten/.

[28] ENTSO-E. "ENTSO-E Transparency Platform", Accessed: Mar. 25, 2024. [Online]. Available: https://transparency.entsoe.eu/.

[29] ENTSO-G. "European Network of Transmission System Operators for Gas - Transparency Platform", Accessed: May 22, 2024. [Online]. Available: https://transparency.entsog.eu/.

[30] JAO. "Auctions — Joint Allocation Office S.A. Leading service provider for TSOs", Accessed: May 22, 2024. [Online]. Available: https://www.jao.eu/auctions#/.

[31] Gas Infrastructure Europe. "GIE - Aggregated Gas Storage Inventory", Accessed: Jun. 5, 2024. [Online]. Available: https://agsi.gie.eu/.

[32] Gas Infrastructure Europe. "GIE - Aggregated LNG System Inventory", Accessed: Jun. 5, 2024. [Online]. Available: https://alsi.gie.eu/.

[33] 50Hertz, Amprion, TenneT, and TransnetBW. "German Balancing Power Datacenter FCR/aFRR/mFRR", Accessed: Jun. 5, 2024. [Online]. Available: https://www.regellei stung.net/apps/datacenter/tenders/.

[34] C. Matke, W. Medjroubi, D. Kleinhans, and S. Sager, "Structure Analysis of the German Transmission Network Using the Open Source Model SciGRID", in *Advances in Energy System Optimization*, V. Bertsch, W. Fichtner, V. Heuveline, and T. Leibfried, Eds., Cham: Springer International Publishing, 2017, pp. 177–188, ISBN: 978-3-319-51795-7. DOI: 10.1007/978-3-319-51795-7_11.

[35] PostGIS Project Steering Committee and others. "PostGIS, spatial and geographic objects for postgreSQL", PostGIS, Accessed: May 27, 2024. [Online]. Available: https://postgis.net/.

[36] Open Geospatial Consortium. "ISO 19125 Simple Feature Access", Open Geospatial Consortium, Accessed: Jun. 5, 2024. [Online]. Available: https://www.ogc.org/standard/sfa /.

[37] E. Stefancova, "Evaluation of the TimescaleDB PostgreSQL Time Series extension", Sep. 2018. Accessed: Dec. 14, 2025. [Online]. Available: https://repository.cern/records/bt7te-g r790.

[38] A. Dunning, M. de Smaele, and J. Böhmer, "Are the FAIR Data Principles fair?", *International Journal of Digital Curation*, vol. 12, no. 2, pp. 177–195, 2 2017, ISSN: 1746-8256. DOI: 10.2218/ijdc.v12i2.567. Accessed: May 22, 2024. [Online]. Available: https://ijdc.net/index.php/ijdc/article/view/567.