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Measuring FAIR Data Compliance in German Energy Research

A Follow-Up Assessment to "Unveiling Openness in Energy Research" Using OpenAlex, F-UJI, and FAIR-Checker

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Abstract. A 2025 study [2] indicated gaps in open publishing practices in the energy systems research domain. In this work, we examine the nature of these gaps by evaluating the quality of published energy-related datasets. Using the FAIR principles as indicators of dataset quality, a set of 384 datasets was evaluated using the automated tools FAIR-Checker and F-UJI. The results show strengths and weaknesses in FAIR principle compliance within the energy domain, providing insights for research data management efforts.

Keywords: FAIR Data, F-UJI, FAIR-Checker, Bibliometrics, Open Science, Energy Systems Research, Metadata Quality, NFDI4Energy, OpenAlex, Research Data Management

1. Introduction

Open science, which encompasses open access (OA) publishing, open educational resources (OER), and open data sharing, plays an increasingly important role in enabling transparent and collaborative energy research. These practices promote broader knowledge exchange and reproducibility, particularly in data-intensive fields like energy system research. The FAIR principles support this transition by ensuring that shared datasets are Findable, Accessible, Interoperable, and Reusable. This, in turn, increases the impact of open access outputs and enables effective reuse of data and OER. However, the implementation of FAIR data management remains inconsistent despite growing policy support, underscoring the necessity to more effectively integrate FAIR practices into open science strategies [1].

A study [2] presented in 2025 examined openness in energy research by analyzing trends in OA publishing and data-sharing practices. The application of bibliometric methods revealed the evolution of OA publications and the utilization of data on a quantitative basis. Based on these results, further research is needed to address the FAIRness of published datasets and to go beyond the descriptive nature of the 2025 study.

This study expands the dataset corpus and applies automated FAIR maturity assessments (FAIR-Checker and F-UJI). Because this study analyzes more than 300 datasets, automated assessment tools are necessary; their API-based workflow enables scalable, consistent, and reproducible FAIR assessments that would be impractical to conduct manually. Furthermore,

this work focuses on how institutional characteristics, repository type, and open access status correlate with FAIR performance, providing an overview of the current FAIR landscape in the energy domain.

This study addresses the following core research questions (RQs):

RQ1: Are FAIR principles adopted in contemporary energy research datasets?

What is the average FAIR score of the datasets?

Which criteria of FAIR yield consistently higher or lower scores? Are there systematic gaps specific to the energy domain?

RQ2: How do the FAIR scores differ between the results from FAIR-Checker and F-UJI, and what can we learn from them?

RQ3: How do FAIR scores correlate with the characteristics of repositories, institutional affiliations, and open access status of datasets?

How does FAIRness differ between repositories/institutions?

What do the FAIR scores look like for the datasets from the top institutions in the earlier study [2]?

2. Related work

Recent efforts to operationalize FAIR principles have produced a range of automated tools, notably F-UJI and FAIR-Checker. These were also suggested in the framework of the NFDI [3]. F-UJI offers a PID-centric, formalized FAIRness assessment aligned with FAIRsFAIR core metrics, providing structured and comparable scoring for research datasets [4][5]. In contrast, FAIR-Checker focuses on landing-page metadata quality, using Semantic Web standards and ontology validation to offer fine-grained, actionable recommendations [6][7]. Sun et al. revealed significant variations in the evaluation outcomes for the tested resources with both tools [8]. Additionally, the design, implementation, and documentation of the evaluation metrics and these systems are equally crucial. Together, these tools reflect the distinction between formal FAIR maturity evaluation and metadata-focused FAIRification support, and their complementary strengths make them well-suited for comparative FAIR assessments.

3. Methodology

3.1 Data corpus

As was the case in the 2025 study [2], the data corpus was collected using OpenAlex. Since November 2025, a new version of OpenAlex has been available, known as "Walden". This version contains 190 million new works, including datasets, software, and other research objects from DataCite and thousands of repositories [9]. Therefore, an expansion of the data corpus has been undertaken with the implementation of this new version of OpenAlex.

The datasets were obtained on November 9, 2025, using the query specifications Field: Energy; Continent: Europe; Year: 2015-2025; Country: Germany; and Type: dataset.

This procedure resulted in **a total of 1,545** datasets. Each dataset entry included metadata fields relevant for FAIR scoring and correlation analyses. These fields included information such as DOIs, repository type, institutions, and open access status. However, conducting a full

FAIR assessment of this corpus was not feasible due to the substantial computational time and manual validation required, even when using automated tools. In order to facilitate a rigorous yet manageable analysis, a random sampling strategy was applied, yielding a representative **subset of 384 datasets** for detailed evaluation. This sample size, selected according to the guidance in [10], balances methodological robustness with practical constraints. The processing can be conducted programmatically within a reasonable time frame using both selected tools (FAIR-Checker and F-UJI).

3.2 FAIR assessment

The FAIR maturity of the data was evaluated using a two-tool automated workflow combining F-UJI and FAIR-Checker via DOIs. The execution of both tools was conducted programmatically via their APIs, thereby facilitating scalable, consistent, and reproducible assessment across the complete sample **of 384** datasets.

Table 1. *Comparison of the evaluated metrics in FAIR-Checker and F-UJI.*

FAIR	Metric	FAIR-Checker [11, 12]	F-UJI [5]
Findable	(Meta)data are assigned a globally unique identifier.	✓	✓
	(Meta)data are assigned a persistent identifier.	✓	✓
	Data are described with structured metadata.	✓	
	Data are described with metadata populated using shared vocabularies.	✓	
	Metadata includes descriptive core elements to support data findability.		✓
	Metadata includes the identifier of the data it describes.		✓
	Metadata is offered in such a way that it can be registered or indexed by search engines.		✓
Accessible	Metadata are retrievable by their identifier using a standardized communication protocol.	✓	✓
	Metadata contains access level and access conditions of the data.	✓	✓
	(Meta)data are retrievable by their identifier.		✓
	(Meta)data are accessible through a standardized communication protocol which supports authentication.		✓
Interoperable	Metadata is represented using a formal knowledge representation language.	✓	✓
	Metadata uses registered semantic resources.		✓
	Metadata includes qualified references between the data and its related entities.	✓	✓
	(Meta)data use vocabularies that follow FAIR principles.	✓	
Reusable	(Meta)data are released with a clear and accessible data usage license.	✓	✓
	(Meta)data are associated with detailed provenance.	✓	✓
	(Meta)data meet domain-relevant community standards.	✓	✓
	Metadata specifies the content of the data.		✓
	Data is available in a file format recommended by the target research community.		✓

Each tool yielded quantitative scores encompassing all four FAIR principles. FAIR-Checker divides these principles into 12 unique metrics - four for findability, two for accessibility, three each for interoperability and reusability. F-UJI takes a different approach,

evaluating 17 metrics - five for findability, four for accessibility, three for interoperability, and five for reusability. See Table 1 for an overview of the evaluated metrics.

The scoring methods also differ for each tool. FAIR-Checker assigns a score of either 0, 1, or 2 for each metric. F-UJI, in contrast, reports aggregate scores per FAIR principle, with a maximum of 7 points each for fairness and accessibility and 6 points each for interoperability and reusability, as well as a total FAIR score of up to 26 points. Furthermore, F-UJI provides an overall FAIR maturity level based on the FAIRsFAIR metrics, reported as a score of 0, 1, 2, or 3. In all cases, a higher score indicates a higher level of FAIR compliance.

For each dataset, the outputs from both tools were collected and processed into a consolidated FAIR score profile. The per-metric scores from FAIR-Checker were averaged into per-principle scores and overall FAIR scores to match the output format of the F-UJI scores, and then rescaled to match the F-UJI score ranges; similar scaling was also carried out to match the FAIR-Checker results to the F-UJI maturity scores. This allowed for a direct comparison of the results from each tool.

4. Results

4.1 Quantitative FAIR scores

The evaluations from FAIR-Checker were compared to both the F-UJI scores, and to the F-UJI maturity levels. A comparison on the score basis is shown in Figure 1, and a comparison on the maturity level basis is shown in Figure 2.

The highest performance was generally observed in Findability and Accessibility across both tools, reflecting the widespread use of open repositories and the consistent use of standardized PID systems. Conversely, Interoperability demonstrated the poorest outcomes in both evaluations, primarily attributable to constrained utilization of machine-readable metadata schemas and controlled vocabularies.

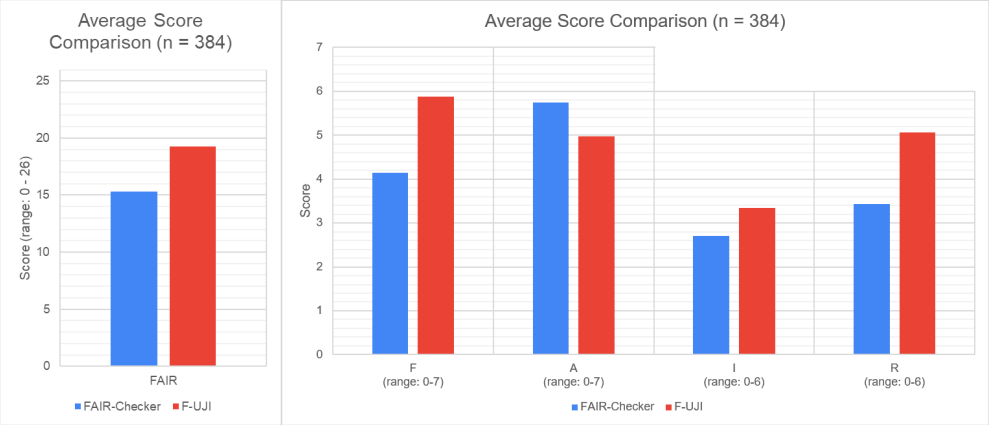

Figure 1. *Comparison of FAIR-Checker and F-UJI scores across all FAIR principles (left) and for each FAIR principle individually (right).*

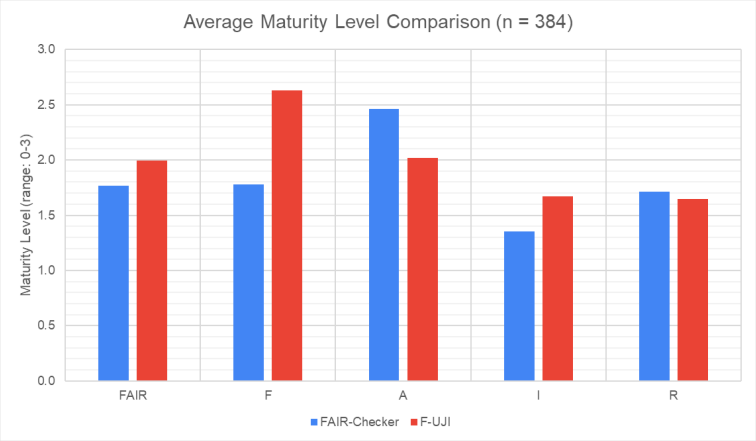

Figure 2. *Comparison of FAIR-Checker and F-UJI maturity levels for each dataset.*

In addition to score comparisons, the percentage change in average FAIR scores and the average FAIR maturity levels between F-UJI and FAIR-Checker were also considered (see Figure 3). Both comparisons showed a similar pattern of generally higher F-UJI results, with the exception of Accessibility (when comparing scores), and both Accessibility and Reusability (when comparing maturity levels). One hypothesis for this discrepancy is that F-UJI evaluates FAIRness at the dataset level using PID-linked repository metadata, which are often more complete. In contrast, FAIR-Checker performs stricter tests on landing-page metadata, which is less standardized and more error-prone. Consequently, FAIR-Checker exposes more granular metadata deficiencies, resulting in lower average scores.

While the Interoperability ratings of the datasets did not change whether looking at scores or at maturity levels (F-UJI ratings were 24% higher than FAIR-Checker ratings for both measures), the Reusability ratings changed drastically between the two measures - from a F-UJI score 48% higher than the FAIR-Checker score, to a F-UJI maturity level 4% lower than the FAIR-Checker maturity level.

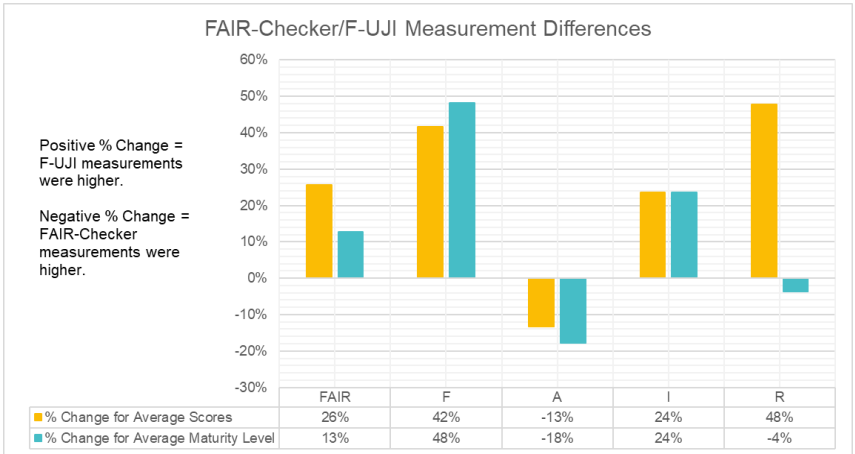

Figure 3. *Differences between FAIR-Checker and F-UJI measurements.*

4.2 Correlative analyses

The correlation between FAIR performance and **open access status, publication repository**, and **institutional affiliation** is important. These elements have a considerable impact on the curation, publication, and exposure of datasets. The OA status of a publication indicates the degree of editorial control, metadata completeness, and licensing clarity. The chosen repository for publication is similarly pertinent, given that certified repositories, domain-

specific platforms, and general-purpose repositories vary in their metadata policies, technical infrastructure, and persistent identifier support. These factors directly impact the FAIRness of a repository.

Open access (OA) status:

In the evaluated sample, only 9 of 384 datasets were classified as closed, while the vast majority fell under green OA. Green OA datasets accumulate the highest total FAIR maturity, reflecting their dominance in the dataset corpus. When considering mean FAIR scores, however, gold OA datasets performed best, with higher average FAIRness than both green OA and closed datasets, indicating that the metadata and licensing practices associated with gold OA tend to be more FAIR-aligned (see Figure 4 and Table 2). These differences are consistent with the more standardized workflows typical of gold OA publishing.

Green and gold OA differ in how openness is implemented. With green OA, research results (before peer review, or before final publication formatting) are often stored in (institutional or disciplinary) repositories, with metadata standards and licensing clarity varying depending on the repository. Gold OA, on the other hand, ensures immediate openness at the time of publication and usually requires standardized metadata, explicit licensing (e.g. CC-BY) and persistent identifiers as part of the publication workflow.

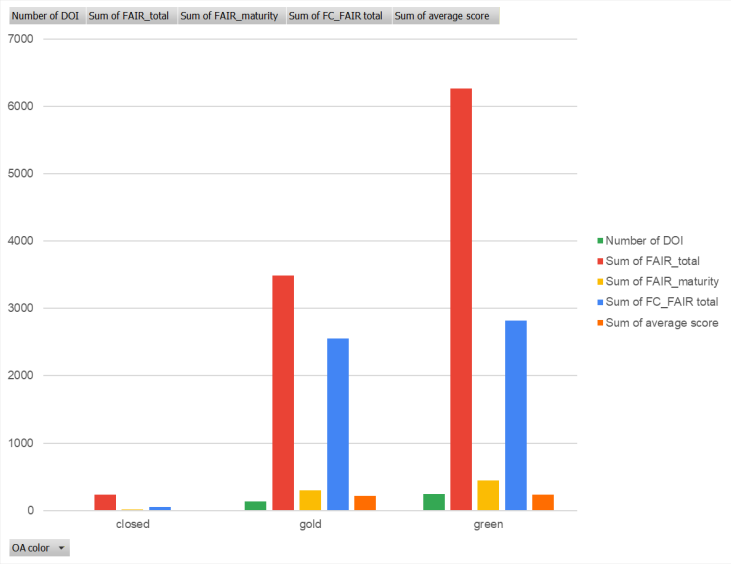

Figure 4. *The correlation between FAIR performance and open access status. Columns indicate the sums of the scores from all datasets with a particular OA status (closed, gold, or green) for each scoring system in F-UJI and FAIR-Checker.*

Table 2. *A comparison of FAIR performance based on open access status.*

OA Color	Number of Datasets	Sum of F-UJI scores	Maturity/Dataset	FAIR-Checker score/dataset
Closed	9	234	1.78	6.33
Gold	134	3484	2.26	19.09
Green	241	6266	1.86	11.70
Total	**384**	**9984**	**1.99**	**14.15**

Publication repository:

The analysis shows that **Straininfo**, which hosts the largest number of datasets, achieved the highest *total* FAIR maturity, although this reflects dataset volume rather than quality. **Zenodo datasets showed higher average FAIR maturity than Straininfo**, and **PANGAEA**

performed best overall, consistent with its domain-specific standards and strict metadata policies (see Table 3). Zenodo benefits from enforced DOIs, structured metadata templates and explicit licensing requirements, all of which support higher FAIR scores.

***Table 3**. A comparison of FAIR performance based on publication repository.*

Repositories	Number of Datasets	Summed Data			Maturity/ Dataset
		F-UJI score	F-UJI maturity	FAIR-Checker score	
(not specified)	195	5070	439.5	3673	2.25
Zenodo (CERN European Organization for Nuclear Research)	48	1248	94.5	928	1.97
Straininfo	89	2314	133.5	356	1.5
IUPAC Standards Online	8	208	12	72	1.5
Publishing Network for Geoscientific and Environmental Data (PANGAEA) (Alfred Wegener Institute for Polar and Marine Research)	3	78	9	66	3
OPAL (Open@LaTrobe) (La Trobe University)	3	78	6.5	66	2.17
Universitätsbibliothek Stuttgart	12	312	22	63	1.83
Göttingen Research Online	5	130	9.25	35	1.85
energyo	3	78	6.75	33	2.25
Universität Hamburg	1	26	2	22	2
PANGAEA	1	26	3	21	3

A substantial subset of the corpus - **195 datasets - lacked repository information altogether**. Because their repository affiliation is unknown, no meaningful interpretation of repository-driven FAIR performance can be drawn for this group. However, the size of this subset highlights an important gap: with over half of the sample lacking repository attribution, it is necessary to examine institutional affiliations in order to understand which organisations produced these datasets and how institutional practices may correlate with FAIRness.

Institutional benchmarking:

Table 4 summarizes the examination of which institutions published the most datasets and the FAIRest datasets. Of note, each of the sets of institutions listed together in this table is a co-authoring partnership; institutions were not evaluated across all co-authoring partnerships in which they may have appeared in the dataset sample.

Several trends can be observed in this data:

The number of datasets published by a given set of institutions does not indicate the FAIRness of the datasets. Among the 10 most prolific publishing institutions in this study, only half were in the top 10 average F-UJI scores. Many of the highest F-UJI scores came from institutions that only published one or two datasets in our sample.

A high average score obtained from one tool does not guarantee a high average score obtained from the other tool. We attribute this to the difference in FAIR criteria examined by each tool (see Table 1).

The structural changes to the OpenAlex database between the time periods of the first study [2] and this study led to a very different data corpus in the two studies. 6 of the most prolific publishing institutions in this study, and an additional 6 institutions among those with the highest average F-UJI scores, were not represented in [2].

Table 4. *A comparison of FAIR scores and publishing frequency for institutions in this 2nd study and in the 1st study [2]. The highlighted scores were among the highest scores observed from each tool.*

	Institution	Number of Datasets		Average FAIR Scores	
		1st Study	2nd Study	F-UJI	FAIR-Checker
Most Prolific Publishing Institutions in the 2nd Study	InfoConsult (Germany)	0	140	**23**	20.19
	Leibniz Institute DSMZ – German Collection of Microorganisms and Cell Cultures	0	89	13	4.33
	BG Consulting Engineers (Switzerland); GEF Ingenieur (Germany)	0	29	**23**	20.58
	GEF Ingenieur (Germany)	0	16	**23**	20.58
	University of Stuttgart	0	12	14.17	5.69
	Bielefeld University; Macquarie University	10	4	**23.75**	**23.83**
	RWTH Aachen University	4	4	17.5	12.46
	Max Planck Society; Karlsruhe University of Education; and 8 other international institutions	11	3	11	9.75
	Centre for European Economic Research	9	3	13	2.17
	Forschungszentrum Jülich; Queen Mary University of London	4	3	20	19.5
	Institut für Bauwerkserhaltung und Sanierung (Germany)	0	3	**23**	20.58
	Karlsruhe Institute of Technology; Southern Illinois University Carbondale	6	3	11	9.75
Most Prolific Publishing Institutions in the 1st Study (not among the most prolific in the 2nd study)	Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR)	6	2	22	**23.83**
	Brandenburg University of Applied Sciences	6	2	21	22.75
	Friedrich Schiller University Jena; Leibniz Institute of Photonic Technology	5	1	20	**23.83**
	Zuse Institute Berlin	3	0	n/a	n/a
	University of Giessen; Technische Universität Berlin	3	0	n/a	n/a
Publishing Institutions with the Highest F-UJI Scores (not among the most prolific in the 2nd study)	Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung	4	1	**25**	**23.83**
	GEOMAR Helmholtz Centre for Ocean Research Kiel; Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung	0	1	**25**	**23.83**
	RWTH Aachen University; University of Bremen; University of Bonn; GEOMAR Helmholtz Centre for Ocean Research Kiel; and 30 other international institutions	0	1	**25**	**23.83**
	Dialog Semiconductor (Germany)	0	1	**23**	20.58
	GEF Ingenieur (Germany); University of Aruba	0	1	**23**	20.58
	Leipzig University	0	2	**23**	23.29
	RWTH Aachen University; Max Planck Institute for Chemical Energy Conversion	2	2	**23**	13
	University of Göttingen; Heidelberg University; Leibniz University Hannover	0	1	**23**	20.58

5. Discussion, Contributions, and Concluding Remarks

The analysis of FAIR indicators across energy research datasets suggests several discussion points. The strong performance in Findability and Accessibility within the data reflects the benefits of long-standing repository infrastructures, PIDs, and repository-level metadata services. In particular, higher F-UJI scores for datasets with PID-linked, repository-managed metadata highlight how centralised, consistently maintained metadata layers can substantially improve FAIRness. Conversely, low FAIR-Checker scores point to uneven metadata quality, which does not necessarily imply problematic decentralisation of repositories, but rather indicates insufficient standardisation and quality control during publication. Domain-specific repositories and metadata schemes tend to score better toward FAIR principles. Here, NFDI4Energy supports energy researchers in providing collections of metadata frameworks and repository services through, e.g., the Leibniz Data Manager [13].

The comparatively weak Interoperability results show a continuing gap in the adoption of machine-readable metadata schemas, controlled vocabularies, and domain standards. This points to a need for clearer guidance, researcher training, and systematic monitoring of

metadata completeness and correctness within repositories. In this light, integrating FAIR requirements directly into publication workflows—rather than expecting researchers to add them as an afterthought—appears particularly effective. This implies the important role of data stewards, and an automation of the necessary data management processes that would be beneficial.

We argue that Gold Open Access is generally more advisable for FAIR data sharing, provided that the authors follow proper data deposition and documentation practices. The OA model removes access restrictions and encourages open licensing, both of which strongly support FAIRness, but the FAIRness of data ultimately depends on the repository, metadata, and technical standards used.

The dataset relies on OpenAlex (Walden version), which was recently relaunched and has received reports of data quality issues that may affect the underlying dataset integrity. However, OpenAlex's data quality ultimately depends on upstream sources, and continuous curation in future releases may improve reliability. Although F-UJI and FAIR-Checker provide automated FAIR assessments, further development is required to enhance transparency, usability, and scalability, especially when evaluating large datasets. The implementation of more streamlined, standardised workflows has the potential to reduce time requirements and facilitate integration into routine research data management practices. The combined use of F-UJI and FAIR-Checker allowed a nuanced understanding of both formal FAIR maturity and metadata quality, providing a solid basis for future monitoring and continued FAIR adoption efforts to support transparent, reproducible, and integrative energy systems research.

This study provides a comprehensive, data-driven assessment of FAIR adoption in energy research. While progress is evident, particularly in findability and accessibility, significant opportunities remain to enhance interoperability and reusability through improved metadata practices, standardized schemas, and consistent institutional policies.

Data availability statement

Data generated or analyzed within this study are partially included in this submission as Tables and Figures. The entire data corpus and the sample corpus are published separately and can be accessed at https://doi.org/10.5281/zenodo.17910342.

Author contributions

Linna Lu contributed in conceptualization, methodology, and writing – original draft.

Amanda Wein contributed in conceptualization, methodology, and writing - editing.

Oliver Werth contributed in writing – original draft, and writing - review & editing.

Competing interests

The authors declare no competing interests.

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