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Prospective Research Trend Analysis on Zero-Energy Building (ZEB): An Artificial Intelligence Approach

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Abstract: While global attention to zero-energy building (ZEB) has surged as a sustainable countermeasure to high-energy consumption, a congruent expansion in research remains conspicuously absent. Addressing this lacuna, our study harnesses public research and development grant data to decipher evolving trajectories within ZEB research. Distinctively departing from conventional methodologies, we employ state-of-the-art natural language processing (NLP) artificial intelligence models to meticulously analyze grant textual content pertinent to ZEB. Our findings illuminate an expansive spectrum of ZEB-related research, with a pronounced focus on the holistic continuum of energy supply, demand, distribution, and actualization within architectural confines. Theoretically, this work delineates key avenues ripe for future empirical exploration, fostering a robust academic foundation for subsequent ZEB inquiries. Practically, the insights derived bear significant implications for practitioners, informing optimal implementation strategies, and offering policymakers coherent roadmaps for sustainable urban development. Collectively, this study affords a panoramic perspective on contemporary ZEB research contours, enhancing both scholarly comprehension and practical enactment in this pivotal domain.

Keywords: zero-energy building (ZEB); natural language process (NLP); research and development (R&D) grant data; research trend; artificial intelligence (AI)

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Citation: Jin, B.; Bae, Y. Prospective Research Trend Analysis on Zero-Energy Building (ZEB): An Artificial Intelligence Approach. *Sustainability* **2023**, *15*, 13577. https://doi.org/10.3390/su151813577

Academic Editor: Christian N. Madu

Received: 25 July 2023
Revised: 4 September 2023
Accepted: 9 September 2023
Published: 11 September 2023

1. Introduction

As global efforts to address climate change and pursue sustainable development intensify, zero-energy building (ZEB) is increasingly considered a viable solution for reducing carbon dioxide (CO_2) emissions and minimizing energy consumption within the building, construction, and architecture sector [1,2]. In many developed countries, the building sector accounts for 30% to 40% of total energy consumption and a sizable proportion of greenhouse gas emissions [3–10]. Consequently, ZEB has become a promising alternative many countries have actively pursued through technology and policy initiatives to improve building energy efficiency [1,11]. Similarly, the building sector accounts for over a quarter of Korea's total energy consumption. Recognizing the need to address climate change, reduce energy demand, and decrease greenhouse gas emissions, the Korean government has prioritized promoting ZEB to foster new industries and technological advancements [12,13].

In conceptual terms, ZEB refers to a building that significantly enhances energy efficiency by incorporating renewable energy sources and minimizing energy losses [6]. In practice, however, ZEB is a complex concept with definitions that vary depending on the emphasis on specific aspects of building management technology. Moreover, the notion of a zero-energy state and how to measure the energy balance of a building remain ambiguous, with no clear consensus [1,11,14,15]. Consequently, a comprehensive understanding of the technical elements and research related to ZEB is still needed [14].

However, this does not imply a lack of research aimed at clarifying the definition of ZEB and calculating and evaluating various related parameters. For instance, Marszal et al. [1] reviewed multiple research papers on ZEB, presented definitions of ZEB and energy calculation methodologies, and elaborated on ZEB-related parameters. Marique and Reiter [15] proposed a framework for exploring the feasibility of ZEB at the neighborhood/community scale from a more realistic perspective. Moreover, Wells et al. [16] introduced the concept of ZEB in the context of Australia, reviewed existing ZEB models, and identified potential avenues for ZEB research through case studies and a literature review.

The mentioned studies provide a comprehensive overview of the research trends related to ZEB and offer insight for future research through a qualitative approach. However, scientometric analysis is also advantageous as a quantitative tool to identify the entire knowledge structure of research on ZEB. The science mapping method, a technique for visualizing bibliographic data, can validate trends and changes in research diachronically and synchronically and provide information on core research topics, researchers, research institutes, and cooperative networks more easily for collaborative research on specific topics [17–21]. Numerous studies have recently used scientometric analysis in architecture and construction (e.g., [22–25]).

Tashiro et al. [14] conducted a study that employed a scientometric approach to ZEB. In this study, scientometric analysis was conducted to analyze the knowledge structure of net-zero-energy building (NZEB). However, the query set to collect paper data included keywords related to indirect component technology comprising NZEB and technology related to NZEB. Thus, the study adopted a scientific approach to the technology related to NZEB in a wider area targeting numerous articles rather than specifically analyzing research on NZEB. Moreover, in the broader category, most studies have primarily been conducted on green building or building information modeling [26–29].

Recent studies have also used bibliometric or scientometric methods to analyze the trend of research on ZEB by collecting and analyzing scientific articles [30–35]. Through bibliometric analysis, Wang et al. [30] and Agbodjan et al. [31] identified influential organizations, leading experts, major research directions, collaboration networks, thematic trends, and challenges of nearly ZEB and ZEB, respectively. Similarly, Omrany et al. [34] used bibliometric analysis techniques to provide a comprehensive overview of three decades of research developments in NZEB, identifying influential researchers, sources, countries, and the main thematic research focus areas and hot topics in the field. Furthermore, Wei et al. [35] created knowledge maps of authors, institutions, and keywords in ZEB research using CiteSpace software(5.8.R3 SE 64-bit). The study found that research on ZEB has significantly advanced since 2000, with most papers published in the areas of energy fuels, construction building technology, civil engineering, and green sustainable science technology. The results revealed that the field has consolidated around three major themes and is expanding with emerging themes, providing valuable information for researchers interested in ZEB.

One attribute of scientific studies related to ZEB is that they typically only analyze data from published papers. However, according to Rotolo et al. [30], scientometrics for scientific papers is a retrospective analysis, which means a time lag exists between the observation (collection) of the data and when the technology is implemented. Therefore, this type of analysis is best suited for researching a particular technology's past and present status, growth, and novelty. Different datasets are required to validate the future orientation or potential of emerging technology. Funding and research and development (R&D) grant-related data have been identified as promising sources to supplement the retrospective perspective of scientometric analysis [30].

This study aims to conduct a comprehensive trend analysis of ZEB research using R&D grant data invested in R&D projects in major countries rather than scientific publication data. The aim is to observe technological opportunities for future-oriented directions of ZEB-related R&D, summarize the latest status of global ZEB R&D, identify the knowledge structure, and seek future research directions. Specifically, this study adopted a methodology of analyzing R&D grant document data and extracting topics through natural language processing (NLP) based on artificial intelligence (AI) models instead of the traditional methodology of bibliometrics or scientometrics. The decision to employ AI-driven NLP techniques in lieu of conventional scientometric analysis stems from several considerations. Firstly, a plethora of studies have already employed scientometric or bibliometric methodologies to probe into ZEB-related research and development trends [29–31]. Adopting a similar approach would, thus, dilute the novelty of this investigation. Secondly, recent advancements in NLP, particularly methodologies harnessing architectures like BERT and Transformer, have demonstrated remarkable efficacy. Consequently, this study posits that leveraging these cutting-edge AI methodologies for analyzing ZEB-related R&D trends can yield more granular and empirically robust insights.

The research questions accordingly are as follows:

(1) How does the trend analysis of ZEB research using R&D grant data differ from those derived from scientific publication data?
(2) What technological opportunities can be observed for the future-oriented directions of ZEB-related R&D using grant data from major countries?
(3) What is the current status of global ZEB R&D based on the analysis of R&D grant data?
(4) How does the knowledge structure of ZEB research manifest when evaluated through R&D grant data?
(5) Which future research directions emerge when R&D grant data for ZEB is analyzed through NLP based on AI models?

From these research questions, the research objectives presented in this paper are as follows:

(1) To conduct a comprehensive trend analysis of ZEB research using R&D grant data from major countries.
(2) To contrast the insights derived from R&D grant data with those typically obtained from scientific publication data.
(3) To pinpoint technological opportunities that elucidate future-oriented directions in ZEB-related R&D.
(4) To encapsulate the present status of global ZEB R&D by examining invested grant data.
(5) To identify and map out the knowledge structure within the ZEB research domain.
(6) To leverage an innovative methodology employing NLP based on AI models for analyzing R&D grant document data, moving away from conventional bibliometric or scientometric methods.

2. Materials and Methods

2.1. Data Collection and Preprocessing

This section outlines the steps for obtaining R&D grant datasets related to ZEB. The task involved creating a query set that includes the concepts of ZEB and NZEB. The R&D grant data related to ZEB were restricted to projects from 2000 to 2022. Data collection post-2000 was strategically chosen to discern shifts in R&D trends encompassing early ZEB-related research up to contemporary advancements. This decision was made in light of the fact that the Kyoto Protocol, an important international treaty aimed at mitigating global warming, was adopted in 1997.

The database used to collect ZEB-related R&D grant data is Dimensions.ai, an integrated research information system provided by Digital Science (https://www.dimensions.ai, accessed on 24 July 2023). This system was chosen due to its ability to organize and provide considerable global R&D grant data systematically. The research category feature offered by Dimensions.ai was used to narrow down data collection to research fields relevant to ZEB to reduce noise in the collected data. During the data collection process, the Australian and New Zealand Standard Research Classification 2020 (ANZSRC 2020) was used to limit research areas based on research field codes. The ANZSRC 2020 is a commonly used statistical classification system for measuring and analyzing R&D activities in Australia and New Zealand. The query set and parameters presented below were used to extract only ZEB-related data from the R&D grant data provided by Dimensions.ai. The asterisk indicates a fuzzy search. A total of 3456 documents were retrieved.

- The data date range was 2000 to 2022.
- Only documents of the grant type were used.
- Research fields (ANZSRC 2020) included engineering (40), built environment and design (33), building (3302), architecture (3301), civil engineering (4004), and environmental sciences (41).
- Duplicated data were removed based on the Grant ID.
- The query set is as follows:
- ((net OR nearly) AND (zero) AND (energy OR carbon OR emission) AND (build* OR hous* OR construction OR home*)) OR ((zero) AND (energy OR carbon OR emission) AND (build* OR hous* OR construction OR home*)) OR ((energy) AND (plus OR ultralow OR ultra-low) AND (build* OR hous* OR construction OR home*)).

Figure 1 displays the number of R&D grants associated with ZEB from 2000 to 2022. As illustrated in Figure 1, grants related to ZEB have exhibited an overall increasing trend throughout the period. Notably, R&D grants related to ZEB demonstrated a substantial surge from 2019 to 2020.

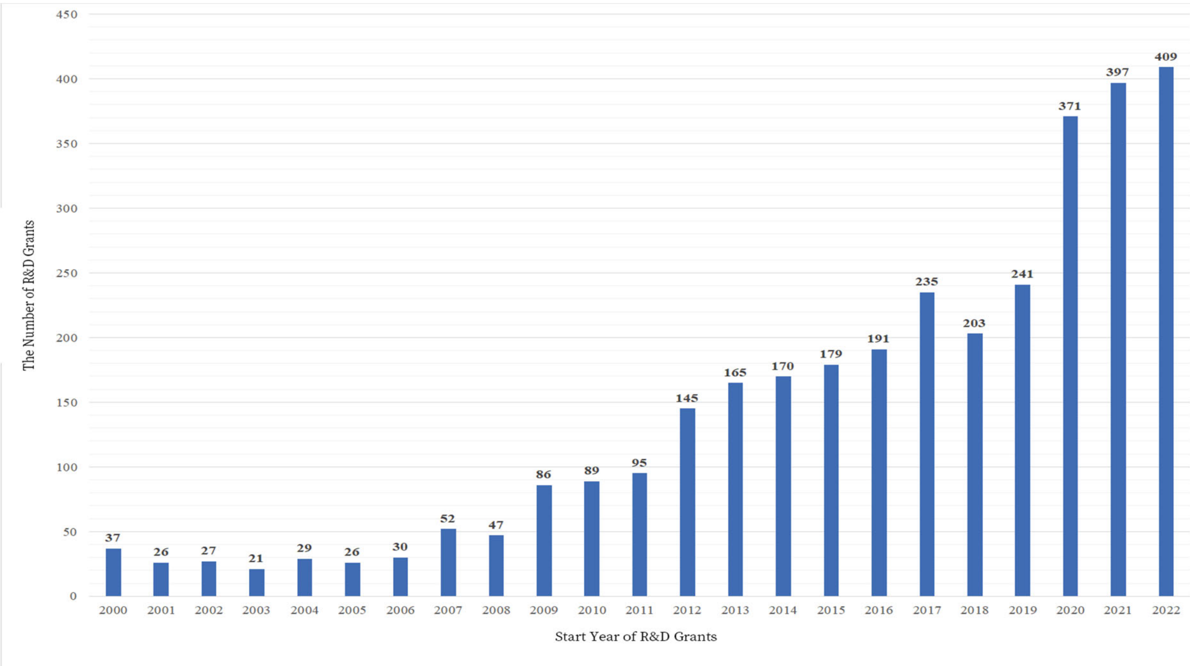

Figure 1. Trend in the number of research and development (R&D) grants by start year, 2000–2022.

2.2. Data Analysis

Many studies previously conducted employed scientometrics to identify the domain of scientific knowledge using quantitative analysis methodologies, such as coauthorship, cocitation, keyword co-occurrence, and cluster analysis, facilitating the exploration of hidden implications and the identification of innovative research areas [35–38]. However, to identify more practical research fields and content related to ZEB, this study employs an AI-based clustering analysis after conducting NLP on the unstructured ZEB-related R&D grant data, specifically the titles and abstracts.

2.2.1. Document Embedding

The initial step in analyzing R&D grants related to ZEB is converting each document into numerical data, called embedding in NLP. In recent years, pretrained language models have become commonplace in the embedding process, and this study employs the widely used bidirectional encoder representations from transformers (BERT) model [39]. As BERT produces distinct embeddings based on word context, it is a suitable embedding method for comprehending ZEB-related research content. Moreover, many pretrained models are available as open sources, making them readily accessible for analysis. Numerous techniques can generate BERT embeddings with text data. This study employs Python and the sentence-transformers package to generate BERT embeddings for ZEB-related R&D grant documents. The sentence-transformers package is acknowledged for producing high-quality document-level embeddings [40,41], making it a suitable tool for this research. This study converts the documents into 512-dimensional numerical data via the BERT embedding.

2.2.2. Dimension Reduction and Document Clustering

A clustering analysis process is necessary to group documents sharing similar topics into clusters. However, numerous clustering algorithms struggle to manage high dimensions effectively, making it imperative to reduce the dimension of embedding beforehand.

Of the various dimensionality reduction algorithms available, uniform manifold approximation and projection (UMAP) [42] is recognized for its efficacy in preserving a significant proportion of high-dimensional local structures in low dimensionality. This study employs the UMAP algorithm for dimensionality reduction by installing the umap-learn package from Python. Through the UMAP algorithm, we reduced the dimension size to five while maintaining the local neighborhood size at 15. If the dimension is excessively low, pertinent information may be lost, whereas if the dimension is overly high, the clustering result may be suboptimal. Thus, we adopted the parameters suggested by the umap-learn package.

After reducing the document embedding dimension to five, we used the hierarchical density-based spatial clustering of applications with the noise (HDBSCAN) algorithm to cluster documents [43,44]. The HDBSCAN is a density-based clustering algorithm that synergizes well with UMAP because UMAP significantly preserves local structures, even in a low-dimensional space [45]. Moreover, HDBSCAN is advantageous because it does not compel data points to belong to clusters, as it considers some data points to be outliers [46]. We installed the hdbscan package of Python to employ this algorithm, as with the previous algorithms.

This process allows similar documents to be grouped to form clusters. Furthermore, reducing the dimension size to two enables the visualization of the cluster analysis result on a two-dimensional plane, while unclustered outliers can be visualized separately. In cases where the number of analyzed clusters is large, the clusters may not be accurately represented on a plane. Nonetheless, reducing the dimensionality to two can still reveal local structures in most cases.

2.2.3. Topic Modeling

This study applied the BERTopic algorithm to identify topics within clusters. The BERTopic technique extracts topics from text embeddings using a language model, such as BERT [47]. The process was implemented by installing the BERTopic package in Python, which is modular and uses a series of steps to create a topic model.

Steps 1 to 3 are identical to the document clustering process described earlier, except that, in topic modeling, the process is performed within the clusters generated in the previous step. In Step 4, to generate topics without assuming any expected structure of the clusters, BERTopic employs a bag-of-words approach by counting the frequency of each word in each cluster. After generating the word frequency representations in Step 4, Step 5 uses class-based term frequency–inverse document frequency (c-TF-IDF) to determine how one cluster differs from another. For instance, it calculates the importance of words within clusters and identifies which words are common in Cluster 1 but not in other clusters. The following equation can be used to calculate c-TF-IDF:

$$\begin{gathered} For\ a\ term\ x\ within\ class\ c \\ W_{x,\,c} = \|tf_{x,\,c}\| \times log\left(1 + \frac{A}{f_x}\right) \\ tf_{x,\,c} = frequency\ of\ word\ x\ in\ class\ c \\ f_x = freqeuncy\ of\ word\ x\ across\ all\ classes \\ A = average\ number\ of\ words\ per\ class \end{gathered} \tag{1}$$

The process of collecting and analyzing ZEB-related R&D grant data in this study is illustrated in Figure 2.

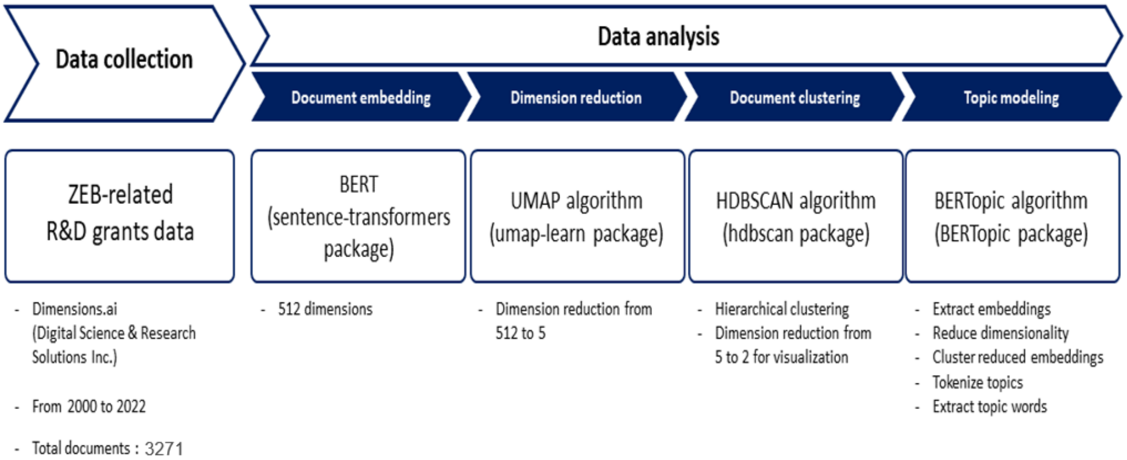

Figure 2. Artificial intelligence-based process of collecting and analyzing related research and development grant data related to zero-energy building.

3. Results

3.1. Descriptive Analysis

This section presents the results of a descriptive statistical analysis of the R&D grant data related to ZEB collected from Dimensions.ai. Between 2000 and 2022, the United Kingdom (UK) funded the most ZEB-related R&D grants, with 719 grants being funded, followed by the United States (US), Canada, Belgium, and China funding 714, 474, 384, and 265 grants, respectively. Most of the grants funded in Belgium account for numerous projects funded by the European Commission (EC) because Belgium is the seat of the EC (Table 1).

Table 1. Top 10 funder countries for research and development (R&D) grants related to zero-energy building.

Funder Country	The Number of Funded R&D Grants
United Kingdom	719
United States	714
Canada	474
Belgium [1]	384
China	265
Japan	132
Germany	118
Norway	103
Switzerland	98
Sweden	82

[1] Belgium is the seat of the European Commission (EC) and includes R&D grants funded by the EC.

In terms of funding institutions, the Natural Sciences and Engineering Research Council in Canada provided the most funding with 431 cases, followed by Innovate UK in the UK with 413 cases, the EC in Belgium with 312 cases, the Engineering and Physical

Sciences Research Council in the UK with 225 cases, and the National Natural Science Foundation of China in China with 194 cases (Table 2).

Table 2. Top 10 funder and funder countries for research and development (R&D) grants related to zero-energy building.

Funder (Funding Institution)	Funder Country	The Number of Funded R&D Grants
Natural Sciences and Engineering Research Council	Canada	431
Innovate UK	United Kingdom	413
European Commission	Belgium	312
Engineering and Physical Sciences Research Council	United Kingdom	225
National Natural Science Foundation of China	China	194
Directorate for Engineering	United States	124
Japan Society for the Promotion of Science	Japan	117
The Research Council of Norway	Norway	103
Federal Ministry for Economic Affairs and Climate Action	Germany	87
University Grants Committee	China	64

Table 3 summarizes the average funding for ZEB-related R&D grants during the study period. The investment amounts were converted into US dollars from each country's respective currency. However, the average funding in Belgium includes grants funded by the EC; thus, it is not a good representation of the funding in Belgium alone. Japan is the top country for funding, followed by Belgium, New Zealand, the UK, and Czechia regarding the average investment for ZEB-related R&D grants. Although New Zealand and Czechia did not rank high in the number of R&D grants, the funding per grant is high given their high average investments.

Table 3. Top 10 funder countries and average funding amount in US dollars for research and development (R&D) grants related to zero-energy building.

Funder Country	The Number of Funded R&D Grants	Average Funding Amounts in USD
Japan	132	22,897,770.76
Belgium [1]	384	3,387,815.35
New Zealand	14	2,182,718.21
Czechia	15	1,566,085.13
Norway	103	1,274,418.77
United Kingdom	719	1,256,160.29
United States	714	884,310.61
Sweden	82	699,569.26
France	15	690,734.27
Australia	23	542,017.91

[1] Belgium is the seat of the European Commission (EC) and includes R&D grants funded by the EC.

3.2. Document Clustering Results

Following the data analysis method, we embedded the text using BERT with the title and abstract of the R&D grants related to ZEB, reduced the dimensionality using the UMAP algorithm, and performed clustering using the HDBSCAN algorithm. Consequently, the documents were grouped into 25 clusters.

Figure 3 presents the results of the document embedding and clustering, reduced to two dimensions. The shaded areas correspond to outliers that did not form clusters. After dimensionality reduction from 512 to five dimensions using the UMAP algorithm, it was possible to identify the clustered structure of similar documents, even when the dimension size was reduced to two for visualization. The size of each cluster is listed in Table 4.

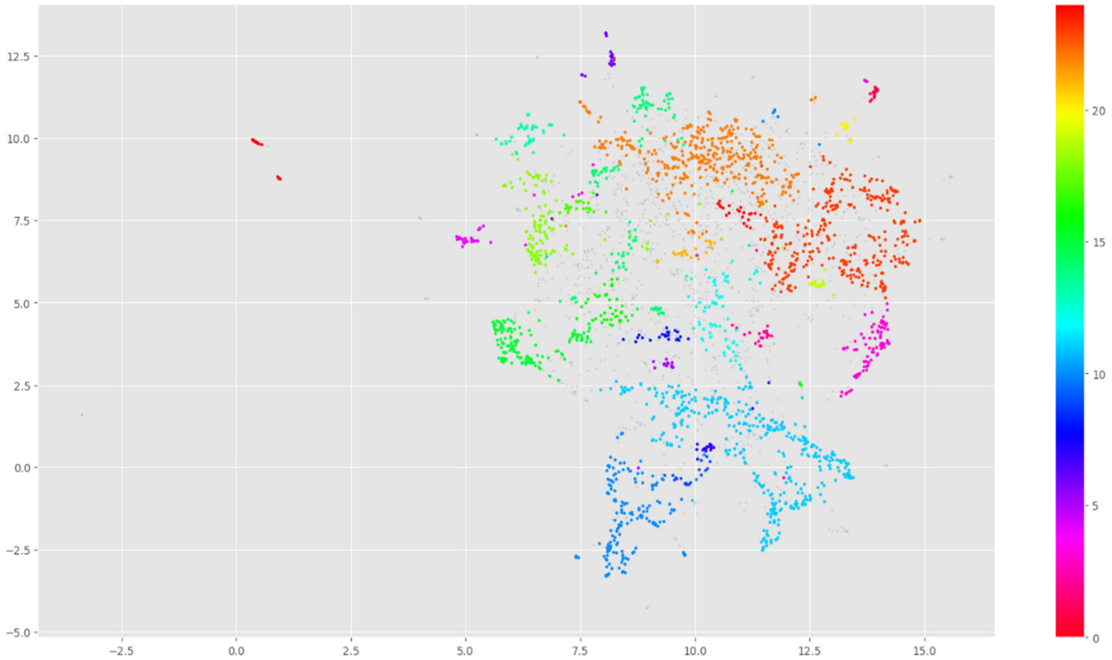

Figure 3. Results of document embedding and clustering for research and development (R&D) grants related to zero-energy building.

Table 4. Sizes of 25 clusters from documents on research and development (R&D) grants related to zero-energy building.

Cluster No.	Cluster Size
Cluster 0	55
Cluster 1	32
Cluster 2	42
Cluster 3	108
Cluster 4	59
Cluster 5	33
Cluster 6	54
Cluster 7	72
Cluster 8	45
Cluster 9	49
Cluster 10	220
Cluster 11	402
Cluster 12	117
Cluster 13	77
Cluster 14	154
Cluster 15	144
Cluster 16	92
Cluster 17	75
Cluster 18	121
Cluster 19	54
Cluster 20	94
Cluster 21	63
Cluster 22	452
Cluster 23	335
Cluster 24	58
Outliers [1]	449
Total	3456

[1] Outliers (documents that do not belong to any clusters) are marked as gray points in Figure 3.

3.3. Results of Topic Modeling and Content Analysis by Clusters

As mentioned, topic modeling was performed for each cluster using the BERTopic algorithm. The number of topic groups extracted per cluster varied depending on cluster size. Figure 4 presents the results of topic modeling for the 25 clusters.

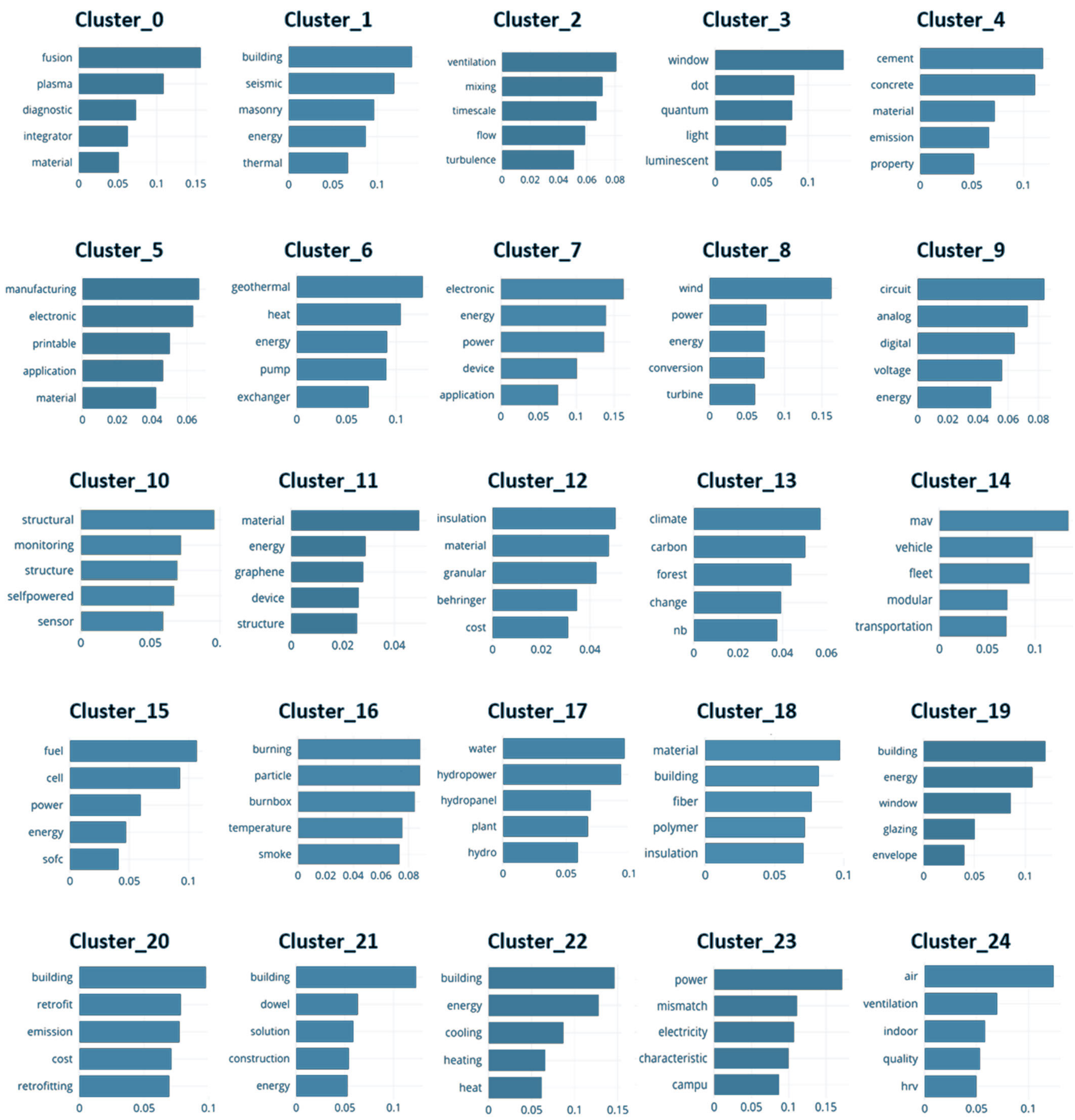

Figure 4. Results of topic modeling by clusters.

The topics by cluster are the representative research content on ZEB-related R&D gathered in each cluster. This study examined the actual R&D grant content for each cluster by identifying the research content centered on the cluster topic. The results of identifying the research content for each cluster are presented in Table 5.

Table 5. Topics in 25 clusters and titles of major research and development (R&D) grants related to zero-energy building (ZEB).

Cluster No.	Topics (c-TF-IDF Scores)	Major R&D Grant by Topic (Funder Country)
Cluster 0	Fusion (0.1565398) Plasma (0.1089145) Diagnostic (0.0736025) Integrator (0.0631729) Material (0.0517642)	Development of PEMD for nuclear coolant systems (UK) Autonomous inspection for responsive and sustainable nuclear fuel manufacture (UK) SMNR Feasibility study—SAGD integration (Canada) Technology enabling zero-EPZ micro modular reactors (US)
Cluster 1	Building (0.1396762) Seismic (0.1193911) Masonry (0.096826) Energy (0.0874309) Thermal (0.0671886)	Development of the technology of multivibrator applications when carrying out high-resolution seismic surveys (Japan) Seismic plus energy upgrading of masonry buildings using advanced materials (EC) NEESR-II large-scale testing and micromechanical simulation of ultralow-cycle fatigue cracking in steel structures (US) Temperature and aging performance of high-damping elastomers for seismic isolation systems (Canada)
Cluster 2	Pollutant (0.0806424) Plume (0.0699436) Concentration (0.0621666) Flow (0.0580113) Dispersion (0.0559499)	Turbulent flows over rough walls under the influence of streamwise pressure gradients (UK) Improvement of ultrahigh lift low-pressure turbine blade aerodynamic performance based on evolutional optimization technique (Japan) EAGER: A non-Boussinesq, non-incompressible framework for studying atmospheric turbulence (US)
Cluster 3	Window (0.1385299) Dot (0.0852777) Quantum (0.0831671) Light (0.0763731) Luminescent (0.0715409)	Concentrated solar energy storage at ultra-high temperatures and solid-state conversion (UK) Energy harvesting in cities with transparent and highly efficient window-integrated multijunction solar cells (EC) Sustainable materials and manufacturing processes for the development of high efficiency, flexible, all-Perovskite tandem photovoltaic modules with a low CO_2 footprint (EC)
Cluster 4	Cement (0.1190123) Concrete (0.1112628) Material (0.072386) Emission (0.0669034) Property (0.0523967)	Engineered UK clays for production of low-carbon cements (UK) Zero-carbon emission concrete (Norway) Toward net-zero infrastructure: Fixing clay with clay (Sweden) Cement-polymer composites from recycled polymers for construction (US)
Cluster 5	Manufacturing (0.0670892) Electronic (0.0636349) Printable (0.0502373) Application (0.0464119) Material (0.0424274)	INSPIRE—Integrated sustainable production through innovative resource efficiency (UK) Ultralow-cost printed flexible sensors for disruptive IoT applications (Canada) Transition lab-scale production of energy storage devices (US) ULTRA: Ultra-powerful cells for low-emission transport) (UK)
Cluster 6	Geothermal (0.1267701) Heat (0.1046461) Energy (0.0909472) Pump (0.0900915) Exchanger (0.0722848)	High-performance ultralow-carbon geopolymer heat battery for thermochemical energy storage in net-zero buildings (UK) Net-zero geothermal research for district infrastructure engineering (NetZero GeoRDIE) (UK) Thermal energy storage for dispatchable geothermal power (US) Advanced design of geothermal heat pump systems (Canada)
Cluster 7	Electronic (0.1634691) Energy (0.1401309) Power (0.137559) Device (0.1015647) Application (0.076598)	TESiC-SuperJ—Trench epitaxy for SiC superjunctions: technology enabling low loss HVDC power electronics (UK) Basic research in wireless inductive power transfer (China) CAREER: SiC high-frequency high-voltage power converters with partial-discharge mitigation and electromagnetic noise containment (US)
Cluster 8	Wind (0.1632284) Power (0.0759507) Energy (0.0739987) Conversion (0.0734308) Turbine (0.060988)	R&D to develop spray applications using a bespoke drone to improve the operating efficacy of wind turbine technology (UK) Bionics research on the conversion mechanism of scorpion wind power for key problems of ultralow wind-speed wind power generation (China) Electromechanical conversion for wind turbines (Canada)

Table 5. *Cont.*

Cluster No.	Topics (c-TF-IDF Scores)	Major R&D Grant by Topic (Funder Country)
Cluster 9	Circuit (0.0840519) Analog (0.0730431) Digital (0.0643271) Voltage (0.0560369) Energy (0.0488632)	Efficient design of ultralow power near-threshold digital processors (EC) Exploring memory and digital circuit boundaries for energy efficient hardware (Canada) Ultralow voltage SRAM architecture-assisted circuitry and logic in memory (Sweden)
Cluster_10	Structural (0.0962864) Monitoring (0.0723541) Structure (0.0697302) Self-powered (0.0674579) Sensor (0.0595926)	Wireless devices for smart energy management systems (EC) NSF-BSF: CNS Core: Small: Reliable and zero-power timekeepers for intermittently powered computing devices via stochastic magnetic tunnel junctions (US) Zero-power wireless sensor network for smart homes (Canada)
Cluster_11	Material (0.0497104) Energy (0.0289135) Graphene (0.0280487) Device (0.0262782) Structure (0.025639)	Development of carbon nanotube-embedded zeolite 13X/$CaCl_2$ composite adsorbents for waste heat-powered adsorption cooling systems (China) A novel instrument for probing near-field radiation and thermophotovoltaic energy conversion in nanostructured and low bandgap materials (US)
Cluster_12	Insulation (0.0505853) Material (0.0479001) Granular (0.0427646) Behringer (0.0347874) Cost (0.0311208)	Highly efficient production of ultra-lightweight clay-aerogel materials and their integrated composites for building insulation (EC) VOC-free, highly flame-resistant hybridsil insulation coatings for next-generation thermal insulation and energy efficiency (US) Nanofiber aerogels—From a fundamental understanding of structure towards transparent flexible insulation and functional hybrids (Switzerland)
Cluster_13	Climate (0.057328) Carbon (0.0504949) Forest (0.0442087) Change (0.0395824) Nb (0.0377946)	Greenhouse gas removal plus (GGR+): sustainable treescapes demonstrator and decision tools (UK) GCRF building capacity for sustainable interactions with marine ecosystems for health, wellbeing, food, and livelihoods of coastal communities (UK)
Cluster_14	Mav (0.1349486) Vehicle (0.0975806) Fleet (0.0942344) Modular (0.0713583) Transportation (0.0703829)	iFuelActive—Smart diesel fuel solutions for the low carbon transition (UK) Development of a new forest monorail using potential energy (Japan) Zero emission hauler (Sweden) Havyard—Zero-emission ROPAX vessel (Norway)
Cluster_15	Fuel (0.1070516) Cell (0.0928153) Power (0.0597689) Energy (0.0475239) Sofc (0.0410947)	Development of a retrofittable dry low-emissions industrial gas turbine combustion system for 100% hydrogen and natural gas blends (US) Collaboration to develop manufacturing methods of electric microreactors for clean hydrogen production (Canada) Safe, low-cost hydrogen storage materials from NZ resources (New Zealand)
Cluster_16	Burning (0.0886949) Particle (0.0886949) Burnbox (0.0847175) Temperature (0.0757506) Smoke (0.0736884)	Zero-emission supercritical carbon dioxide oxy-combustor development and testing (US) SCC-CIVIC-PG Track A: Novel fuel-flexible combustion to enable ultra-clean and efficient waste-to-renewable energy in changing climate (US) Full-field laser vibrometry for combustion diagnostics (Austria)
Cluster_17	Water (0.0964855) Hydropower (0.0935625) Hydropanel (0.0696353) Plant (0.0674266) Hydro (0.0594059)	Compact hydro energy device (UK) Wave-energy converter performance and cost optimization through novel controls strategies (US) Development of micro water generator for household water pipes (Japan) Advanced modeling and simulation development of hydroelectric power generators, including electronic excitation circuits (Canada)
Cluster_18	Material (0.0973246) Building (0.0820252) Fiber (0.0768128) Polymer (0.0720646) Insulation (0.0710307)	Development, characterization, and study of the durability of flexible polymer eco-composites based on milkweed fibers for the building envelope (Canada) DL: Systems analysis and fundamental control of bacterial processes in the production of bio-concrete for construction purposes BioZEment 2.0 (Norway)

Table 5. *Cont.*

Cluster No.	Topics (c-TF-IDF Scores)	Major R&D Grant by Topic (Funder Country)
Cluster_19	Building (0.1199088) Energy (0.1072639) Window (0.0858524) Glazing (0.0505132) Envelope (0.0402427)	AIR Option 1: Technology translation: Smart windows for the improved energy efficiency of buildings (US) Lightweight switchable smart solutions for energy-saving large windows and glass façades (Canada) Advanced switchable glazing using different composite layers of energy-efficient and sustainable material for zero-emission buildings (UK)
Cluster_20	Building (0.0979072) Retrofit (0.0784874) Emission (0.0774825) Cost (0.0711959) Retrofitting (0.0696268)	Energy management system incorporating integrated retrofit decision model (EMSIRDecMo) (UK) Sustainable solutions for affordable retrofit of domestic buildings (EC) Achieving nearly zero-energy buildings—A life-cycle assessment approach to retrofitting existing buildings (Ireland) Self-heating social housing–The zero carbon retrofit (UK)
Cluster_21	Building (0.1231205) Dowel (0.0635298) Solution (0.0588042) Construction (0.0542916) Energy (0.0529605)	Ultralow energy green building based on renewable wood material (Slovakia) Affordable zero-carbon construction (UK) Low environmental impact building with timber and lime-based alternative mass composites (EC) Wood framed buildings of the future tools for near-zero-energy (Sweden)
Cluster_22	Building (0.1464935) Energy (0.1281587) Cooling (0.0871157) Heating (0.0659637) Heat (0.0619441)	Increasing green retrofits and installation of renewable technologies by SMEs through next-generation, cloud-based CAD/estimating tools to reduce UK housing carbon emissions (UK) Demonstration of an integrated renovation approach for energy efficiency at the multibuilding scale (EC) Envelope material system with low impact for zero energy buildings and renovation (EC)
Cluster_23	Power (0.1721829) Mismatch (0.111584) Electricity (0.1075348) Characteristic (0.1002816) Campu (0.0875007)	Design and control of advanced building energy systems (Canada) Hybrid air conditioning for net ZEB featuring heat pipe and ice storage (Canada) Digitalization of electrical power and energy systems operation (UK) Advanced energy matching for ZEB in future smart hybrid networks (Finland)
Cluster_24	Air (0.1243019) Ventilation (0.0700261) Indoor (0.0585206) Quality (0.0536354) Hrv (0.0501317)	Robust technology combining both air filtration and purification with zero chemicals used and zero residues produced (EC) Thermochemical seasonal solar energy storage for building applications (seasonal storage) (UK) Heat and moisture exchangers for energy-efficient buildings: Fouling, frosting and sorption (Canada) Heat recovery ventilation for IEQ in inner city dwelling (Canada)

For example, the present thesis posits that the R&D grants attributed to Cluster 0 are primarily dedicated to conducting R&D endeavors on advanced nuclear technology. Moreover, these grants emphasize advancing the development of sustainable ZEB by incorporating innovative nuclear reactor designs, advanced fuel assemblies, and state-of-the-art diagnostic and monitoring tools.

The R&D grants belonging to Cluster 1 focus on developing advanced materials, innovative structural systems, and seismic design methods for enhancing the seismic safety and energy efficiency of buildings. These research studies aim to optimize the thermal and acoustic performances of masonry housing and develop sustainable and low-risk structural buildings using high-strength materials, timber composites, and energy-dissipating elements. These studies also investigate the response characteristics of super-high-rise structures under long-term ground motion and establish damping control mechanisms to improve their seismic performance.

The field of studies in Cluster 2 focuses on the dynamics and transport of fluids in complex systems, including developing advanced numerical methods and models for simulating turbulent flows and investigating the influence of numerous factors, such as rough surfaces, pressure gradients, and interfacial area concentration on the behavior of fluids. This work encompasses research areas, such as aerodynamics, hydrodynamics, and atmospheric physics, and applications in energy, urban air quality, and material science. Table 6 similarly summarizes the research areas and content of the 25 clusters. In this study, we organized clusters derived from a comprehensive analysis of R&D grants. Utilizing the BERTopic model, a state-of-the-art topic modeling technique, we extracted key thematic elements to inform the titles of each cluster. These titles were formulated based on keyword prominence and their relevance to the overarching themes of the respective R&D grants.

Table 6. Topics for 25 clusters and the titles of major research and development (R&D) grants related to zero-energy building (ZEB).

Cluster No.	The Name of Cluster	Summary of R&D Grants Related to ZEB
Cluster 0	Advanced nuclear technologies & applications for ZEB	These R&D grants cover various aspects of advanced nuclear technologies and their development. Research fields include developing nuclear coolant systems, new fuel assemblies, and small modular reactor technology. Other research areas include advanced diagnostics for fusion energy R&D, high-fidelity digital twins for critical systems, and plasma focus generators for material research in nuclear fusion. Additionally, the grants cover innovative solutions for nuclear waste containment, cost reduction of advanced reactor operation and maintenance, and integral benchmark evaluations of zero-power tests and multicycle depletion experimental data.
Cluster 1	Seismic safety, energy efficiency, and sustainable building design	These R&D grants cover a wide range of research related to seismic safety, energy efficiency, and sustainability of building structures. The grants explore different approaches to improve the seismic resistance of building structures, such as the use of novel materials, advanced design methods, and innovative structural systems. Some grants focus on upgrading energy and the sustainability of masonry buildings, whereas others investigate the seismic behavior and performance of high-rise structures. Additionally, grants are dedicated to developing new seismic isolation and vibration control technologies, such as self-centering buckling restrained braces and high-damping elastomers. These grants aim to improve the environmental performance of building materials, such as the development of sustainable ceramic brick masonry veneer walls for building envelopes.
Cluster 2	Fluid dynamics and turbulence modeling for ZEB	These R&D grants encompass research fields related to fluid dynamics and mathematical physics, focusing on turbulence, flow dynamics, and modeling. Specific research topics include the study of rough-walled turbulent flows, developing anti-icing materials, investigating interfacial area concentration transport in bubbly flows, effects of surfactants on drag reduction, and constructing vortex-wave-based turbulence models.
Cluster 3	Advanced photovoltaic technologies and integration for ZEB	These R&D grants cover various research fields on developing more efficient and sustainable photovoltaic technologies. These research areas include the development of high-transparency, high-conductivity spectrally selective coatings, solution-processed inorganic thin-film photovoltaic devices, atomically thin photovoltaics, organic semiconducting materials, concentrated solar energy storage, and solar energy storage into redox flow batteries. The grants also encompass developing sustainable materials and manufacturing processes, designing efficient solar cells with a low CO_2 footprint, and integrating solar panels into building materials. Other research areas include developing defect-tolerant photovoltaic materials, interfacial engineering of photovoltaic devices, and integrating radiative cooling into photovoltaic/thermal panels in buildings.

Table 6. *Cont.*

Cluster No.	The Name of Cluster	Summary of R&D Grants Related to ZEB
Cluster 4	Low-carbon cementitious products and innovations	These R&D grants relate to research fields aimed at reducing carbon emissions of cementitious products and developing low-carbon alternatives to traditional concrete for a net-zero future. Research includes developing novel additives and technology to enhance the performance of low-carbon cement, valorizing waste materials (e.g., contaminated waste glass and steel slag) for use in construction, and producing zero-emission and low-cost concrete materials using bio-catalytic calcium carbonate cementation and ultralow binder content. Other projects focus on the life-cycle assessment of sustainable cement, using IoT, machine learning, and big data to transform the cement supply chain, and testing and reusing concrete-encased steel from the 1950s.
Cluster 5	Sustainable production and advanced tech integration	These R&D grants cover various topics related to sustainable production, energy efficiency, and advanced technology development. The grants support research in sustainable cement production, low-emission transport, ultralow-cost sensors, energy storage, embedded systems, and communication systems infrastructure.
Cluster 6	Geothermal energy and thermal storage systems	These research grants cover various topics related to geothermal energy, thermal energy storage, and mathematical modeling for the energy-efficient design of underground systems. The grants aim to advance the development of sustainable energy systems for ZEB, including designing and optimizing geothermal heat pump systems, thermal energy storage, and underground mine ventilation systems.
Cluster 7	Power electronics in ZEB	These R&D grants focus on various aspects of power electronics and their applications in ZEB. The research topics include developing high-performance power converters using new materials (e.g., silicon carbide (SiC)), analyzing and modeling switching arcs, designing switching-cell-array-based power electronics for electric vehicles, developing smart switching devices for energy-saving applications, and investigating efficient and power-dense modular power electronic architectures for utility-scale DC-AC conversion.
Cluster 8	Energy generation, storage, and conversion technologies	These R&D grants cover diverse topics related to energy generation, storage, and conversion. Some of the research areas include wind turbine technology, laminar flow seals, green air transportation, ultralow wind-speed wind power generation, active sensor technologies, energy storage technology for power grids and micro-grids, electromechanical energy conversion, propeller aerodynamic interaction and noise characteristics, resonant gyro micro hemispherical concave arrays, nutating disk engines, linear synchronous permanent magnet motors, high-speed generators, mathematical modeling of nonlinear effects in electrical systems, spacecraft flywheel energy storage, energy-efficient control algorithms for advanced aircraft, robust control of stochastic delay Hamiltonian systems, DC-saturation-relieving contra-rotating wind energy conversion systems, and light pressure for space propulsion. These grants aim to improve the efficiency, reliability, and sustainability of energy systems for various applications.
Cluster 9	Ultralow power electronic circuits and hardware	These R&D grants focus on energy-efficient hardware and circuits for ultralow power consumption, including efficient processor design, memory and digital circuit boundary exploration, ultralow voltage SRAM architectures, adiabatic circuits, cryogenic adiabatic CMOS, and of analog integrated system development for ultralow voltage applications. The grants also cover developing novel capacitor-less dynamic random access memory technology, very low-power system-on-a-chip super dynamic voltage regulator key technology research, and high-bandwidth sensing for wide-bandgap power conversion.

Table 6. *Cont.*

Cluster No.	The Name of Cluster	Summary of R&D Grants Related to ZEB
Cluster 10	Energy-efficient devices for smart systems	The listed R&D grants cover research on developing energy-efficient and ultralow power devices, systems, and technology for different applications, including building control, wireless communication, sensing systems, and Internet of Things (IoT) devices. The research content encompasses designing and optimizing digital and analog circuits, memory architectures, micro-electromechanical devices, energy harvesting systems, wireless sensors, antennas, and communication protocols for ultralow power and zero-power operation.
Cluster 11	Nanotechnology and advanced material systems for ZEB	The listed R&D grants explore the use of molecular conformational dynamics for electromechanical qubits, semiconducting carbon nanotube polaritonic devices, and graphene spintronics. Additionally, the grants cover developing solid-state electrolytes for all-solid thin-film Li-ion batteries, 3D nanophotonic devices, and particulate-based functional macromolecules, among others.
Cluster 12	Advanced materials and technologies for ZEB and transportation	The listed R&D grants cover research on ZEB. Some of the research areas include developing disruptive polyurethane foams with improved passive fire protection, pressure-efficient hydrogen storage, preform technology for automotive part production, material science, digital materials, ultralow wear coatings, ultra-lightweight clay-aerogel materials, electromechanical formation, hybrid lightweight foam cores, gradient structures for flexible components, vacuum insulation panels, multiscale investigation and mimicry of naturally occurring composite materials, and fire protection systems for munitions. These research projects aim to improve energy efficiency, safety, insulation, and lightweight building materials and vehicles and develop advanced materials and coatings.
Cluster 13	AI-driven marine ecosystem interactions and sustainable energy monitoring	These grants focus on researching and developing monitoring systems, applying AI and computer models, optimizing sustainable energy production, restoring ecosystems, and building capacity for sustainable interactions with marine ecosystems.
Cluster 14	Zero-emission solutions for sustainable transportation	The listed R&D grants cover various fields related to ZEB and sustainable transportation. The research content encompasses developing and optimizing smart diesel fuel solutions; zero-carbon power solutions for ships; renewable fuel range extenders; clean fuel supply solutions; climate effects reduction of construction materials; electrified road transports; and zero-emission vehicles, marine vessels, and machinery. These projects also involve feasibility studies, data analytics tools, and life-cycle modeling to support the transition to a sustainable zero-emission transportation system.
Cluster 15	Hydrogen solutions and carbon management for ZEB	These R&D grants are related to various ZEB research fields, including clean hydrogen production, hydrogen storage and transportation, carbon capture and utilization, energy efficiency, and fuel cell technology. The research content encompasses a range of topics, such as developing efficient and flexible hydrogen production methods, assessing hydrogen embrittlement in pipelines, exploring novel hydrogen-resistant materials, and improving fuel cell technology for low-emission transportation and remote site energy production.

Table 6. *Cont.*

Cluster No.	The Name of Cluster	Summary of R&D Grants Related to ZEB
Cluster 16	Combustion systems and alternative fuels for ZEB	These R&D grants focus on developing ZEB technology, including combustion systems, carbon capture, hydrogen fuel technology, and biomass burning systems. Specific research areas include advanced pressurized fluidized bed combustion power plants, low-emission local heaters for almost-zero-energy consumption, coal gasification, ultra-clean and efficient waste-to-renewable energy, and combustion chemistry of novel diesel fuels. Other research areas include using electric fields in combustion science, developing noninvasive sensor systems for measuring enthalpy and mass flux, and studying combustion in microgravity.
Cluster 17	Water-based renewable energy and storage technologies	These R&D grants are related to renewable energy generation from water, such as tidal, wave, and hydroelectric power and technology for energy storage and distribution. The research topics cover flow control, system design and optimization, reliability and risk management, control strategies, and numerical modeling and simulation. The grants also focus on developing novel devices and prototypes, such as the PAX rotor and the SOURCE hydropanel, for sustainable energy generation and supply.
Cluster 18	Sustainable ZEB solutions in water treatment and industrial manufacturing	These R&D grants focus on achieving ZEB. The covered topics include carbon capture and utilization in biomanufacturing, sustainable waste management solutions, energy-neutral wastewater treatment, decentralized water technology, zero-carbon concrete production, low-energy water treatment processes, and efficient nitrogen removal from wastewater. Other research areas include developing innovative membranes, using bioreactors and biofilms for water treatment, and exploring new manufacturing processes and materials for building envelopes. Some grants address the challenges facing specific industries, such as glass manufacturing and textile production, whereas others focus on water disinfection and contaminated groundwater remediation.
Cluster 19	Advanced window systems for energy-efficient buildings	These research grants focus on developing technology and materials for improving the energy efficiency of buildings through advanced window systems, including ultra-thin glass membranes, polyurethane window systems, smart windows with high thermal and acoustic insulation, affordable high-performance windows, and lightweight switchable smart solutions. Other projects aim to develop new framing technology for highly insulating glazing, adaptable envelopes for building refurbishment, and water flow glazing systems. The goal is to reduce building energy consumption and promote sustainable materials and manufacturing processes.
Cluster 20	Retrofitting and energy optimization in existing buildings	These R&D grants are related to retrofitting existing buildings to improve energy efficiency and move toward ZEB. The research fields include technology development, manufacturing processes, smart textiles, energy management systems, modular and versatile process units, performance analysis, machine learning, life-cycle assessment, indoor climate and energy performance, and profitability analysis.
Cluster 21	Wood-centered approaches for ZEB and sustainable constructions	These R&D grants focus on ZEB using wood as a primary material. The research can include designing ultralow energy green buildings with renewable wood materials, enhancing the collapse resistance of cross-laminated timber buildings, developing finishing and densification solutions for interior wood products, creating affordable zero-carbon constructions, developing sustainable solutions for structural floor systems, optimizing transformation processes and machine tools for wood, creating new wood-fiber panels for wood buildings, achieving net-zero energy and carbon in wooden buildings, developing bulk insulation from cedar transformation co-products, and stabilizing wood in a circular economy.

Table 6. *Cont.*

Cluster No.	The Name of Cluster	Summary of R&D Grants Related to ZEB
Cluster 22	Holistic ZEB development and urban-scale energy optimization	The listed R&D grants pertain to ZEB research. The research fields include envelope material systems, building energy retrofits, installation of renewable technology, smart net-zero energy communities, qualified training programs for building nearly ZEBs, sustainable industry, urban-scale energy use optimization, intelligent net-zero energy modular homes, circular economies, achieving near zero and positive energy settlements, decarbonizing precast concrete, and more. These grants cover developing low-impact envelope material systems, creating cloud-based CAD/estimating tools for retrofitting buildings, designing smart net-zero energy communities, developing qualified training programs for building professionals and blue-collar workers, delivering sustainable industry through smart-process heat decarbonization, optimizing urban-scale energy use with occupant behavior uncertainty, developing intelligent net-zero energy modular homes for cold regions, advancing the circular economy potential of waste-to-value processes, achieving near zero and positive energy settlements, and developing modeling and assessment capabilities to optimize the design and production of sustainable home and personal care consumer products to meet net-zero carbon targets.
Cluster 23	ZEB technologies and building-integrated renewable systems	The listed R&D grants cover diverse ZEB fields, including envelope material systems, building retrofits, renewable energy technology, energy optimization in communities, smart energy management systems, circular economies, decarbonization of energy systems, and modeling and optimization of building integrated renewable energy systems. The grants also cover various types of technology, such as air source heat pumps, solar thermal and photovoltaic systems, storage systems, gas networks, and regenerative high-performance curtain walls.
Cluster 24	Advanced energy systems and sustainable building innovations	These R&D grants relate to various aspects of zero energy building, including design and control of advanced energy systems, digitalization of power and energy systems, hybrid air conditioning, grid energy storage, sustainable energy systems, anaerobic digestion, thermochemical energy storage, ground-source heating and cooling, and heat recovery ventilation. Other topics include innovative energy-saving devices, low-carbon heating and cooling systems, and microbial contamination in energy-saving ventilation equipment. The grants also cover optimizing thermal energy storage, effectively using renewables, and employing energy-efficient building materials, such as radiative cooling paints.

4. Discussion

The clustering results highlight the diverse range of ZEB research, covering a spectrum from advanced nuclear technology to fluid dynamics in complex systems. Document categorization into 25 distinct groups signifies the breadth of subjects under the purview of ZEB research. Cluster 0 points to a nascent inclination towards harnessing advanced nuclear technology for sustainable ZEB outcomes. The focus on innovative reactor designs and advanced diagnostic tools alludes to a potential pivot towards nuclear energy as a sustainable solution for zero-energy buildings. This warrants an in-depth exploration of its feasibility, associated ramifications, and public perception. Cluster 1 accentuates the relevance of innovations in material science and the imperative of seismic safety in ZEB. Given the mounting concerns over environmental calamities, there is an increased emphasis on seismic design techniques and ensuring the resilience of towering structures. It is essential to evaluate how such advancements might redefine the established architectural and engineering paradigms in ZEB. The attention to fluid dynamics, as highlighted in Cluster 2, is of particular interest. When explored in the context of aerodynamics and atmospheric physics, fluid dynamics can profoundly impact building design, ventilation strategies, and energy conservation approaches. Delving into the interplay between these elements and ZEB design promises fresh perspectives.

The employment of AI tools, like BERT and UMAP, facilitates a nuanced exploration of ZEB-focused R&D trends. Yet, it remains critical to reflect on potential biases, ascertain the results' reliability, and acknowledge the limitations of this AI-driven approach. The ungrouped outliers could represent untapped knowledge, potentially pointing to emerging or niche research areas on the verge of broader recognition. An in-depth analysis of these outliers could delineate emerging directions in ZEB research. Using AI to investigate prospective research trends in ZEB has demarcated clear clusters echoing the field's multifaceted nature. Each cluster epitomizes a distinct aspect of ZEB, shedding light on the intricate avenues of sustainable building design research. Nevertheless, while these clusters serve as a valuable guide to current ZEB research, inherent limitations and potential areas of deeper inquiry emerge.

Despite BERT's proven effectiveness in text embedding, biases innate to its pre-trained model can creep in. Moreover, while UMAP is proficient at dimensionality reduction, its sensitivity to hyperparameters might skew the clustering outcome. Furthermore, HDBSCAN's capability in capturing diverse density clusters might occasionally miss more diffuse ones, categorizing certain research areas as outliers.

The study's focus on only the titles and abstracts of R&D grants may inadvertently neglect subtle nuances or emergent themes present in the full text. Additionally, as this study provides a snapshot of ZEB trends, it may not trace the entire thematic evolution, especially emerging or waning research facets. Outliers, which do not neatly fit into the predefined 25 clusters, could be hinting at avant-garde, cross-disciplinary, or specialized research trajectories. An exhaustive qualitative probe into these outliers might unearth pioneering ZEB research directions.

Undertaking a time-based examination of the R&D grants might illuminate the temporal evolution of ZEB research. Such an inquiry can chronicle the birth, growth, and possible waning of distinct research themes, furnishing a fluid overview. Subsequent studies stand to gain from extending their scope to the full text of R&D grants, thereby ensuring a more holistic grasp of the research nuances. Complementing this with external datasets, like citation networks or patent databases, would bestow a comprehensive perspective on the ZEB research's impact and innovative pathways.

5. Conclusions

Energy consumption in the building and construction sectors remains a salient challenge across many nations. Amid the global agreement to transition from fossil fuels to renewable energies, Zero-Energy Building (ZEB) stands out as a viable alternative, garnering extensive research attention [1,2]. This research introduced an AI-driven methodology to examine ZEB-centric R&D grants, aiming to decipher future trajectories and enrich our understanding of the discipline.

Diverging from conventional scientific analyses that primarily focus on academic articles, our study prioritized R&D projects to illuminate the prospective avenues of ZEB research. Despite inherent challenges in analyzing all ZEB-related R&D undertakings due to data accessibility constraints, such a methodological choice is pivotal. These projects often epitomize national R&D agendas, overseen by governmental or public entities. Our analysis emphasized concerted efforts to amplify ZEB efficiency, elevate photovoltaic performance, and blueprint smart cities integrating ZEB with transportation and avant-garde technologies, such as ICT and sensors. These insights resonate with Rotolo et al. [36], underscoring the relevance of R&D funding data in spotlighting imminent research directions. The value proposition of our study lies in its novel methodology to envisage the ZEB research horizon. By leveraging R&D project data, we offer a holistic vantage point and insights distinct from those gleaned through traditional article analyses. Moreover, this endeavor affirms the potency of AI techniques as instrumental scientific apparatuses, thereby extending the frontiers of such inquiries.

Our findings can serve both theoretical and applied facets, assisting entities in strategizing R&D initiatives, budget allocations, and outcome evaluations. Furthermore, this work provides a scaffold for assessing the contemporary status and prognosticating ZEB research's forthcoming trends. Nonetheless, certain limitations persist, such as potential miscategorization of R&D grants or human biases affecting thematic assessments. Pioneering language models, exemplified by OpenAI's ChatGPT or Google's Bard, could proffer resolutions in future research endeavors.

There exists an imperative for subsequent studies to explore the intrinsic attributes and the juxtaposition of R&D grant data with scientific publications. Such endeavors would accentuate the significance of R&D grant data, augmenting its analytical utility, and paving the way for diverse AI-driven scientometric evaluations. Our AI-enhanced assessment underscored the multifaceted nature of ZEB research, spanning domains from nuclear technology to material science. The emphasis on fields such as advanced nuclear technology heralds potential paradigm shifts in ZEB's energy and sustainability blueprints, signaling a renaissance in sustainable architectural design.

Based on the derived clusters, it is prudent for stakeholders to channel investments into emergent domains, such as cutting-edge materials, seismic safety paradigms, and novel nuclear innovations, as these could dictate ZEB's future trajectory. This work epitomizes AI's prowess in sifting through and categorizing intricate research vectors, suggesting that embracing such tools can refine the granularity and scope of scientific evaluations, thereby equipping stakeholders with actionable insights. Given the fluidity of ZEB research, a periodic reassessment of these trends becomes indispensable. A steadfast monitoring regimen, buttressed by state-of-the-art methodologies, is quintessential to ensure alignment with evolving technological advances and societal imperatives. A meticulous exploration of anomalies or outliers could also proffer a visionary perspective on the research frontier of ZEB.

By comprehensively mapping the ZEB terrain through AI, this study offers indispensable insights for a broad audience, ranging from researchers and policymakers to industry frontrunners. The ever-evolving tapestry of ZEB research necessitates sustained scrutiny and recalibration to propel sustainable and trailblazing architectural innovations.

Author Contributions: Methodology, Y.B.; Software, B.J.; Formal analysis, B.J.; Investigation, B.J.; Visualization, B.J.; Supervision, Y.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by "Regional Innovation Strategy (RIS)" through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (MOE)(2021RIS-002).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Restrictions apply to the availability of these data. Data was obtained from Digital Science & Research Solutions Inc. and are available at https://app.dimensions.ai/discover/publication with the permission of Digital Science & Research Solutions Inc.

Conflicts of Interest: The authors declare no conflict of interest.

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