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CLEAN ENERGY TECHNOLOGY OBSERVATORY

Early stage technologies in the field of Energy

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Contents

Abstract

Within the context of the Clean Energy Technology Observatory, 77 emerging technologies related to Energy have been detected using a hybrid approach that combines text mining with expert knowledge. The report provides a concise description of these 77 technologies, including key indicators. Furthermore, the report includes a short analysis outlining the involvement of public and private entities, patenting activity, and the relative performance of major economies (EU, US, CN, KR, JP) in these emerging technologies.

Executive Summary

Detecting and understanding emerging technologies enables policymakers to make informed decisions about regulation, funding allocation, and strategic planning. Such foresight activity allows them to create a policy framework that is conducive to the development and widespread adoption of these technologies. Considering the potential of certain technologies to significally alter the economic landscape and disrupt markets, establishing a sound regulatory evironment is crucial as it can support the creation of new business and job opportunities, and drive economic growth and competitiveness in the global market. It is equally important for policymakers to anticipate and address the broader implications of these technologies, including ethical considerations, societal impact, environmental sustainability, and public health and safety concerns. Additionally, emerging technologies carry significant implications for national and EU security, and are pivotal in maintaining Europe's technological sovereignty. By addressing these complex challenges from the onset, policymakers can strike a balance that promotes technological advancement while ensuring the welfare and security of society.

For the present exercise, a process that integrates the JRC TIM Technology software with expert knowledge was used. This approach involves the use of customized text mining and keyword extraction techniques, as well as novelty indicators, to identify technology weak signals from two document corpuses: the Scopus database of scientific publications from Elsevier and the Patstat database of patents from the European Patent Office, both from 1996 onwards. Throughout the process, expert knowledge was leveraged to enhance the recall of relevant documents related to the identified technologies and validate the list of potential weak signals.

As a result of this process, 77 early stage technologies related to the field of Energy have been detected and are presented in this report. Environmental considerations and the transition to renewable energy sources appear to drive the development of most of the identified early stage technologies as many of these directly relate to energy storage and to photovoltaics.

The analysis reveals that public research organisations play a crucial role in fundamental research on these early stage technologies, as evidenced by their prominent contribution to scholarly publications. As these technologies mature and progress towards the patenting phase, the engagement of private companies increases, as reflected by their larger share of patent filings. When it comes to specialization, the revealed technological advantage (RTA) index[1] indicates that Europe is more specialized in areas such as carbon capture, sequestration and utilization, district heating and wind energy, compared to other major economies. At the same time, European organisations are less focused on R&D in technologies related to batteries, geothermal energy, solar fuels, energy storage and smart grids, as evidenced by fewer patents and scientific publications, and lower RTA index values. In contrast, China and South Korea emerge as frontrunners in most of these technologies, whereas Japan and, surprisingly, the US, do not show high levels of specialisation in any category.

A dashboard has been set up in TIM Technology to allow further exploration of the 77 early stage technologies[2].

1 This index is adapted from the OECD definition of the RTA and gives an indication of the relative specialisation of a country in a weak signal. See point 5 page 13 for more details.

2 http://www.timanalytics.eu/TimTechPublic2/dashboard/index.jsp#/space/s2185?ds=298852

Batteries
Aluminium suflur
Aqueous zinc
Dendrite-free lithium ion batteries
Dual ion
Flexible zinc ion
Human-robot recycling
Potassium metal
Lithium CO2
Lithium argyrodite
Magnesium sulfur
Multivalent ion
Organic flow
Quasi-solid-state lithium-metal
Retired batteries
Small molecule organic cathode
Zinc graphite
Zinc air
Zinc CO2

Biomass
Chemical looping gasification

Carbon Capture, Utilization, Sequestration
Blue hydrogen
Deep eutectic solvents

District heating
5th generation
Digital twin
Urban building energy

Energy storage
Aqueous hybrid supercapacitors
Aqueous supercapacitors
Cloud energy storage
Compressed CO2
Electrochromic storage
Geological hydrogen storage
Hydrogen in aquifers
Liquid organic carrier for hydrogen
Metal foam phas change materials
MOF-based supercapacitors
Mxene supercapacitors
Nanoencapsulated phase change materials
Polyetherimide
Potassium hybrid capacitors
Potassium hybrid supercapacitors
Shared energy storage
Shell-and-tube thermal storage
Zinc hybrid supercapacitors

Geothermal energy
Deep borehole heat exchanger
Hybrid nanofluid
Medium deep geothermal eneregy

Miscellaneous
Interfacial solar evaporation
Hemispherical solar distiller
Microgrid island clusters
Lacustrine shale oil
Energy injustice
Levelized cost of hydrogen/heat/storage

Ocean energy
Triboelectric nanogenerator

Photovoltaics
Agrivoltaics
Bifacial perovskite solar cell
Hydrovoltaics
Indoor organic PV
Offshore solar power
Perovskite/silicon tandem solar cells
Ternary organic photovoltaics
Tin perovskite solar cells
Vehicle integrated PV

Solar fuels
Covalent organic framework
PEC reduction of CO2
Photocatalytic CO2 reductio
S scheme heterojunction catalysis
Z scheme heterojunction catalysis

Renewable fuels
Cold direct ammonia fuel cel
Direct seawater electrolysis
sustainable ammonia
Sustainable aviation fuel

Smart grids
Blockchain
Edge computing
Electricity theft detection
Machine learning
Internet of things

Wind energy
Wake steering
Fast frequency support

Foreword on the Clean Energy Technology Observatory

The European Commission set up the Clean Energy Technology Observatory (CETO) in 2022 to help address the complexity and multi-faced character of the transition to a climate-neutral society in Europe. The EU's ambitious energy and climate policies create a necessity to tackle related challenges in a comprehensive manner, recognizing the important role for advanced technologies/innovation in the process.

CETO is a joint initiative of the European Commission Joint Research Centre (JRC), who run the observatory, and Directorate Generals Research and Innovation (R&I) and Energy (ENER) on the policy side. Its overall objectives are to:

- monitor the EU research and innovation activities on clean energy technologies needed for the delivery of the European Green Deal
- assess the competitiveness of the EU clean energy sector and its positioning in the global energy market
- build on: existing Commission studies, relevant information/knowledge in Commission services/agencies, the Low Carbon Energy Observatory (2015-2020)
- publish reports on the Strategic Energy Technology Plan (SET-Plan) online platform

CETO provides a repository of techno- and socio-economic data on the most relevant technologies and their integration in the energy system. It targets in particular the status and outlook for innovative solutions as well as the sustainable market uptake of both mature and inventive technologies. The project serves as primary source of data for the Commission's annual progress reports on competitiveness of clean energy technologies. It also supports the implementation and development of EU research and innovation policy.

The observatory produces a series of annual reports addressing the following themes:

- Clean Energy Technology Status, Value Chains and Market: covering advanced biofuels, batteries, bioenergy, carbon capture utilisation and storage, concentrated solar power and heat, geothermal heat and power, heat pumps, hydropower & pumped hydropower storage, novel electricity and heat storage technologies, ocean energy, photovoltaics, renewable fuels of non-biological origin (other), renewable hydrogen, solar fuels (direct) and wind (offshore and onshore).
- Clean Energy Technology System Integration: building-related technologies, digital infrastructure for smart energy system, industrial and district heat & cold management, standalone systems, transmission and distribution technologies, smart cities and innovative energy carriers and supply for transport.
- Foresight for Future Clean Energy Technologies using Weak Signal Analysis
- Clean Energy Outlooks: Analysis and Critical Review
- System Modelling for Clean Energy Technology Scenarios
- Overall Strategic Analysis of Clean Energy Technology Sector

More details are available on the CETO web pages

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1. Introduction

1.1 Technology foresight

Technology foresight plays a crucial role in identifying new emerging technologies that have the potential to reshape or disrupt society and markets. In an era marked by accelerating technological change and hyperconnectivity, early awareness of disrupting technologies and of new scientific breakthroughs is of strategic importance for the timely development of innovation policies aimed at promoting both a stable business environment and a safe, secure society for citizens[3,4,5]. Early technology awareness is especially relevant in the context of Energy and Climate policies, the effective design and implementation of which might be disrupted by shifts in the technological frontier[6].

Proactively shaping policies not only guides and frames the development of emerging technologies but can also catalyze the generation of new knowledge and markets[7] and increase EU technological sovereignty. In the context of Energy and Climate policies, it will help to achieve decarbonization goals and to establish a sustainable and resilient energy future for the EU. To no one's surprise, forward-looking initiatives have increasingly played a pivotal role in policy-making processes since the 1990s[8]. Among other methods, technology foresight has gained substantial momentum and now holds a central position in supporting policy-making mechanisms, particularly in areas heavily impacted by the rapid evolution of new technologies and innovations.

Many techniques can be applied to perfom technology foresight, from interactive and creative processes involving scientists, technologists, futurologists, or other experts, to sophisticated data analytics processes. In the last decades, there has been growing interest among academics in the identification of emerging technologies through the use of data[9]. Bibliometrics techniques are often used in that context as they enable researchers to explore, organize and analyse large amounts of data to identify 'hidden patterns'[10]. These techniques apply mathematical and statistical methods to scientific publications, books and other media[11] and are used extensively in the quest for detecting emerging technologies[12,13].

Other scientometric approaches use for example patent databases to detect the emergence and maturation of technologies[14,15], text mining of online news articles from the Web[16], network

3 Bakhtin, P., Saritas, O., Chulok, A. et al. Trend monitoring for linking science and strategy Scientometrics 111, 2059–2075 (2017).

4 Martin, B.R., Technology Analysis & Strategic Management, Volume 7, Issue 2, 1 January 1995, Pages 139-168, Foresight in Science and Technology.

5 Henry Small, Kevin W. Boyack, Richard Klavans, Identifying emerging topics in science and technology, Research Policy, Volume 43, Issue 8, 2014, Pages 1450-1467.

6 OECD, Energy and Climate Policy: Bending the Technological Trajectory, OECD Studies on Environmental Innovation, OECD Publishing (2012)

7 Martin, B. R. (1995). Foresight in science and technology. Technology Analysis and Strategic Management, 7(2), 139–168.

8 I. Miles, The development of technology foresight: a review, Technol. Forecast. Soc. Change, 77 (9) (2010), pp. 1448-1456.

9 Rotolo, D., Hicks, D., & Martin, B. R. (2015). What is an emerging technology?. Research policy, 44(10), 1827-1843.

10 M.J. Norton, Introductory concepts in information science ; Information Today Inc., for the American Society for Information Science, Medford, NJ: 2000, v, 127, [3] pp.

11 Pritchard A., Statistical bibliography or bibliometrics?, Journal of Documentation, 25 (4) (1969), pp. 348-349

12 John Mingers, Loet Leydesdorff; A review of theory and practice in scientometrics, European Journal of Operational Research,Volume 246, Issue 1, 2015, Pages 1-19.

13 Abercrombie, R.K., Udoeyop, A.W. & Schlicher, B.G. A study of scientometric methods to identify emerging technologies via modeling of milestones. Scientometrics 91, 327–342 (2012).

14 Changyong Lee, Ohjin Kwon, Myeongjung Kim, Daeil Kwon, Early identification of emerging technologies: A machine learning approach using multiple patent indicators, Technological Forecasting and Social Change, Volume 127, 2018, Pages 291-303.

15 Liu, S. J., & Shyu, J. (1997). Strategic planning for technology development with patent analysis. International journal of technology management, 13(5-6), 661-680.

16 Janghyeok Yoon, Detecting weak signals for long-term business opportunities using text mining of Web news, Expert Systems with Applications, Volume 39, Issue 16, 2012, p. 12543-12550.

analysis[17,18], the use of information extracted from the internet[19], other alternative data sources like social media[20], or mixed approaches e.g. combining citations indicators and count of online clicks on scientific publications platforms to determine the prominence of scientific topics[21,22].

The JRC initiated the development of an in-house quantitative process for technology foresight in 2018[23,24,25]. This data-driven approach is designed to identify early signs of emerging technologies and scientific developments (often called weak signals[26]) using a mix of text mining techniques and scientometric indicators derived from a corpus of peer-reviewed scientific publications, patents and EU R&D projects[27,28,29]. Methods to extract weak signals and predict the emergence of new technologies based on text mining techniques remain subject of ongoing exploration within the academic community, for example with some recent attempts at developing predictive models of emergence based on the analysis of keywords occurence over time[30].

1.2 Methodology

1.2.1 Data

Two sets of data have been used to detect early stage technologies: scientific publications (Scopus database of scientific publications from Elsevier[31] dating 01/1996 to 04/2023) and patents (Spring 2023 edition of Patstat[32] from the European Patent Office). The underlying assumption is that promising technological developments in a specific domain are typically accompanied by a noticeable surge in the number of scientific publications or patents fillings (as illustrated in Figure 1). When signals are reconstructed in TIM Technology (see “reconstruction in TIM” below), a third database is used in addition to Scopus and Patstat: Cordis[33], the repository of EU funded R&D projects and activities.

17 Huang, L., Chen, X., Ni, X., Liu, J., Cao, X., & Wang, C. (2021). Tracking the dynamics of co-word networks for emerging topic identification. Technological Forecasting and Social Change, 170, 120944.

18 Fefie Dotsika, Andrew Watkins, Identifying potentially disruptive trends by means of keyword network analysis, Technological Forecasting and Social Change, Volume 119, 2017, p.114-127, ISSN 0040-1625,

19 Dirk Thorleuchter, Dirk Van den Poel, Weak signal identification with semantic web mining, Expert Systems with Applications, Volume 40, Issue 12, 2013, Pages 4978-4985, SSN 0957-4174.

20 X. Zhou et al., "Identifying and Assessing Innovation Pathways for Emerging Technologies: A Hybrid Approach Based on Text Mining and Altmetrics," in IEEE Transactions on Engineering Management, vol. 68, no. 5, pp. 1360-1371, Oct. 2021.

21 https://joint-research-centre.ec.europa.eu/system/files/2018-06/fta2018-paper-b3-rota.pdf

22 Alan L. Porter, Denise Chiavetta, Nils C. Newman, Measuring tech emergence: A contest, Technological Forecasting and Social Change, Volume 159, 2020.

23 Eulaerts O., Joanny G., Giraldi J., Fragkiskos S., Perani S., Weak signals in Science and Technologies - 2019 Report, EUR 29900 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-76-12386-6.

24 Eulaerts O., Joanny G., Perani S., Weak signals in Science and Technologies 2019 - Analysis and recommendations, EUR 30061 EN, Publications Office of the European Union, Luxembourg.

25 Eulaerts et al, Weak signals in Science and Technologies –Weak signals in 2020, EUR 30714 EN, Publications Office of the European Union, Luxembourg.

26 Mari Holopainen, Marja Toivonen, Weak signals: Ansoff today, Futures, Volume 44, Issue 3, 2012, Pages 198-205,

27 G. Joanny, S. Perani, O. Eulaerts, Detection of disruptive technologies by automated identification of weak signals in technology development. Proceedings of the ISSI, International Society for Scientometrics and Informetrics (2019), pp. 2644-2645.

28 A. Moro, E. Boelman, G. Joanny, J.L. Garcia, A bibliometric-based technique to identify emerging photovoltaic technologies in a comparative assessment with expert review, Renewable Energy, 123 (2018), pp. 407-416

29 A. Moro, G. Joanny, C. Moretti, Emerging technologies in the renewable energy sector: a comparison of expert review with a text mining software, Futures, 117 (2020).

30 Taehyun Ha, Heyoung Yang, Sungwha Hong,Automated weak signal detection and prediction using keyword network clustering and graph convolutional network, Futures, Volume 152, 2023.

31 https://www.elsevier.com/solutions/scopus

32 https://www.epo.org/fr/searching-for-patents/business/patstat#:~:text=PATSTAT%20vous%20aide%20%C3%A0%20effectuer,juridiques%20en%20mati%C3%A8re%20de%20brevets.&text=PATSTAT%20contient%20des%20donn%C3%A9es%20brevets,grands%20pays%20industriels%20et%20d%C3%A9velopp%C3%A9s.

33 https://cordis.europa.eu/fr

1.2.2 TIM Technology

The software used for the present exercise, created and developed by the JRC, is an advanced monitoring system called TIM Technology. This system integrates science, technology and innovation data from several data sources including Scopus, PATSTAT and Cordis. This platform is designed to track the development of both established and emerging technologies, using semantic analysis, robust data mining, and sophisticated data visualization techniques. TIM Technology assesses activity levels, such as R&D articles and patents, and uncovers collaboration patterns and technological evolution. It has the capability to track the progression of keywords over time and across different domains. Additionally, TIM employs network analysis to detect events related to technology change by identifying, clustering, and visualizing intricate relationships and connections among topics, institutions, and countries or regions.

1.2.3 Detection of raw weak signals

The detection of weak signals relies on a text-mining generated dictionary of multi-words concepts which is built using the corpus of scientific publications and patent documents retrieved from Scopus and Patstat respectively. Single and compound words as well as acronyms are extracted from the title, abstract and keyword fields in the reference corpus. To capture the most recent vocabulary used in scientific publications, documents from the last seven years (2016-04/2023) of the Scopus database (~12 million scientific publications) are used to compile the dictionary. The extracted words are subsequently processed to group instances of the same concept, remove inconsistencies such as spelling or wording variations, rank the concepts by relevance using a modified TFIDF[34] method, and store them in the dictionary. For the present exercise, the resulting dictionary was composed of around 8 millions concepts. A similar process is applied to the corpus of patents, using the last 5 years of Patstat to build the dictionary.

This dictionary is used to build document collections through two complementary processes. In the first one, referred to as the “large process”, all keywords from the dictionnary are used in individual search queries to build collections of documents that are then ranked and selected according to various indicators. In the second process, referred to as the “targeted process”, targeted searches are made directly in TIM Technology to build specific collections of documents that are then explored through various functionalities. Signals detected through these two processes are then reconstructed in TIM technology[35] for final validation.

1.2.3.1 ***“Large”*** *process*

Each keyword contained in the above described dictionary is used in an automated semantic query process that builds an equivalent number of document collections. Each query retrieves scientific publications, patents, and EU-funded projects dating from 01/1996 to 04/2023[36].

A custom-built indicator called "activeness" is then used to rank the datasets obtained by the automated query process. This indicator is defined as the ratio between the number of documents retrieved for a certain period and the total number of documents retrieved for the full period

34 Term Frequency, Inverse Document Frequency is a measure of importance of a word/concept to a document in a collection or corpus, adjusted for the fact that some concepts appear more frequently. For each of these concepts, the Inverse Document Frequency (IDF) is calculated:
IDF = log (number of documents with the concept / total number of documents)
The idea behind the IDF calculation is that more weight is given to the terms that are rarer. In TIM Technology, a ranking is then calculated as follow: *Ranking = frequency x IDF x mod_field*
where frequency is the number of times the concept appears in the dataset and mod_field is a modifier that gives more or less weight to the terms depending on where they are found (title, abstract or keyword). In this specific case, the modifier is calculated as follows: Title: 1 Abstract: 0.5 Keyword: 2 This is made so that the more “important” words are attributed a higher rank.

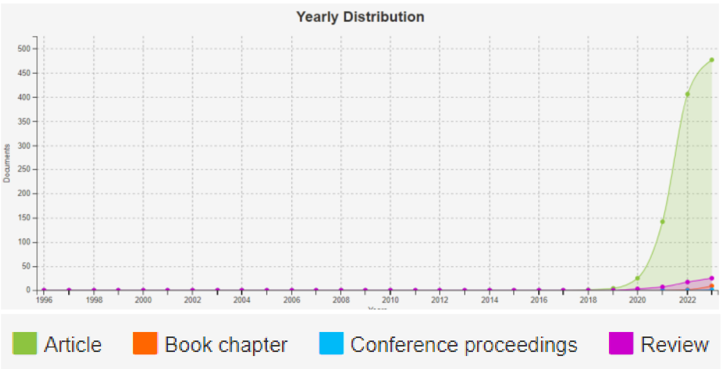
35 https://knowledge4policy.ec.europa.eu/text-mining/tim_technology_editor_en

36 Detecting weak signals implies looking into the past to verify novelty.

01/1996-04/2023[37]. A high activeness score means that a high percentage of the documents in the dataset have been published during the selected period. Activeness indicators covering different periods are used to detect raw weak signals in Scopus and Patstat[38]. The underlying assumption is that datasets of scientific articles or patents with a high activeness score are related to emerging topics in science or emerging technologies.

Another type of indicator, called "coverage" is used to isolate raw weak signals on specific topics. This indicator is defined as the percentage of documents in which a specific text value appears in specific fields, such as title, abstract, journal categories, Cooperative Patent Classification (CPC) codes. The coverage indicator thus allows to prioritize raw weak signals that exhibit a certain threshold of relevance, as determined by the occurrence of selected keywords. For instance, in a scenario where the focus is on advancements in photovoltaic technology, the coverage indicator can be calibrated to highlight only those signals where at least 50% of the documents feature the term "photovoltaic" within their titles. The outcome of the large process consists of lists of document collections ordered by activeness, which serve as the raw data to identify raw weak signals.

Figure 1: Typical shape of a weak signal on a graph #documents (Y-axis) Vs years (X-axis). The graphic shows the distribution of documents with time for a document collection in TIM Technology for "S scheme heterojunction catalyst". The sudden increase of the number of scientific articles over the last years indicates emergence. *Source: TIM Technology, search query: topic:("s scheme heterojunction"~2)*



1.2.3.2 "Targeted" process

In this process, targeted semantic searches are made in TIM Technology to collect a maximum of documents for each specific topic. The selection of potential raw weak signals is made by analysing lists of extracted keywords ranked by activeness [2020-2023], for each of the datasets. Some of the specific topics covered by CETO have also been used directly for weak signals detection (see Tables 1 and 2 below).

Various types of keywords are available in TIM Technology and can be used to detect weak signals. Author keywords, but also keywords calculated with the following algorithms: automatic KW, KPminer,

[37] For example, the indicator activeness[2020-2022] corresponds to the ratio [#documents published during the period 2020-2022] / [#documents published during the period 1996-2022]

[38] An activeness indicator for patent is usually slightly shifted to the past to account for the 18 months grace period inherent to the patent process e.g. activeness 18-20 will be used for analysis made in 2021

TextRank, PositionRank, Yake, Rake[39,40,41,42,43,44,45]. The selection of potential raw weak signals is made by evaluating the activeness indicator for the various keywords, for each of the targeted semantic search. The implementation of sophisticated keywords extraction algorithms like KPminer, Textrank, Position Rank, Yake and Rake, allowed to reduce the noise in the lists of calculated keywords (e.g. stop words, ambiguous words, jargons pecific words, fluff words, filler phrases, misspelings). In particular, the TextRank and PositionRank methods significantly decrease the level of noise, which facilitates the analysis and selection of potential weak signals.

The outcome of the targeted process consists in lists of keywords ordered by activeness, which are then reconstructed in TIM Technology and reviewed by analysts to isolate raw weak signals.

1.2.3.3 Additional focused searches

To further detect potential raw signals, several additional targeted searches have also been made for some subtopics that have been detected during the analysis of the potential raw weak signals obtained by the two processes e.g. solid-state batteries or termochemical energy storage (table 3). The lists of keywords are then reviewed using the activeness indicator to detect the most novel concepts for each document collection, and each potential weak signal is reconstructed in TIM Technology for further analysis and validation.

1.2.3.4 Processes and searches

The three tables below list the searches and type of processes that have been used to build the initial set of 280 raw weak signals (see annex 1 for this list). Emerging technologies suggested by JRC experts have also been added to the list of potential raw weak signals.

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39 "Emerging technologies in the renewable energy sector: A comparison of expert review with a text mining software", Alberto Moro, Geraldine Joanny, Christian Moretti; Futures Volume 117, 2020, 102511, ISSN 0016-3287.

40 "PositionRank: An Unsupervised Approach to Keyphrase Extraction from Scholarly Documents, Corina Florescu and Cornelia Caragea, Computer Science and Engineering, University of North Texas, USA." https://www.cs.uic.edu/~cornelia/papers/acl17.pdf

41 "Bringing Order into Texts", Rada Mihalcea and Paul Tarau, Department of Computer Science, University of North Texas https://www.researchgate.net/publication/200042361_TextRank_Bringing_Order_into_Text

42 "Biased TextRank: Unsupervised Graph-Based Content Extraction", Ashkan Kazemi, Veronica Perez-Rosas, Rada Mihalcea, Department of Computer Science & Engineering, University of Michigan, Ann Arbor" - https://arxiv.org/abs/2011.01026

43 "KP-Miner: A keyphrase extraction system for English and Arabic documents", Samhaa R. El-Beltagy a, Ahmed Rafea" - Information Systems, Volume 34, Issue 1, March 2009, Pages 132-144

44 "YAKE! Keyword extraction from single documents using multiple local features".
Ricardo Campos, Vítor Mangaravite, Arian Pasquali, Alípio Jorge, Célia Nunes, Adam Jatowt
Information Sciences 509 (2020) pages 257–289 »

45 "Automatic Keyword Extraction from Individual Documents. Text Mining: Applications and Theory. 1"; Rose, Stuart & Engel, Dave & Cramer, Nick & Cowley, Wendy. (2010): - 20.10.1002/9780470689646.ch1.

Table 1: Processes and searches used for detecting raw weak signals using scientific publications.

Detection of weak signals using Scientific Publications		
Topic	**Process**	**Search**
Advanced Biofuel	targeted search	topic:("advanced biofuel") AND source:scopus
Battery	large process	coverage "battery" on field description
CCUS	targeted search	topic:("carbon capture" OR CCUS) AND source:scopus
biomass	large process	coverage "biomass" on field description
geothermal	targeted search	topic:("geothermal power"~2 OR "geothermal electricity"~3 OR "geothermal heating"~2 OR "geothermal energy" OR "geothermal direct use") AND source:scopus
renewable fuels	targeted search	topic:("renewable fuels") AND source:scopus
energy storage	targeted search	topic:("energy storage") AND source:scopus
smart grid	targeted search	topic:("smart grid") AND source:scopus
district heating	targeted search	topic::("district heating") AND source:scopus
ocean energy	targeted search	topic:("ocean energy") AND source:scopus
Hydropower	large process	coverage "hydropower" on field description
PV	large process	coverage "photovoltaics" on field description
Wind	large process	coverage "wind" on field description
Bioenergy	large process	coverage bioenergy on field "description"
Energy	large process	coverage energy on field "description"
Energy	large process	coverage "2100;2101;2102;2103;2104;2105" on field "scopus journal categories"

Table 2: Processes and searches used for detecting raw weak signals using patents.

Detection of weak signals using Patents		
Advanced Biofuel	**targeted search**	**topic:("biofuel") AND source:patstat**
Battery	large process	coverage battery on field "description"
CCUS	targeted search	topic:("carbon capture" OR CCUS) AND source:patstat
biomass	targeted search	topic:(biomass AND (energy OR power) AND (production OR generation)) AND source:patstat
geothermal	targeted search	topic:("geothermal")
renewable fuels	targeted search	topic:("renewable fuels") AND source:patstat
energy storage	targeted	topic:("energy storage") AND source:patstat
smart grid	targeted	topic:("smart grid") AND source:patstat
district heating	targeted	topic::("district heating") AND source:scopus
ocean energy	targeted	topic:("ocean energy") AND source:patstat
Hydropower	large process	coverage hydropower on field "description"
PV	large process	coverage photovoltaics on field "description"
Wind	large process	coverage Wind on field "description"
Bioenergy	large process	coverage bioenergy on field "description"
Energy	large process	coverage energy on field "description"
Energy	large process	coverage "Y02E" on field "CPC classes"

Table 3: search queries for subtopics.

Search queries for subtopics	
Subtopics	**Search queries**
Air energy storage	topic:("air energy storage"~2)
Biofuel feedstock	topic:("biofuel feedstock"~4)
Biomass in energy	topic:("biomass heat production"~5 OR "biomass heat generation"~5 OR " biomass power production"~5 OR "biomass power generation"~5 OR "biomass electricity production"~5 OR "biomass electricity generation"~5 OR "biomass heat and power"~3 OR "biomass chp production"~5 OR "biomass chp plant"~2 OR "biomass energy source"~3 OR "biomass energy production"~3)
Compressed Air Energy Storage	topic:("Compressed Air Energy Storage"~2)
Concentrated solar power	topic:("concentrated solar power" OR "solar thermal electricity")
Deep geothermal	topic:("deep geothermal")
Energy storage supercapacitors	topic:("energy storage supercapacitors"~2)
Heat pumps	topic:("heat pumps") AND emm_year:[2012 TO 2023]
High-performance supercapacitor	topic:("high-performance supercapacitor")
Hydrogen storage	topic:("hydrogen storage" OR "H2 storage") AND emm_year:[2012 TO 2023]
Organic Rankine cycle	topic:("Organic Rankine cycle")
Photovoltaic waste	topic:("photovoltaic waste"~2 OR "PV waste"~2 OR "solar waste"~1 OR "photovoltaic recycling"~2 OR "PV recycling"~2)
Renewable fuels	topic:((renewable AND fuel) AND (RFNBO OR "non biological" OR electrofuel OR "electro fuel" OR "synthetic fuel" OR "recycled carbon fuel" OR efuel OR "e-fuel" OR ammonia OR "e-alcohol" OR "synthetic alcohol" OR "e-diesel" OR "synthetic diesel" OR "e-gasoline" OR "synthetic gasoline" OR "synthetic petroleum" OR "e-methane" OR "e-jet" OR "e kerosene" OR "synthetic kerosene" OR "e-butanol" OR "synthetic butanol" OR "e-methanol" OR "synthetic methanol" OR "e-ethanol" OR "synthetic ethanol" OR "e-ammonia" OR "synthetic natural gas" OR "synthetic methane"))
Renewable fuels 2	topic:("renewable fuels")
Smar grids	ti:("smart grid") AND emm_year:[2012 TO 2023]
Smart energy	topic:(("smart energy"~1 OR "smart grid") AND ("digital infrastructure" OR "IT infrastructure" OR "ICT infrastructure"))
Smart grid	topic:(blockchain AND "smart grid")
Solar fuel	topic:("solar fuel")
Solid state batteries	topic:("solid state batteries")
Thermo chemical energy storage	topic:("thermo chemical energy storage"~2 OR "thermochemical energy storage"~2)

1.2.3.5 Reconstruction of raw weak signals in TIM Technology

To arrive at the final selection of weak signals, new sets of documents are created for each of the 280 promising raw weak signals in the TIM Technology system which, in addition to scientific publications and patents, also contains EU R&D grants. This phase involves extensive manual work as well as expert validation to maximize the recall of relevant documents. This involves optimising the search queries to increase the recall of documents by e.g. including synonyms and alternative wording that are commonly used within the field, and to further validate the list of signals by analysing the documents they contain. Because of the semantic nature of the process, it may be that what was initially identified as a weak signal appears in reality to be a strong signal (e.g. a well-established trend or a long-known issue). For example, a new term or semantic concept can appear in the context of a technology after a few years, creating the appearance of novelty although the technology itself is not new. False positives can also include typographical errors or references to specific conference names. Domain knowledge can be used to enrich the search queries for a particular scientific area or policy field. For the present exercise, experts from JRC have been consulted to improve the search queries.

1.2.3.6 Selection of the Weak Signals

After careful revision and improvement of the queries for the 280 raw weak signals, the selection of weak signals has been made using two criteria:

- raw weak signals with activeness[2020-2023] between 70% and 100% have been automatically considered as weak signals.

- raw weak signals activeness[2020-2023] between 50% and 70% but with a strong increase of the number of scientific publications over the last three years have been added to the list of weak signals as well.

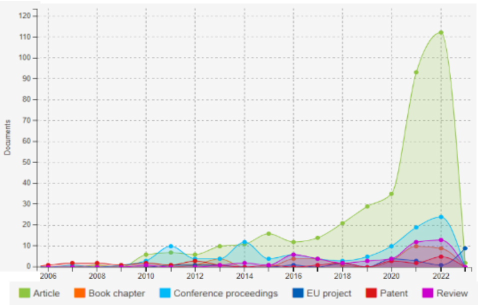
As a result, 77 weak signals were selected and are presented in this report. They are listed in Table 4 below, grouped by CETO categories.

1.2.3.7 Description of the Weak Signals

Chapter 2 of this report presents the 77 weak signals detected. In addition to a short description, five visualisations are provided for each signal:

1. A time series of the documents behind each weak signal, including 6 document types: scientific articles, book chapter, conference proceedings, patents, EU projects, review papers. The colour coding is the same for all weak signals.

Figure 2: time series for the document types for the weak signal "sustainable aviation fuel".



2. Top 5 Organisations worldwide, based on the number of documents (minimum 2 documents).

3. Top 5 organisations in EU (27 Member States), based on the number of documents.

4. Share of public institutions (universities, governmental organisations and research centres) and of private entities (companies, fundations).

5. Revealed Technological Advantage (RTA), adapted to weak signals, for the United States, Japan, China, Korea, and the EU (27 Member States). This index is adapted from the OECD definition of the RTA[46] and gives an indication of the relative specialisation of a country in a weak signal. It is based on scientific publications in Scopus and defined as a country's share of scientific publications in a particular weak signal divided by the country's share in all scientific publications. The index is equal to zero when the country holds no scientific publications in a given weak signal, is equal to 1 when the country's share in the WS equals its share in all fields (no specialisation), and is above 1 when a specialisation is observed.

[46] OECD (2023), "OECD Science, Technology and Industry Outlook: Revealed technology advantage in selected fields", OECD Science, Technology and R&D Statistics (database), https://doi.org/10.1787/data-00673-en

Table 4: List of weak signals (with the value for activeness [2020-2023]).

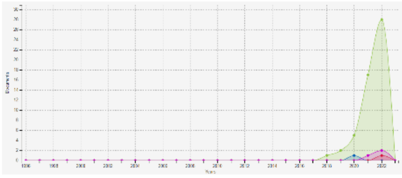
Dataset	act20-23	Dataset	act20-23
batteries - Zn CO2	94.83	energy storage - Zn hybrid supercapacitor	90.09
batteries - quasi-solid-state Li-Metal	93.33	energy storage - K hybrid capacitor	86.51
batteries - aqueous zinc	88.43	energy storage - polyetherimide	85.48
batteries - K metal	85.23	energy storage - aqueous hybrid supercap	80.56
batteries - flexible Zinc ion	81.25	energy storage - K hybrid supercapacitor	80.00
batteries - small molecule organic cath	76.00	energy storage - mxene supercapacitors	79.48
batteries - human-robot recycling	75.00	energy storage - h2 in aquifers	78.26
batteries - Zinc graphite	75.00	energy storage - electrochromic	77.24
batteries - retired batteries	74.25	energy storage - shared energy storage	75.71
batteries - dendrite-free	74.07	energy storage - compressed CO2	72.39
batteries - multivalent ion	68.31	energy storage - MOF-based suprcapacitor	71.04
Batteries - Li CO2	65.22	energy storage - cloud energy storage	63.77
batteries - dual ion	64.65	energy storage - nanoencap phs chang mat	61.76
batteries - Al suflur batteries	62.67	energy storage - mobile energy storage	61.25
batteries - Zn air	59.67	energy storage - aqueous supercap	61.16
batteries - Mg Sulfur	57.69	energy storage - liquid organic h2 carr	59.25
batteries - Lithium Argyrodite	57.33	energy storage - metal foam phas chng ma	56.30
batteries - Organic Flow	56.90	energy storage - shell-and-tube thermal	55.49
biomass - chemical looping gasification	67.39	PV - indoor organic PV	88.41
		PV - Agrivoltaics	87.63
CCUS - Blue h2	90.67	PV - tin perovskite solar cells	77.15
CCUS - deep eutectic solvents	55.56	PV - bifacial perovskite solar cell	75.61
		PV - vehicle integrated PV	71.88
district heating - 5th generation	92.31	PV - Perovskite/silicon tandem sol cells	66.87
district heating - digital twin	90.91	PV - offshore solar power	62.76
district heating - urban building energy	63.94	PV - hydrovoltaics	60.55
		PV - ternary organic photovoltaics	54.72
geothermal - hybrid nanofluid	100.00		
geothermal - medium deep geothermal ener	78.43	Renewfuel - Direct seawater electrolysi	89.19
geothermal - deep borehole heat exchange	66.67	RenewFuel - sustainable ammonia	85.84
		RenewFuel - cold direct ammonia fuel cel	79.17
ocean - triboelectric nanogenerator	68.10	RenewFuel - geological H2 storage	72.57
		RenewFuel - Sustainable aviation fuel	60.06
other - interfacial solar evaporation	94.00		
other - hemispherical solar distiller	89.74	smart grid - blockchain	76.29
other - energy injustice	74.07	smart grid - edge computing	72.94
other - microgrid island clusters	73.68	smart grid - electricity theft detection	66.05
other - lacustrine shale oil	54.49	smart grid - machine learning	64.60
other - Levelized cost of hydrogen	82.08	smart grid - Internet of things	53.26
other - Levelized cost of storage	82.03		
other - Levelized cost of heat	67.67	Solar fuel - S scheme heterojunction cat	99.20
		Solar Fuel - covalent organic framework	85.71
Wind - wake steering	74.17	Solar fuel - Z scheme heterojunction cat	82.97
Wind - fast frequency support	64.91	Solar Fuel - photocatalytic CO2 reductio	63.47
		Solar fuel - PEC CO2	56.52

2. Description of the weak signals related to Energy

2.1 Weak signals related to Batteries

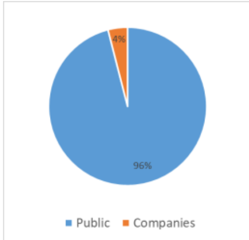
Zinc CO2 batteries

These batteries operate on the principles of electrochemical reactions involving zinc as the anode material and carbon dioxide as the cathode material. They have gained attention for their potential advantages: high energy density, abundance and low cost materials, low environmental impact, long life cycle, carbon capture, high safety; scalability, fast charging/discharging, ease to integration to the grid, versatility for applications ranging from portable electronics to stationary energy storage. Still at laboratory stage, Zinc CO2 batteries might become a sustainable energy storage solution for the future.

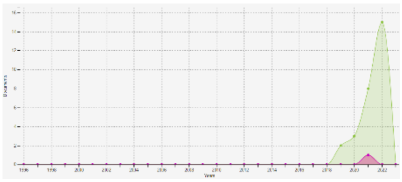


Top organisations	Value
Chinese Academy Of Sciences	18
Zhejiang University	10
Tianjin University of Technology	8
Zhengzhou University	7
Central South University	5

Top EU organisations	Value
Technische Universität Dresden	2
Université Clermont Auvergne	1
Technical University of Ilmenau	1

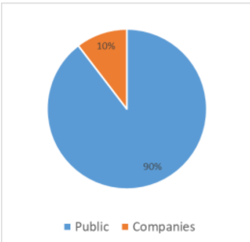


Country	RTA
CN	3.95
EU	0.40
JP	0.50
KR	0
US	0.81



Top organisations	Value
Chinese Academy Of Sciences	8
Karlsruhe Institute of Technology KIT	3
Helmholtz Institute Ulm	3
Cheongju University	3
Shenzhen University	2

Top EU organisations	Value
Karlsruhe Institute of Technology KIT	3
Helmholtz Institute Ulm	3
University of the Basque Country UPV…	1
University of Oulu	1
Politecnico di Torino	1



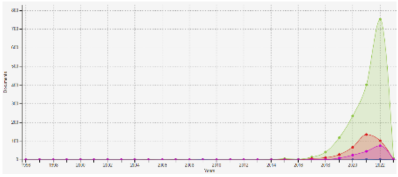
Country	RTA
CN	3.50
EU	1.10
JP	0
KR	4.07
US	0

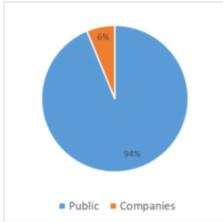
Quasi-solid-state Li-metal batteries

This type of battery is an advanced Li-ion battery technology that incorporates a solid or gel-like electrolyte material, to replace or enhance the traditional liquid electrolyte found in conventional Li-ion batteries. These batteries offer several advantages due to their unique design: enhanced safety, high energy density, longer life cycle, a wide operating temperature range, a reduced risk of dendrite formation, improved fast charging, flexibility in their design, and use of more environmentally friendly materials. There are still challenges to address related to manufacturing scalability, cost reduction, and further improving their performance and safety.

Aqueous Zinc batteries

These use a water-based electrolyte and offer several advantages that make them attractive for various applications. They are safer compared to other chemistries and are cost-effective (zinc is abundant and relatively low-cost). They have the potential for high energy density, a low self-discharge rate and can endure many rapid charge/discharge cycles. Their durability, long cycle life, and ability to withstand harsh conditions make them suitable for remote and off-grid applications (telecommunications towers, remote sensors). Finally, they are considered environmentally friendly due to their water-based electrolyte and the high recyclability of zinc. Various aqueous zinc batteries are being investigated e.g. zinc-nickel batteries, zinc-iron batteries, zinc-manganese batteries, zinc-air batteries, zinc-silver batteries, zinc-chlorine flow batteries, zinc-Manganese dioxide flow batteries, zinc-cerium batteries.





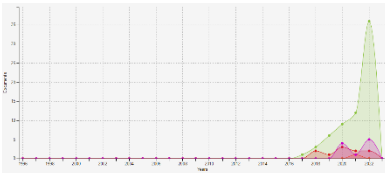
Top organisations	Value
Central South University	164
Chinese Academy Of Sciences	142
Nankai University	77
University of Science and Technology ...	56
Fudan University	56

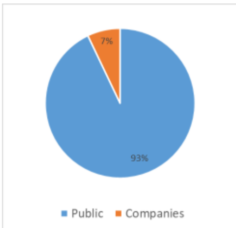
Top EU organisations	Value
Leibniz Institute for Solid State and Materials Resea...	9
Karlsruhe Institute of Technology KIT	9
Universität Bremen	7
Helmholtz Institute Ulm	7
Fraunhofer Institute for Manufacturing Technology a...	3

Country	RTA
CN	3.58
EU	0.16
JP	0.34
KR	1.28
US	0.36

Potassium metal batteries

They use potassium as the anode material and are interesting for energy storage applications due to: potential for high energy density, abundant and low-cost material (potassium), high charge and discharge rates for rapid energy transfer and high-power performance, low self-discharge rate, increased safety compared to other types of batteries, and finally, potassium is a more environmentally friendly material compared to some other metals used in batteries, such as lithium or cobalt. Research is ongoing to avoid the formation of dendrites, increase electrolyte compatibility, and optimize production costs. As the technology matures, it has the potential to become a competitive energy storage solution for various industries and applications.





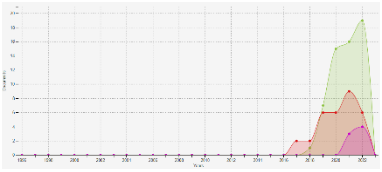
Top organisations	Value
University of Texas at Austin	9
University of Science and Technology of China	6
Central South University	6
Tsinghua University	5
Shanghai University	5

Top EU organisations	Value
Karlsruhe Institute of Technology KIT	2
International Graduate School	1
Fraunhofer Institute for Ceramic Technologies and ...	1
CNRS	1
Avenida Mestre Jose Veiga	1

Country	RTA
CN	3.26
EU	0.44
JP	0.78
KR	1.08
US	1.35

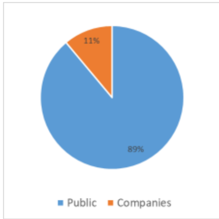
Flexible zinc-ion batteries

They are a promising energy storage technology for various applications, particularly those requiring flexibility, lightweight design, and safe operation. These batteries are indeed lightweight and can conform to various shapes and sizes without compromising their performance, which is particularly valuable for applications like wearable electronics where traditional rigid batteries are impractical. They are also safer and have a lower environmental impact than some other battery chemistries, such as lithium-ion batteries. As zinc is affordable and relatively abundant, zinc-ion batteries are also cost-effective. This is still an emerging battery type, which requires research to optimise their performance (notably to improve the energy density) and explore new applications.



Top organisations	Value
City University of Hong Kong	9
University of Science and Technology of China	6
Nanjing Forestry University	6
Nankai University	5
DONGHUA UNIVERSITY	4

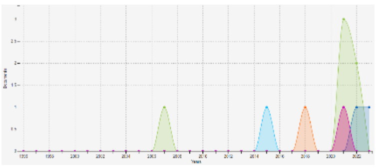
Top EU organisations	Value
Universidad de Alcalá	1



Country	RTA
CN	3.60
EU	0.15
JP	0
KR	0.64
US	0.57

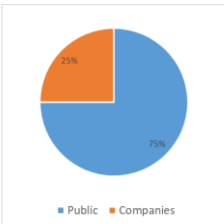
Human-robot collaboration in battery recycling

This involves assisting humans with robotic systems to enhance the recycling process of batteries. This “collaboration” offers various advantages: increased safety (robots can handle hazardous materials), improved efficiency (continuous, precise robotic work), better quality control, and the ability to collect and analyse data. Robots bring flexibility, scalability, and adaptability to recycling operations, and they help reduce the environmental impact of batteries by recovering valuable materials. Additionally, they address labour shortages, ensuring that recycling facilities can operate effectively even with limited human resources.



Top organisations	Value
TU Braunschweig	1
Technische Universität Braunschweig	1
SKODA AUTO AS	1
Harbin University of Science and Technology	1
DIRECT CONVERSION AB	1

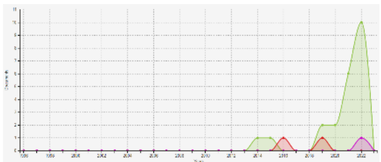
Top EU organisations	Value
ERION COMPLIANCE ORGANIZATION SCARL	1
FUNDACIO EURECAT	1
SKODA AUTO AS	1
Technische Universität Braunschweig	1
WASTE OF ELECTRICAL AND ELECTRONICAL EQUIPMENT FORUM AISBL	1



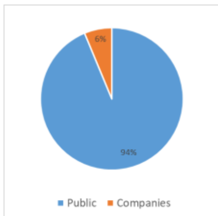
Country	RTA
CN	2.05
EU	0.71
JP	0
KR	0
US	0.90

Small molecule organic cathode

This type of cathode material used in batteries consists of relatively simple organic molecules with low molecular weights. These offer several advantages in battery applications. They provide high energy density (allowing them to store a significant amount of energy) and can be lightweight and flexible, which makes them particularly suitable for applications like portable electronics and electric vehicles. Additionally, they support fast charge and discharge rates, are customizable, environmentally friendly, and cost-effective. However, they also face challenges when it comes to their long-term stability and research and development are ongoing to address this.



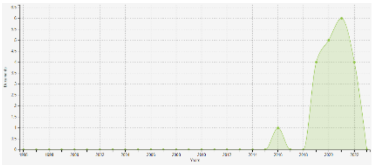
Top organisations	Value
University of Electronic Science and Technology of China	8
Wuhan University	2
National Cheng Kung University	2
Chinese University of Hong Kong	2
Chinese Academy Of Sciences	2



Country	RTA
CN	3.46
EU	0
JP	1.39
KR	0
US	0.85

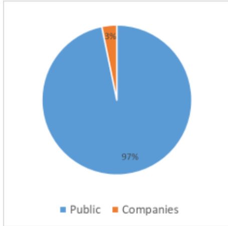
Zinc Graphite battery

These batteries offer several advantages particularly in specific applications. They have a low production cost, a long shelf life and because they contain non-toxic materials they can easily be disposed of regular household waste. However, zinc-graphite batteries also have limitations, including lower capacity and performance compared to more advanced battery technologies like alkaline, nickel-metal hydride (NiMH), and lithium-ion (Li-ion) batteries. Therefore, while zinc-graphite batteries offer advantages in terms of cost and simplicity, additional R&D is needed to make them suitable for high-drain or demanding applications.

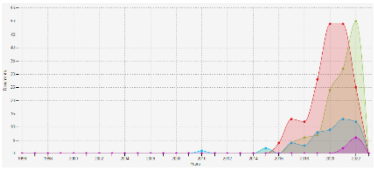


Top organisations	Value
Chinese Academy Of Sciences	5
Technische Universität Dresden	3
Leibniz-Institut für Polymerforschung Dresden E.V.	2
Chulalongkorn University	2
Czech Academy of Sciences	1

Top EU organisations	Value
Technische Universität Dresden	3
Leibniz-Institut für Polymerforschung Dresden E.V.	2
TU Chemnitz	1
Technology Centre	1
Czech Academy of Sciences	1

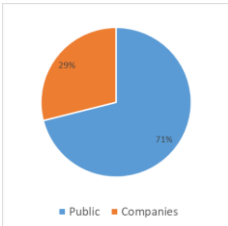


Country	RTA
CN	3.01
EU	1.41
JP	1.76
KR	0
US	0.36



Top organisations	Value
STATE GRID	19
Tsinghua University	17
Shandong University	17
Shanghai University of Electric Power	14
China University of Mining and Technology	14

Top EU organisations	Value
School of Electrical Engineering	4
University of Limerick	2
RWTH Aachen University	2
Aalto University	2
Institut de Recerca en Energia de Catalunya	1



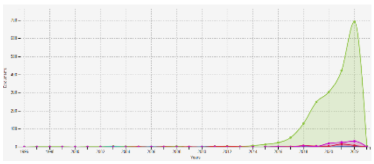
Country	RTA
CN	3.19
EU	0.43
JP	0
KR	0.74
US	0.40

Retired batteries

This refers to batteries that are no longer suitable for their original intended purpose. They have typically undergone numerous charge/discharge cycles and have reduced capacity and overall performance. Their residual capacity makes them nonetheless potentially adequate for less demanding applications, such as energy storage for stationary systems. Recycling and proper disposal of retired batteries are essential to mitigate environmental impacts and recover valuable materials like lithium, cobalt, and nickel. Recycling can also help reduce the demand for new raw materials and promote sustainability in the battery industry.

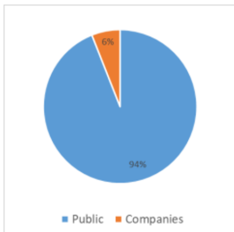
Dendrite-free lithium-ion batteries

Getting rid of dendrite formation is one of the important quests in the development of lithium-ion batteries. Dendrite-free batteries will be safer, more reliable and have an extended lifetime. Dendrites are tiny needle-like structures that can form on the electrodes of certain types of batteries, particularly lithium-ion. Recent efforts in battery research focus on preventing dendrite formation through the use of e.g. advanced materials or improved battery designs. The absence of dendrites would significantly reduce the risk of short circuits and thermal runaway, making batteries much safer, particularly in applications like electric vehicles and consumer electronics.



Top organisations	Value
Chinese Academy Of Sciences	243
Tsinghua University	120
University of Science and Technology of China	86
Central South University	84
Zhengzhou University	67

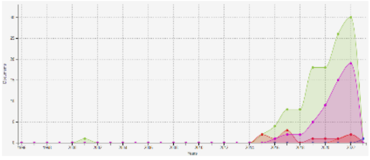
Top EU organisations	Value
Helmholtz Institute Ulm	16
Karlsruhe Institute of Technology KIT	13
International Graduate School	9
Uppsala University	7
Technische Universität Dresden	7



Country	RTA
CN	3.55
EU	0.23
JP	0.42
KR	1.78
US	0.57

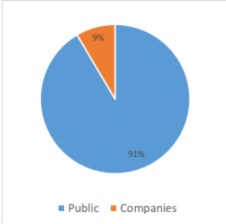
Multi-ion batteries

A promising type of rechargeable battery that utilises the movement and storage of multiple types of ions, extending beyond traditional lithium-ion batteries. Their advantages include a higher energy density, faster charging and discharging rates, and a reduced risk of lithium dendrite formation. They also use materials that are both abundant and ecologically responsible. Their characteristics make them suitable for a variety of applications, including electric vehicles, renewable energy storage, and grid-scale energy storage.



Top organisations	Value
Chinese Academy Of Sciences	12
Wuhan University of Technology	9
National University of Singapore	7
Argonne National Laboratory	6
Nanyang Technological University	5

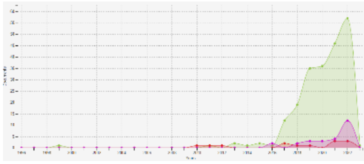
Top EU organisations	Value
CNRS	3
Helmholtz Institute Ulm	3
Institut de Ciència de Materials de Barcelona	2
Max Planck Institute for Solid State Research	2
Sorbonne University	2



Country	RTA
CN	2.60
EU	0.39
JP	0.66
KR	3.36
US	0.81

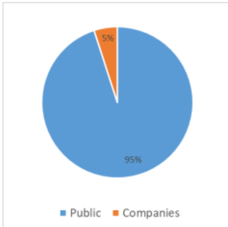
Lithium-Carbon Dioxide batteries

An experimental battery technology with several potential advantages: high energy density, the use CO2 from the atmosphere, showing therefore potential for carbon capture and utilization. Li-CO2 batteries can offer a long cycle life (many charge/discharge) and can be used in various applications, from storing intermittent renewable energy to powering portable electronics and electric vehicles. Li-CO2 batteries are still in the R&D phase, and many technical challenges need to be addressed before they can be widely adopted (e.g. improving CO2 reduction, ensuring safety in practical applications).



Top organisations	Value
Chinese Academy Of Sciences	31
Nanjing University	17
Zhengzhou University	15
Fudan University	14
Jilin University	9

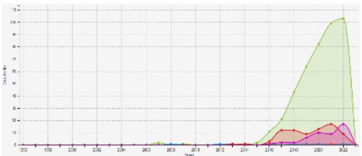
Top EU organisations	Value
Collège de France	2
CNRS	2
LAMPERT RICO	1
Bosch Corp	1
ALISTORE-European Research Institute	1



Country	RTA
CN	3.49
EU	0.05
JP	1.50
KR	1.38
US	0.48

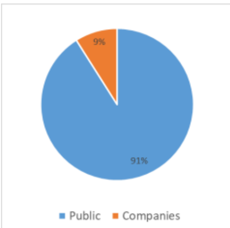
Dual-ion batteries

A specific type of multi-ion battery technology that uses two different types of ions (usually lithium and one other). These batteries offer several advantages: potentially higher energy density and faster charging/discharging rates, improved cycle life, and reduced environmental impact through the use of eco-friendly materials. They also tend to generate less heat during operation and mitigate issues such as lithium dendrite formation, enhancing overall safety. Dual-ion batteries are still in the R&D phase, and their wide adoption may take some time.



Top organisations	Value
Chinese Academy Of Sciences	112
University of Science and Technology of China	48
City University of Hong Kong	25
Northeast Normal University	22
University of Münster	21

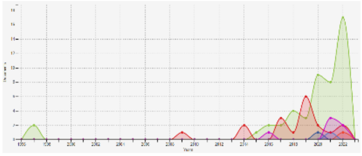
Top EU organisations	Value
University of Münster	21
Forschungszentrum Jülich	18
Technische Universität Dresden	9
Helmholtz Institute Ulm	4
CNRS	4

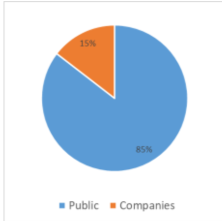


Country	RTA
CN	2.93
EU	0.42
JP	1.30
KR	1.13
US	0.43

Aluminium-sulphur batteries

Experimental rechargeable battery systems that offer several potential advantages like a high energy density, relying on the use of abundant and sustainable materials (aluminium and sulphur), environmental friendliness due the use of non-toxic and non-flammable components, potential contributions to reducing greenhouse gas emissions, long cycle life and fast charging/discharging capabilities, and the potential to operate efficiently at high temperatures. However, R&D is still ongoing to address issues like cathode degradation and more suitable electrolytes.





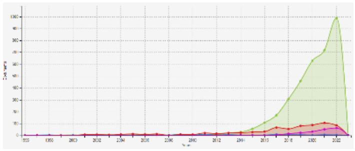
Top organisations	Value
Chinese Academy Of Sciences	8
China University of Mining and Technology	7
University of Southampton	5
University of Science and Technology of China	5
Shanghai Jiao Tong University	5

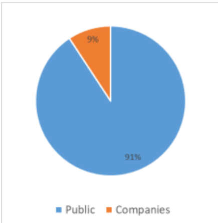
Top EU organisations	Value
Technical University of Denmark	3
Technische Universität Berlin	2
Technische Universität Graz	1
SOLVIONIC SA	1
AGENCIA ESTATAL CONSEJO SUPERIOR DE INVESTIGACIONES CIENTIFICAS	1

Country	RTA
CN	2.81
EU	0.62
JP	0.64
KR	0
US	0.26

Zinc-air batteries

This type of battery is under development for its various advantages: high energy density, cost-effectiveness and eco-friendliness (zinc is both non-toxic and cheap), long shelf-lie, safety, reliable voltage output throughout the discharge cycle (stable power supply). Non-rechargeable zinc-air batteries find use in various applications, including hearing aids, medical devices, remote sensors, and backup power systems. Researchers are actively exploring the development of rechargeable variants, a promising advancement that would extend their lifespan and reduce waste. Another concern is the limited cycle life in certain designs and the gradual consumption of the zinc anode, fostering research efforts to optimize the technology and expand its applications.





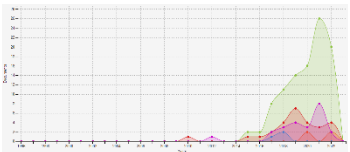
Top organisations	Value
Chinese Academy Of Sciences	426
Tsinghua University	132
University of Science and Technology of China	130
Beijing University of Chemical Technology	119
Tianjin University	111

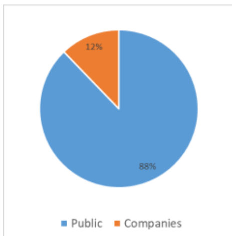
Top EU organisations	Value
Technische Universität Dresden	18
Ulm University	13
Technical University of Denmark	13
Helmholtz Institute Ulm	12
University of Salento	11

Country	RTA
CN	3.45
EU	0.27
JP	0.72
KR	1.64
US	0.38

Magnesium-sulphur batteries

These are a type of rechargeable battery that utilizes magnesium as the anode and sulphur as the cathode, with an electrolyte facilitating ion movement. They have a potential for high energy density, low cost, and environmental friendliness, as magnesium is abundant and non-toxic, and sulphur is also readily available. During discharge, magnesium ions migrate from the anode to the cathode, reacting with sulphur to form magnesium sulphide, releasing energy. Rechargeability is achieved by reversing this process. Although still in the R&D phase, the Mg-S battery might become of interest for energy storage applications.





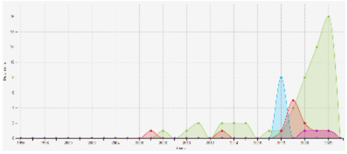
Top organisations	Value
Chinese Academy Of Sciences	24
Helmholtz Institute Ulm	15
Shanghai Jiao Tong University	13
Karlsruhe Institute of Technology KIT	13
Tsinghua University	10

Top EU organisations	Value
Helmholtz Institute Ulm	15
Karlsruhe Institute of Technology KIT	13
University of Stuttgart	11
Ulm University	5
Max Planck Institute for Solid State Research	5

Country	RTA
CN	1.61
EU	1.50
JP	0.33
KR	0.93
US	0.82

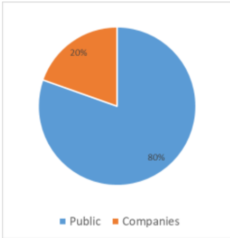
Lithium argyrodite

A solid-state electrolyte material under investigation for advanced lithium-ion batteries, known for its potential to enhance battery safety and performance. This material conducts lithium ions as a solid-state material, reducing the risk of flammability and thermal issues associated with liquid electrolytes. It can support higher energy density, potentially enabling the use of lithium metal anodes and extending cycle life. Practical implementation is still in the research and development phase, with challenges related to scalability, cost, and electrode interface to be overcome before commercial adoption.



Top organisations	Value
Justus-Liebig-University Giessen	9
Mitsui Corp	8
Huazhong University of Science and Technology	8
University of Münster	6
National University of Singapore	6

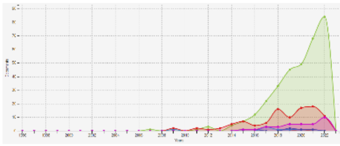
Top EU organisations	Value
Justus-Liebig-University Giessen	9
University of Münster	6
Karlsruhe Institute of Technology	5
Technische Universität München	3
Max Planck Institute for Solid State Research	2



Country	RTA
CN	1.69
EU	1.41
JP	3.39
KR	4.70
US	0.97

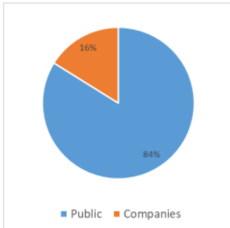
Organic flow batteries

This type of flow battery uses organic molecules dissolved in an electrolyte solution to store electrical energy, offering distinct advantages over traditional solid-state batteries. They use two separate tanks for the electrolyte solution, with the energy stored and released by reversible redox reactions in the organic molecules. Organic flow batteries are scalable, adaptable (variety of organic molecules), safe, and environment-friendly. They find applications in e.g. grid-scale energy storage, renewable energy integration, backup power systems, or load shifting within electric grids. Ongoing research focuses on enhancing their energy density and cost-effectiveness to make them more competitive in various energy storage applications.



Top organisations	Value
Harvard University	28
CHINASALT JINTAN CO., LTD.	23
Joint Center for Energy Storage Research	21
Pacific Northwest National Laboratory	20
University of Science and Technology of China	18

Top EU organisations	Value
Friedrich-Schiller-University Jena	14
Aalto University	9
Technical University of Denmark	8
CNRS	7
JenaBatteries GmbH	5

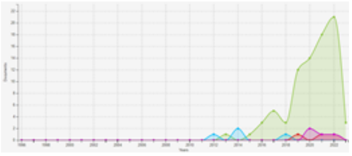


Country	RTA
CN	1.27
EU	1.19
JP	0.12
KR	2.95
US	1.23

2.2 Weak signals related to Biomass

Chemical looping gasification

This process is used to convert biomass, coal, or natural gas, into high purity syngas for the production of clean energy, chemicals, or fuels. When biomass is used, it not only provides a cleaner way to produce syngas but also has the potential to be carbon-neutral when the carbon emissions are captured and stored. The use of biomass in chemical looping gasification aligns with the goals of reducing carbon emissions, promoting sustainable energy production, and minimizing the environmental impact associated with energy and fuel production. It is a promising technology for a cleaner and more sustainable energy future.



Top organisations	Value
Chinese Academy Of Sciences	17
Southeast University	12
South China University of Technology	6
Instituto de Carboquimica ICB-CSIC	5
Nanyang Technological University	4

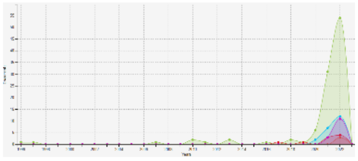
Top EU organisations	Value
Instituto de Carboquimica ICB-CSIC	5
Hamburg University of Technology	2
Forschungszentrum Jülich	2
National Renewable Energy Centre	1
CSIC	1

Country	RTA
CN	2.81
EU	1.13
JP	0.88
KR	0
US	0.27

2.3 Weak signals related to Carbon Capture, Utilisation and Storage

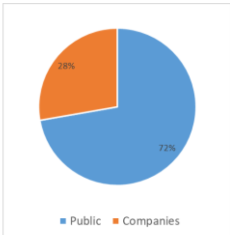
Blue hydrogen

Name given to hydrogen produced by natural gas through a process called steam methane reforming. The primary advantage of blue H2 is its potential to significantly reduce carbon emissions compared to "grey" hydrogen. By capturing and storing CO2 emissions, blue hydrogen production processes can achieve a much lower carbon footprint, making it an attractive option for industries seeking to decarbonize. Ongoing research efforts focus on making its production more efficient and sustainable while continuing to reduce its carbon footprint (it still relies on natural gas, a finite fossil resource). The future of blue hydrogen depends on the effective implementation of carbon capture and storage technologies and the availability of suitable storage sites.



Top organisations	Value
STIFTELSEN SINTEF	6
University of Calgary	4
Rice University	4
Low Carbon Energies	4
China University of Mining and Technology	2

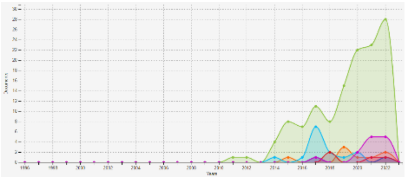
Top organisations	Value
Universidad Politécnica de Madrid	3
Politecnico di Milano	3
NL ORGANISATIE VOOR TOEGEPAST NATUURWETENSCHAPPELIJK ONDERZOEK TNO	2
Delft University of Technology	2
Lorraine Université d'excellence (Impact UHLYS)	1

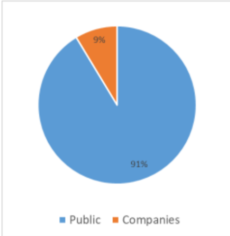


Country	RTA
CN	0.35
EU	1.51
JP	0.41
KR	1.70
US	1

Deep eutectic solvents for Carbon Capture, Utilization, and Storage

This emerging and promising class of materials can be used as absorbents to capture CO2 from flue gas emissions of industrial processes, such as power plants, cement plants, and refineries. The solvents chemically react with CO2, effectively removing it from the exhaust gases. They can also be used in post-combustion carbon capture technologies, where they are used in contactor columns or packed beds to capture CO2. Deep eutectic solvents require low energy input, have a high CO2 absorption capacity, and have low volatility hence low solvent loss and minimized emissions to the atmosphere. Their properties such as viscosity, density, and polarity, can be adjusted to suit specific conditions to allow not only CO2 capture but also the capture of other industrial gases. They have a low environmental impact and can be regenerated and reused for multiple capture cycles, reducing the overall cost of capture. Practical implementation in large-scale industrial settings may require further refinement and cost reduction. However, the potential of deep eutectic solvent for more sustainable and energy-efficient carbon capture solutions makes them an exciting area of development in CCUS.





Top organisations	Value
Luleå University of Technology	11
Umeå University	9
Universidad de Burgos	9
University of Science and Technology	9
Åbo Akademi University	9

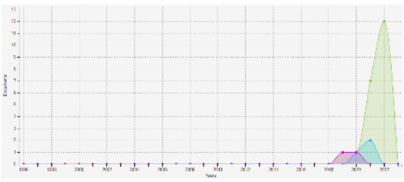
Top EU organisations	Value
Luleå University of Technology	11
Åbo Akademi University	9
Universidad de Burgos	9
Umeå University	9
CSIC	3

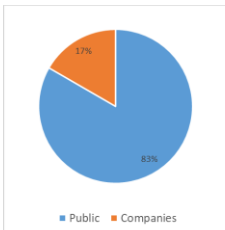
Country	RTA
CN	1.38
EU	1.24
JP	0.29
KR	0.80
US	0.35

2.4 Weak signals related to District Heating

5th-Generation District Heating

These systems promise to provide efficient, sustainable, and environmentally friendly heating and cooling solutions for urban and rural areas They are characterized by several key features and technologies that differentiate them from earlier generations: low-temperature heat sources, energy efficiency by using advanced heat exchangers and heat pumps, smart control systems, integration of various heat sources (including renewable sources), storage of excess heat produced during low demand periods, low environmental impact by using renewable and waste heat sources. These systems are cost effective, flexible and scalable, making them adaptable to different geographical areas and varying energy demands.





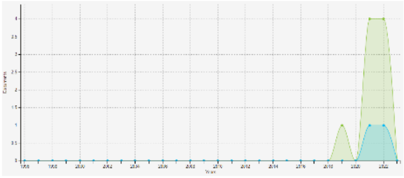
Top organisations	Value
RWTH Aachen University	3
University of Naples Federico II	2
Universidad de Sevilla	2
Riga Technical University	2
Energie PLUS Concept GmbH	2

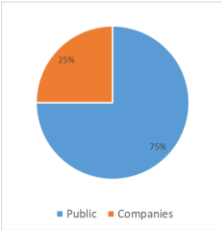
Top EU organisations	Value
RWTH Aachen University	3
University of Naples Federico II	2
Universidad de Sevilla	2
Riga Technical University	2
Energie PLUS Concept GmbH	2

Country	RTA
CN	0.17
EU	3.18
JP	0
KR	0
US	0

Digital twin for district heating

In the field of district heating, a digital twin is a virtual representation of the entire district heating system (physical infrastructure, components, and processes). They are used for a variety of purposes: to enhance the efficiency, reliability, and sustainability of district heating systems (simulation, predictive maintenance, real-time monitoring, demand forecasting, load balancing, etc.). Digital twins play a crucial role in optimizing district heating systems by improving their performance, reducing energy consumption, and enhancing their resilience and sustainability. They are a valuable tool for operators and engineers, helping to meet the increasing demands for efficient and environmentally friendly heating solutions.





Top organisations	Value
Technical University Darmstadt	2

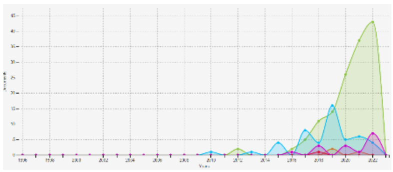
Top EU organisations	Value
Technical University Darmstadt	2
Università degli Studi di Ferrara	1
Luleå University of Technology	1
Graz University of Technology	1
AIT Austrian Institute of Technology GmbH	1

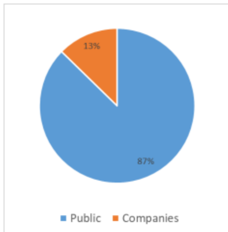
Country	RTA
CN	0.41
EU	2.97
JP	0
KR	0
US	0

Urban building energy

In the context of district heating, this refers to the energy needs of buildings within an urban area or city that are supplied with heat or hot water through a district heating system. District heating systems provide centralized heating to multiple buildings within a specific geographic area, typically a city or urban district, through a network of pipes that distribute hot water or steam from a central heat source, such as a power plant or a dedicated heat generation facility.

The concept of urban building energy in the context of district heating is significant for urban planning, energy management, and sustainability efforts in cities. By optimizing district heating systems and improving the energy efficiency of urban buildings, it is possible to reduce energy consumption, lower greenhouse gas emissions, and enhance the overall sustainability of urban environments.





Top organisations	Value
Massachusetts Institute of Technology	17
Lawrence Berkeley National Laboratory	16
Concordia University	11
Southeast University	8
Hunan University	8

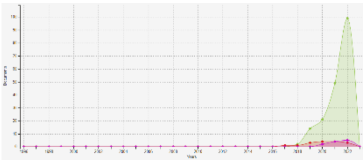
Top EU organisations	Value
Politecnico di Milano	7
University of Padova	5
University College Dublin	5
Uppsala University	4
Delft University of Technology	3

Country	RTA
CN	0.62
EU	1.98
JP	0.60
KR	0.28
US	1.50

2.5 Weak signals related to Energy Storage

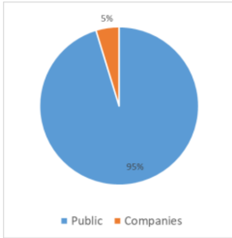
Zinc Hybrid Supercapacitor

This advanced energy storage technology combines the characteristics of a supercapacitor and those of a battery, using zinc-based materials, harnessing the strengths of both to provide high-capacity and high-power energy storage solutions. They have long life cycles, can be charged and discharged rapidly, can operate in a wide temperature range, and are using safe and non-toxic zinc-based materials. In addition, zinc is abundant and environmentally friendly. Recycling options for zinc-based materials are well-established, contributing to the sustainability of zinc hybrid supercapacitors. They can be used in a wide range of applications, including electric vehicles, renewable energy storage, consumer electronics, and industrial equipment, supplementing or replacing batteries. R&D is ongoing to increase their energy density which is still lower than that of traditional lithium-ion batteries, limiting their use for long-term energy storage.



Top organisations	Value
Anhui University	12
Chinese Academy Of Sciences	15
North Minzu University	9
Tsinghua University	8
Xinjiang University	11

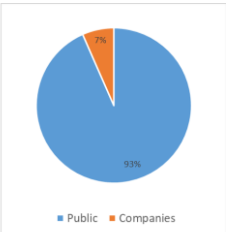
Top EU organisations	Value
Linköping University	3
University of Siegen	2
Universidad de Córdoba	2
Max Planck Institute for Solid State Research	1
Institut Universitaire de France	1



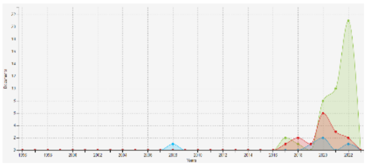
Country	RTA
CN	3.61
EU	0.42
JP	0.88
KR	1.02
US	0.15

Polyetherimide, a new plastic for energy storage applications

This high-performance thermoplastic polymer shows several advantages when used in energy storage applications, particularly in the context of electrochemical energy storage devices like batteries and supercapacitors. PEI exhibits excellent thermal stability, allowing it to withstand elevated temperatures without degradation, and is highly resistant to a wide range of chemicals, including acids, bases, and organic solvents, making it compatible with various electrolyte solutions and additives. In addition, they have high mechanical strength and maintain their dimensional stability and are excellent electrical insulator, ensuring safe operation of energy storage devices. Their unique properties make them suitable for energy storage applications in aerospace or health.



Country	RTA
CN	3.62
EU	0.20
JP	0
KR	0
US	1.28

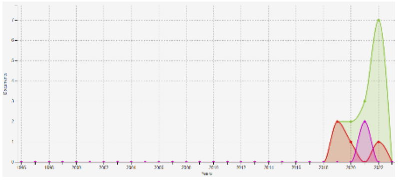


Top organisations	Value
Harbin University of Science and Technology	8
Chinese Academy Of Sciences	7
XI'AN JIAOTONG UNIVERSITY	6
Tsinghua University	6
Pennsylvania State University	4

Top EU organisations	Value
Central European Institute of Technology	1
Deutsches Elektronen-Synchrotron DESY	1
Sapienza University of Rome	1

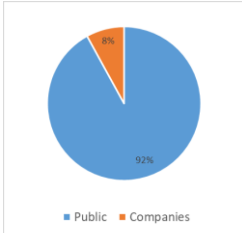
Potassium hybrid capacitor

This is an emerging energy storage device that combines features of a traditional capacitor with potassium ions as the charge carriers. Potassium hybrid capacitors are suited for applications where higher energy storage capacity is more important than quick discharge/charge, and where longer cycle life, and safety (they are non-flammable and with a low risk of thermal runaway) are critical. Potassium-based electrolytes are also more environmentally friendly and easier to recycle than materials used in some other energy storage devices.



Top organisations	Value
Ocean University of China	5
Chinese Academy Of Sciences	2
China University of Petroleum	2
Shaanxi University of Technology	1
Jishou University	1

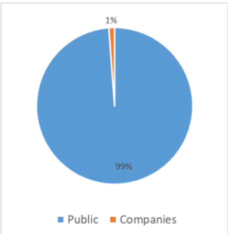
Top organisations	Value
CEA	1
Eberhard-Karls-Universität Tübingen	1



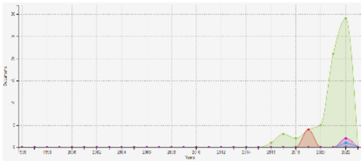
Country	RTA
CN	3.82
EU	0.61
JP	0
KR	0
US	0

Aqueous hybrid supercapacitors

These are advanced energy storage devices combining aqueous electrolyte-based supercapacitors with battery-like electrodes. They typically have one electrode acting as a supercapacitor electrode and another electrode as a battery electrode. This allows aqueous hybrid supercapacitors to store more energy than conventional supercapacitors. They offer several advantages, making them attractive for various energy storage applications (high power density, long life cycle, fast charging, safety, low cost, reduced self-discharge, to name but a few). R&D is ongoing to increase their energy density to make them suitable for long term storage solutions.



Country	RTA
CN	3.06
EU	0.32
JP	0.73
KR	2.02
US	0.45

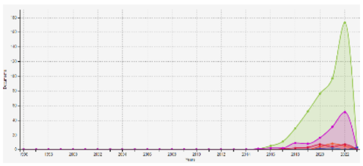


Top organisations	Value
North Minzu University	5
Tsinghua University	4
PEKING UNIVERSITY SHENZHEN GRADUATE S...	3
Lanzhou University	3
East China Normal University	3

Top EU organisations	Value
Chalmers University of Technology	1
Karlsruhe Institute of Technology KIT	1
Luleå University of Technology	1
Universidad Del País Vasco UPV/EHU	1
Universitãe Montpellier	1

MXene supercapacitors

MXenes are two-dimensional nanomaterials with a layered structure, often derived from transition metal carbides, nitrides, or carbonitrides. When used in supercapacitors, they offer several advantages: high energy and power density, rapid charging and discharging, they can endure thousands of charge/discharge cycles without significant degradation and demonstrate good stability and low self-discharging over a wide range of operating conditions. They are produced using abundant/non-toxic materials, making them more environmentally friendly than other nanomaterials. They are safe, flexible and lightweight and suitable for applications like portable electronics, electric vehicles, grid energy storage, renewable energy systems.



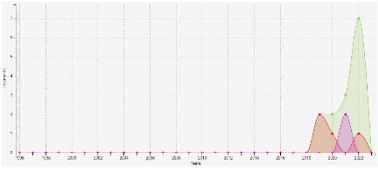
Top organisations	Value
Chinese Academy Of Sciences	39
Drexel University	24
XI'AN JIAOTONG UNIVERSITY	15
Jain University	15
Tsinghua University	12

Top EU organisations	Value
Linköping University	9
University of Chemistry and Technology Prague	7
Trinity College Dublin	7
Universidad de Córdoba	4
Brno University of Technology	3

Country	RTA
CN	2.68
EU	0.48
JP	0.40
KR	2.99
US	0.59

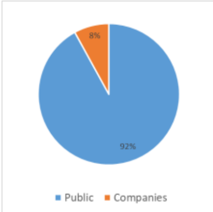
Potassium Hybrid Supercapacitor

This is an emerging energy storage device that combines features of a supercapacitor with potassium ions as charge carriers. This technology offers high power density allowing quick energy release, quick charging and high-power performance, in addition to a wide temperature operating range, scalability, and potential for energy harvesting. Potassium-based electrolytes are also more environmentally friendly and easier to recycle than materials used in some other energy storage devices.



Top organisations	Value
Ocean University of China	5
Chinese Academy Of Sciences	2
China University of Petroleum	2
Shaanxi University of Technology	1
Jishou University	1

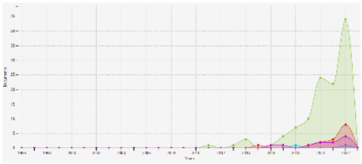
Top EU organisations	Value
CEA	1
Eberhard-Karls-Universität Tübingen	1



Country	RTA
CN	3.82
EU	0.61
JP	0
KR	0
US	0

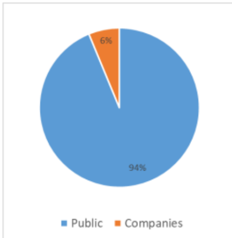
Electrochromic energy storage

These devices can change their optical properties in response to voltage variations, combining energy storage and light modulation capabilities. They dynamically control the amount of sunlight or artificial light entering a space, saving energy by reducing the need for lighting and heating/cooling. They do not store energy in the traditional sense but they modulate the transmission of light and heat, which has energy-saving effects in building and environmental applications. They can be integrated into smart building control systems and use renewable energy sources, enhancing the overall energy efficiency and sustainability of buildings.



Top organisations	Value
Chinese Academy Of Sciences	13
Nanyang Technological University	10
Seoul National University of Science and Technology	9
Beihang University	8
Hefei University of Technology	5

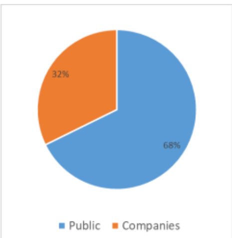
Top EU organisations	Value
Università di Milano-Bicocca	1
Università di Camerino	1
Università di Bologna	1
University of Patras	1
University of Bergamo	1



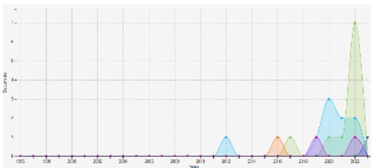
Country	RTA
CN	2.82
EU	0.21
JP	0.27
KR	5.92
US	0.27

Hydrogen storage in aquifers

Underground storage of H2 within geological formations known as aquifers offers several advantages: extensive storage capacity, allowing for the accumulation of substantial hydrogen quantities to meet varying energy demands; release of stored H2 during peak demand periods or energy shortages, contributing to grid stability and reliability; utilisation of existing natural infrastructure; decentralization of storage, reducing the requirement for long-distance transportation; low environmental impact when managed responsibly; suitable for long-term energy storage needs. Challenges: the selection of suitable storage sites, infrastructure development, safety protocols, and cost-effectiveness, all of which require ongoing research and development efforts. (See also Hydrogen geological storage in others).



Country	RTA
CN	0.48
EU	0.75
JP	0
KR	0
US	0.95

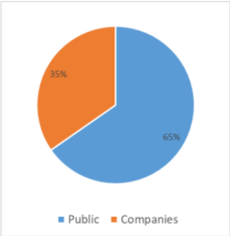


Top organisations	Value
RAS	3
University of Texas	2
University of Edinburgh	2
HERIOT-WATT UNIVERSITY	2
AGENCIA ESTATAL CONSEJO SUPERIOR DE IN...	1

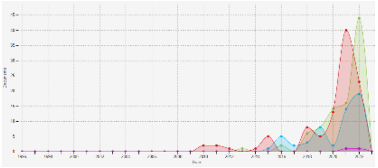
Top EU organisations	Value
AGENCIA ESTATAL CONSEJO SUPERIOR DE INVESTIGACIONES CIENTIFICAS	1
CGG	1
ENI SPA	1
Polish Academy of Sciences	1
UNIVERSITA DEGLI STUDI DI NAPOLI FEDERICO II.	1

Shared energy storage

This refers to a system where multiple users or entities collectively use a centralised energy storage facility or network. One of the advantages is to enable participants to divide initial investment and operational expenses, making energy storage more financially viable. It also optimizes energy use by efficiently balancing energy supply and demand among participants. When connected to a grid, shared energy storage can help with peak shaving and voltage regulation, enhancing grid stability, and facilitate the integration of renewable energy sources by storing surplus energy during peak production periods. In case of power outages, it can provide backup power to ensure uninterrupted operations. Additionally, shared energy storage contributes to environmental sustainability by promoting efficient energy use and reducing reliance on fossil fuels. These systems are scalable, accommodating the needs of a growing number of users, including users without grid access. Some challenges remain for effective management and coordination among participants, like for example ownership models, user agreements, and grid integration.



Country	RTA
CN	3
EU	0.38
JP	0
KR	1.32
US	0.53

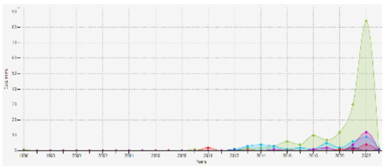


Top organisations	Value
STATE GRID	31
Tsinghua University	26
Zhejiang University	11
Qinghai University	11
ANHUI ELECTRIC POWER COMPANY	8

Top EU organisations	Value
Polytechnic of Bari	5
University of Porto	3
School of Electrical Engineering	2
Information Technology	2
Institute of Economics	1

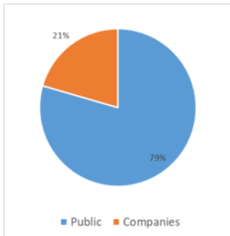
Hydrogen geological storage

Also known as underground H2 storage or H2 cavern storage, it is a method of storing H2 gas in geological formations below the Earth's surface. This solution is particularly adapted to large-scale and seasonal energy storage. Geological formations are stable and can provide long-term storage solutions with high safety. When H2 is produced using renewable energy sources or through carbon capture and utilization techniques, hydrogen geological storage can be a low-carbon or even zero-carbon energy storage solution. It also leverages existing underground infrastructure, saving costs and repurposing infrastructure for a clean energy future. See also Hydrogen storage in aquifers.



Top organisations	Value
Edith Cowan University	26
Clausthal University of Technology	17
Curtin University	16
Université de Lorraine	15
King Fahd University of Petroleum and Minerals	12

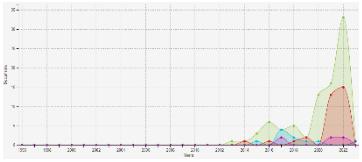
Top EU organisations	Value
Clausthal University of Technology	17
Université de Lorraine	15
Delft University of Technology	7
Państwowy Instytut Badawczy	6
Mineral and Energy Economy Research Institute of ...	6



Country	RTA
CN	0.40
EU	1.61
JP	0.16
KR	0.22
US	0.53

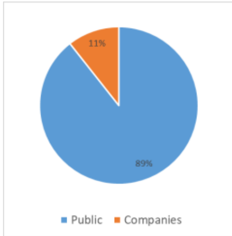
Energy storage with compressed CO_2

This technology uses compressed CO_2 to store excess energy, which is advantageous because it can store large quantities of energy, respond rapidly to energy demand, and is energy-efficient, especially when waste heat is harnessed. It contributes to reducing greenhouse gases emissions by using surplus renewable energy for compression, supports grid stability, and can be tailored to various applications. Additionally, compressed CO_2 energy storage can have a long cycle life (many charge/discharge) and can potentially use existing infrastructure for CO_2 storage, making it a versatile and environmentally compatible energy storage solution.



Top organisations	Value
XI'AN JIAOTONG UNIVERSITY	17
North China Electric Power University	10
Chinese Academy Of Sciences	10
Shanghai Maritime University	8
Qingdao University of Science and Technology	7

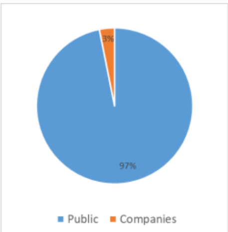
Top EU organisations	Value
Silesian University of Technology	2
Mälardalen University	2
TIGF - Transport et Infrastructures Gaz France	1
Tallinn University of Technology	1
Centre Scientifique	1



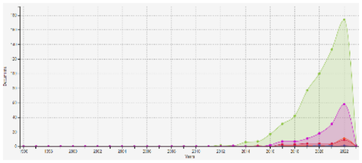
Country	RTA
CN	3.26
EU	0.50
JP	0
KR	2.70
US	0.56

Metal Organic Framework Supercapacitor

MOF supercapacitors are a type of energy storage device that combines the high surface area and tuneable properties of metal-organic frameworks with supercapacitor technology. Their advantages include their ability to store a large amount of electrical charge due to MOFs' high surface area, tuneable properties that allow optimisation for specific applications, enhanced energy storage capabilities, improved cycling stability for longer device lifespan, and environmental friendliness as MOFs are indeed often made from abundant materials. They have potential applications in renewable energy systems and other high-power applications. Challenges such as their long term stability in the presence of electrolytes or the scalability of production are being addressed in ongoing research.



Country	RTA
CN	2.65
EU	0.21
JP	0.64
KR	4.39
US	0.35

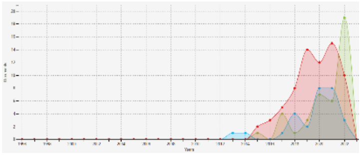


Top organisations	Value
Chinese Academy Of Sciences	41
Yangzhou University	31
Jiangsu University	20
Peking University	17
NORTHWESTERN POLYTECHNICAL UNIVERSITY	16

Top EU organisations	Value
Technische Universität Dresden	4
Université de Strasbourg	3
School of Science	3
VSB-Technical University of Ostrava	2
Leibniz Institute for Solid State and Materials Resea…	2

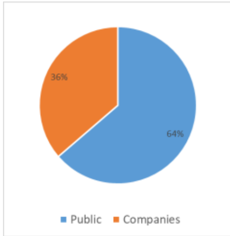
Cloud energy storage

This new type of energy storage business model aims to address the high costs associated with traditional energy storage facilities. It is inspired by the sharing economy and utilises cloud-based platforms to aggregate distributed energy storage resources. It involves the use of a shared pool of grid-scale energy storage resources that provide storage services to consumers. By leveraging the cloud, cloud energy storage can reduce the investment and operation while still meeting the requirements of consumers. This innovative approach has the potential to make energy storage more affordable and accessible, supporting the integration of renewable power and decarbonizing power systems. It also has the potential to connect different types of energy systems, such as district heating and natural gas systems, making it a versatile solution.



Top organisations	Value
Tsinghua University	16
STATE GRID	12
Guangdong Power Grid Corporation	11
Zhejiang University	6
Shanghai University of Electric Power	6

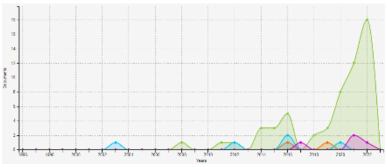
Top EU organisations	Value
Aalborg University	1
Autonomous University of Madrid	1
Complutense University of Madrid	1
RWTH Aachen University	1
SCHNEIDER ELECTRIC INDUSTRIES SAS	1



Country	RTA
CN	2.82
EU	0.17
JP	0
KR	1.44
US	0.74

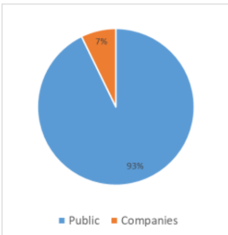
Nano-encapsulated phase change materials

NEPCMs are innovative materials where phase change materials are encapsulated within tiny nanoscale polymer capsules. They use the thermodynamics of phase change to store energy under the form of latent heat: when the temperature increases, they change phases (typically from solid to liquid) and absorb energy (endothermic process). The reverse phase change takes place when the environment cools down, releasing the energy that was stored (exothermic process). NEPCMs can therefore be used to regulate temperatures and store energy. These materials will find various applications, including efficient thermal energy storage, indoor temperature regulation through building materials and textiles, safeguarding perishable goods in the cold chain industry, and enhancing energy efficiency in heating, ventilation, and air conditioning systems.



Top organisations	Value
Islamic Azad University	12
Ton Duc Thang University	11
Prince Sattam Bin Abdulaziz University	11
King Khalid University	9
Duy Tan University	6

Top EU organisations	Value
Université de Lyon	4
Centre Scientifique et Technique du Bâtiment	2
Universitat Jaume I	1
KTH Royal Institute of Technology	1
Institute of Space Sciences	1

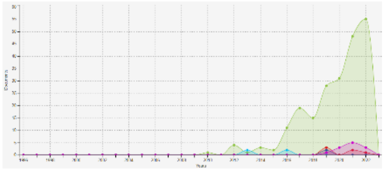


Country	RTA
CN	0.88
EU	0.81
JP	0.63
KR	0.87
US	0.39

Aqueous supercapacitors

In these energy storage devices, electrolytes based on water (usually water mixed with ternary salts or metal hydroxides) are used. Like in traditional supercapacitors, the storage of energy is realised through electrostatic charge separation at the interface between the electrolyte and an electrode. They offer several advantages compared to traditional supercapacitors. They are safer and more environmentally friendly due to the absence of flammable or toxic materials. They also tend to have a wider operating voltage range, leading to increased energy storage capacity. They are more cost-effective and simpler to manufacture compared to their non-aqueous counterparts, which contributes to their practicality for mass production. These characteristics, together with their durability, make them suitable for energy storage in renewable energy systems, electric vehicles, and various portable electronic devices.

Country	RTA
CN	3.06
EU	0.32
JP	0.73
KR	2.02
US	0.45

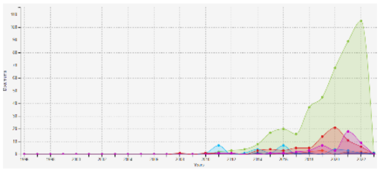


Top organisations	Value
Chongqing University	12
Nanjing University	9
Lanzhou University	9
University of California	8
Chinese Academy Of Sciences	7

Top EU organisations	Value
Universidad Del Pais Vasco UPV/EHU	2
Information Technology	1
ICN2 (CSIC-ICN)	1
Helmholtz-Zentrum Berlin für Materialien und Energie	1
Foundation for Research and Technology Hellas	1

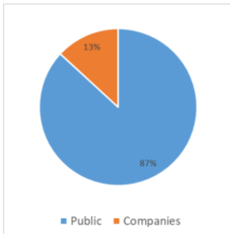
Liquid organic hydrogen carrier

This signal relates to chemical compounds used for storing and transporting H2 in a liquid form, serving as an alternative to traditional hydrogen storage methods like high-pressure gas cylinders or cryogenic liquid hydrogen. Common examples of LOHCs include dibenzyltoluene, methylcyclohexane, or decalin. These compounds absorb H2 gas under mild conditions and release it when needed, making them a reversible storage solution. Absorbed H2 can be safely transported as a stable liquid, which is typically non-toxic and non-flammable, reducing safety risks. The desorption process releases H2 for various applications like power generation and fuel cells. LOHCs offer advantages such as safety, high energy density, ease of handling, and the ability to decouple hydrogen production and utilisation, promoting the use of hydrogen as a clean energy carrier.



Top organisations	Value
Friedrich-Alexander-Universität Erlangen-Nürnberg	77
Forschungszentrum Jülich	42
University of Rostock	25
China University of Geosciences	20
Chinese Academy Of Sciences	10

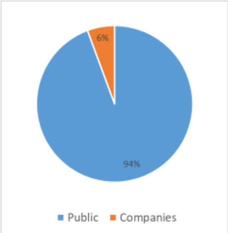
Top EU organisations	Value
Friedrich-Alexander-Universität Erlangen-Nürnberg	77
Forschungszentrum Jülich	42
University of Rostock	25
Helmholtz Institute	16
University of Erlangen-Nuremberg	14

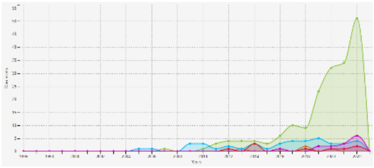


Country	RTA
CN	0.90
EU	1.58
JP	0.43
KR	6.49
US	0.34

Metal foam phase change materials for energy storage

This innovative approach to energy storage combines metal foams with phase change materials to create efficient and versatile energy storage systems. Phase Change Materials are substances that absorb and release large amounts of thermal energy during phase transitions (usually solid-liquid) at a specific temperature. PCM are adsorbed or encapsulated within the structure of a metal foam, a highly porous materials with a three-dimensional network of interconnected metal structures. Combining these two materials brings some advantages: high thermal conductivity of metal foam allow for efficient heat transfer; PCM have a high energy storage capacity per unit volume; reduced heat loss during energy storage; suitable for temperature regulation in various applications, including building HVAC systems and solar energy storage; long cycle life which makes them suitable for long-term energy storage; high energy density in a compact form, making them suitable for applications with space limitations; possibility for storage of thermal energy generated by renewable sources like solar and wind. Overall, these materials show potential to become efficient solution for thermal energy storage and applications in the building, industrial, and renewable energy sectors.





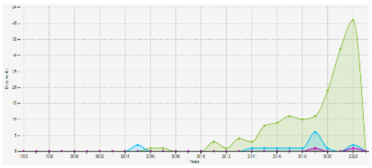
Country	RTA
CN	1.83
EU	0.95
JP	0
KR	0.26
US	0.66

Top organisations	Value
XI'AN JIAOTONG UNIVERSITY	29
Università degli Studi	11
Shanghai Jiao Tong University	11
University of Baghdad	9
Prince Sattam Bin Abdulaziz University	9

Top EU organisations	Value
Università degli Studi	11
University of Padova	5
Université de Lyon	3
Università degli Studi di Napoli Federico II	3
Mälardalen University	3

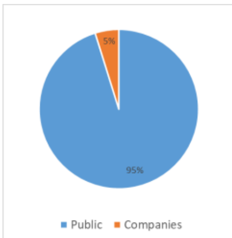
Shell and Tube Energy Storage

This energy storage system consists of a large outer shell and a series of interconnected tubes inside this shell, containing a heat transfer fluid (water or a specialized fluid). The system operates by circulating a heat transfer fluid through the tubes: thermal energy is stored within the system during charging phases and transferred to a secondary fluid which is then used for heating or cooling applications. Shell and tube thermal energy storage systems are known for their efficient thermal energy storage capabilities and their reliability and scalability. They are ideal for applications that require decentralized energy storage and precise temperature control, such as district heating and cooling systems.



Top organisations	Value
XI'AN JIAOTONG UNIVERSITY	21
Zhejiang University	9
Shanghai Jiao Tong University	8
Prince Sattam Bin Abdulaziz University	8
Islamic Azad University	8

Top EU organisations	Value
University of Rijeka	5
Politecnico di Torino	5
Université de Lyon	3
University of the Basque Country UPV/EHU	3
Polish Academy of Sciences	2

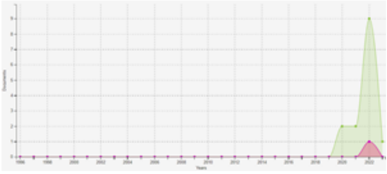


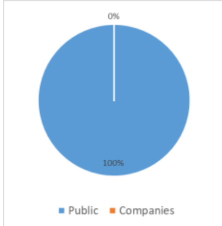
Country	RTA
CN	1.97
EU	0.84
JP	0
KR	0.76
US	0.45

2.6 Weak signals related to Geothermal

Hybrid Nano fluids in geothermal applications

This weak signal involves the dispersion of nanoparticles (metal oxides like alumina, copper oxide) or carbon-based materials (e.g., carbon nanotubes, graphene), into the working fluids used in geothermal heat exchangers or heat transfer systems. This enhances thermal conductivity, improves heat transfer, reduces fouling and scaling, enhances thermal stability, and requires less pumping power. The properties of hybrid nano fluids can be tailored to meet specific requirements for different geothermal applications. Their practical implementation in geothermal systems requires further R&D and careful consideration of factors such as nanoparticle stability, potential impact on the environment, and cost-effectiveness.





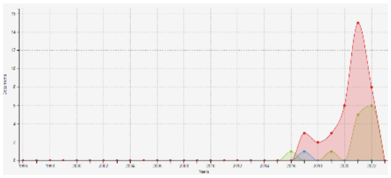
Top organisations	Value
Universiti Kebangsaan Malaysia	2
Sukkur IBA University	2
King Khalid University	2
King Abdulaziz University	2
Islamic Azad University	1

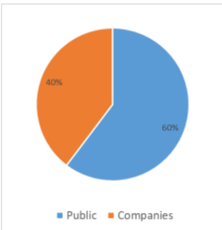
Top EU organisations	Value
Institute of Space Sciences	1
Universitatea Babes-Bolyai	1

Country	RTA
CN	0
EU	0.53
JP	0
KR	2.29
US	0

Medium deep geothermal energy

This refers to geothermal energy resources at moderate depths, typically reservoirs at 1,500 meters to 3,000 meters below surface, and characterized by moderate to high temperatures (150°C to 300°C). Energy is harnessed through drilling of deep wells and injection of fluids to capture heat. The resulting steam/hot water is used for generating electricity, district heating, and industrial processes. Medium deep geothermal energy is considered relatively environmentally friendly because it produces little to no greenhouse gas emissions and has a minimal environmental footprint. Though medium deep geothermal energy has some advantages, it has a high initial drilling and exploration costs.





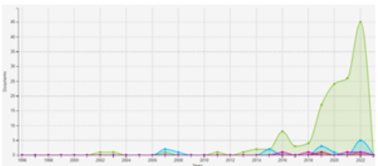
Top organisations	Value
Shandong Jianzhu University	4
UNIV HEBEI ENGINEERING	3
SHAANXI COAL GEOLOGY GROUP CO LTD	3
China University of Mining and Technology	3
China Academy of Building Research	2

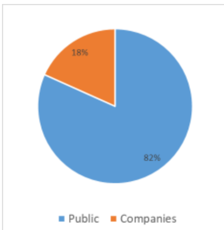
Top EU organisations	Value
Züblin Ground Engineering	1
Université de Strasbourg	1

Country	RTA
CN	3.74
EU	0.39
JP	0
KR	0
US	0

Deep borehole heat exchange

Is a geothermal technology that involves drilling deep boreholes into the Earth's crust to extract or store heat, making it an interesting solution for sustainable and efficient heating and cooling. The process is suitable for a wide range of applications, even in urban areas with limited space, and is grid-independent, making it an option for off-grid locations. With a long lifecycle and minimal maintenance requirements, the deep borehole heat exchange process contributes to sustainable building practices and the global shift towards clean energy sources.





Top organisations	Value
XI'AN JIAOTONG UNIVERSITY	21
Chinese Academy Of Sciences	19
Shandong Jianzhu University	13
Tianjin University	11
Helmholtz Centre for Environmental Research-UFZ	8

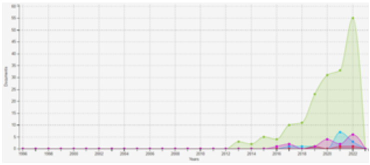
Top EU organisations	Value
Helmholtz Centre for Environmental Research-UFZ	8
University of Zagreb	4
Technische Universität Darmstadt	4
Freiberg University of Mining and Technology	3
Dresden University of Technology	3

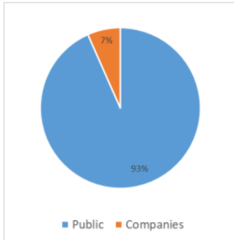
Country	RTA
CN	3.12
EU	0.77
JP	0.25
KR	0
US	0.41

2.7 Weak signals related to Ocean Energy

Triboelectric nanogenerator in ocean energy

These devices convert mechanical energy into electrical energy through the triboelectric effect. In the context of ocean energy, they are used to harness the mechanical energy generated by ocean waves, currents, and motion for various applications. They can also capture energy from salinity gradients when freshwater and seawater meet. Integrated into wave energy conversion systems, they capture the motion and vibrations from waves to produce electricity for offshore sensors, on-board electronics, communication systems, and navigation equipment, or to power autonomous underwater vehicles or underwater sensor networks that monitor ocean conditions, marine life, and detect events like tsunamis. These devices are compact and lightweight and can operate in harsh and remote ocean conditions, making them a promising technology for harnessing ocean energy.





Top organisations	Value
Chinese Academy Of Sciences	106
School of Materials Science and Engineering	78
Guangxi University	24
Chongqing University	17
Dalian Maritime University	14

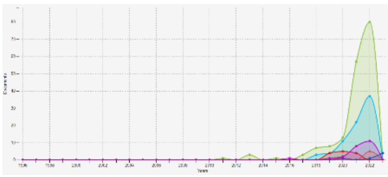
Top EU organisations	Value
University of Porto	5
Edifício FC6	3
Information Technology	2
Centre of Marine and Environmental Research	2
Graphene Labs	1

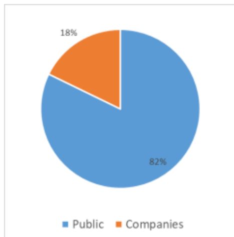
Country	RTA
CN	3.32
EU	0.30
JP	0.19
KR	2.08
US	1.65

2.8 Weak signals related to Photovoltaics

Agrivoltaics

This sustainable agricultural practice involves the co-location of solar photovoltaic panels with agricultural crops or other types of land use. Solar panels are installed above crops or within agricultural fields, maximising land usage by allowing both solar energy generation and crop cultivation on the same land. Solar panels also provide shade for crops, reducing heat stress and water evaporation. Integrating solar panels with agriculture can lead to more efficient use of land, water, and other resources, contributing to sustainability. Technological advances and optimization are ongoing to make agrivoltaics systems more efficient, cost-effective, and adaptable to various agricultural practices and crops.





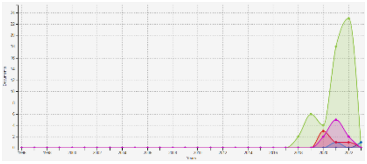
Top organisations	Value
Oregon State University	12
Universiti Putra Malaysia	10
University of Hohenheim	8
Michigan Technological University	8
Western University	7

Top EU organisations	Value
University of Hohenheim	8
Fraunhofer Institute for Solar Energy Systems ISE	6
Università Cattolica del Sacro Cuore	5
University of Rome II Tor Vergata	5
UMR SYSTEM	4

Country	RTA
CN	0.27
EU	1.60
JP	0.96
KR	2.37
US	1.31

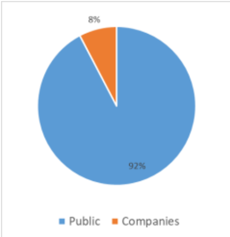
Indoor organic photovoltaics

A special type of solar cells designed to generate electricity in indoor lighting conditions. They have a high efficiency under low light conditions and can harvest light over a broad spectrum. They are cheap to produce, have a low environmental impact and are lightweight, flexible, and resistant. They can be customized to facilitate their integration in buildings and buildings materials (e.g. windows) and are well-suited for powering internet of things devices, sensors, and other wearable electronics.



Top organisations	Value
Korea University	22
IND ACADEMIC COOP FOUND YONSEI UNIV	20
Chinese Academy Of Sciences	8
Shandong University	6
Hong Kong University of Science and Technology	6

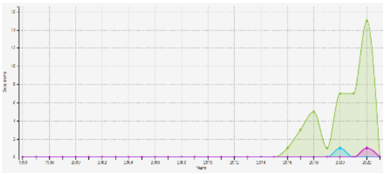
Top EU organisations	Value
University of Freiburg	1
Ribes Tech s.r.l.	1
Epishine AB	1
CNRS UMR	1
AGENCIA ESTATAL CONSEJO SUPERIOR DE IN...	1



Country	RTA
CN	1.42
EU	0.39
JP	0.48
KR	16.66
US	0.49

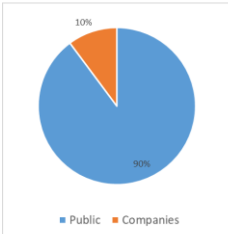
Bifacial perovskite solar cells

They offer some advantages compared to traditional bifacial solar panels, primarily due to the unique characteristics of perovskite materials: higher power conversion, thinner and more lightweight materials than silicon-based solar cells (making them suitable for flexible and lightweight applications like portable solar chargers and building-integrated photovoltaics), lower energy payback time, integration in tandem solar cell, potential for low-cost production. Challenges remain related to their stability, longevity, and commercial scalability, but their unique characteristics and potential for higher efficiency make them a promising option for future solar energy applications.



Top organisations	Value
XIDIAN UNIVERSITY	4
University of Toledo	3
Helmholtz-Zentrum Berlin für Materialien und Energie	2
Dalian University of Technology	2
Changchun University	2

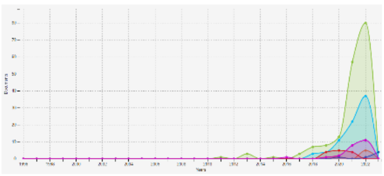
Top EU organisations	Value
Zuse Institute Berlin	2
Helmholtz-Zentrum Berlin für Materialien und Energie	2
Università Niccolò Cusano	1
Partner in Solliance	1
Karlsruhe Institute of Technology	1



Country	RTA
CN	1.46
EU	1.09
JP	0.85
KR	3.55
US	1.04

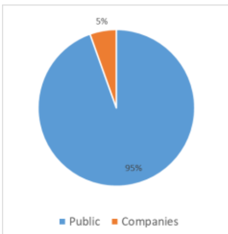
Tin perovskite solar cells

A type of photovoltaic cell using tin-based perovskite materials as the light-absorbing layer. While they can be manufactured using inexpensive materials and processes, these cells nevertheless exhibit high light-absorption efficiency and have a higher tolerance to defects and impurities than other perovskite materials. These solar cells can be fabricated as thin films, making them suitable for applications where film flexibility is required (e.g. integration in buildings, windows, roofing, or for portable electronics, electric vehicles, satellites), and they can also be used in tandem solar cell configurations to improve efficiency. Compared to more traditional lead-perovskite, they are less toxic and therefore more environmentally friendly.



Top organisations	Value
Chinese Academy Of Sciences	22
Zhengzhou University	17
University of Tokyo	17
Shanghai Jiao Tong University	16
National Institute for Materials Science	13

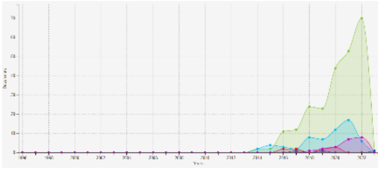
Top EU organisations	Value
Helmholtz-Zentrum Berlin für Materialien und Energie	8
University of Naples Federico II	5
University of Groningen	5
Universitat Jaume I	5
Technische Universität München	2



Country	RTA
CN	2.21
EU	0.48
JP	4.32
KR	2.22
US	0.35

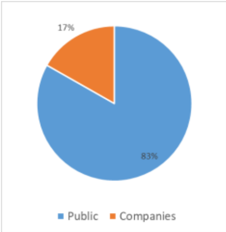
Perovskite/silicon tandem solar cells

A type of solar cell that combines perovskite and silicon materials to enhance efficiency by combining the strengths of both materials to capture a broader spectrum of sunlight. Tandem solar cells benefit from the stability and durability of silicon while retaining the cost-effective manufacturing techniques of perovskite. They have a higher energy production density and can be tailored for specific applications. Their long-term stability and scalability still need to be improved before they can become commercially mainstream.



Top organisations	Value
Helmholtz-Zentrum Berlin für Materialien und Energie	29
Nankai University	24
King Abdullah University of Science and Technology	23
Ecole Polytechnique Fédérale de Lausanne EPFL	18
Collaborative Innovation Center of Chemical Science and Engineering	18

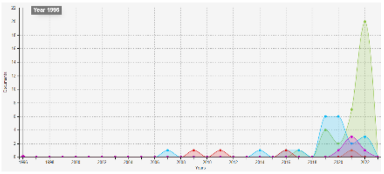
Top EU organisations	Value
Helmholtz-Zentrum Berlin für Materialien und Energie	29
Fraunhofer Institute for Solar Energy Systems ISE	15
University of Freiburg	12
Zuse Institute Berlin	10
Helmholtz-Zentrum Berlin	9



Country	RTA
CN	1.25
EU	1.58
JP	1.92
KR	2.83
US	0.39

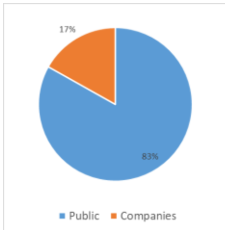
Vehicle Integrated Photovoltaics

This refers to the integration of solar panels into various parts of a vehicle to generate electricity from sunlight, reducing reliance of vehicles on fossil fuels and lowering greenhouse gas emissions. Solar panels on a vehicle could charge the on-board battery, increasing the electric range of electric and hybrid vehicles and reducing fuel consumption. Energy Independence of the vehicles could be improved, for example in the case of power consumption when a vehicle is parked or idle, or when batteries are depleted, enabling functions like battery conditioning, pre-cooling or pre-heating, and powering auxiliary equipment. The battery lifespan could be increased, as integrated PV would help maintain a higher state of charge.



Top organisations	Value
University of Miyazaki	8
Toyota Technological Institute	5
Nagaoka University of Technology	4
Leibniz University Hannover	4
Eindhoven University of Technology	4

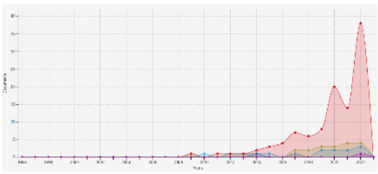
Top EU organisations	Value
Leibniz University Hannover	4
Eindhoven University of Technology	4
University of Twente	3
Helmholtz-Zentrum Berlin	3
Forschungszentrum Jülich	3



Country	RTA
CN	0.63
EU	2.21
JP	6.89
KR	3.19
US	0.47

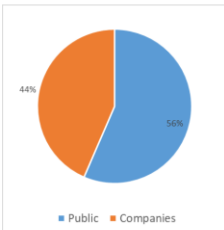
Offshore solar power

Installing solar panels on bodies of water (oceans, lakes, reservoirs) allows to convert solar energy into electricity. This approach conserves land resources in densely populated areas, efficiently uses water bodies, and benefits from the cooling effect of water, enhancing solar panel efficiency. Offshore solar power is scalable, reliable, and can be combined with other renewable energy sources for integrated energy solutions. R&D is ongoing to improve mooring and anchoring systems, and address environmental considerations and potential detrimental impacts on ecosystems. It's an emerging technology with great potential to contribute to sustainable energy generation.



Top organisations	Value
UNIV TIANJIN	11
HUANENG CLEAN ENERGY RES INST	10
KR HYDRO&NUCLEAR POWER CO LTD	6
UNIV SHANGHAI JIAOTONG	5
China University of Mining and Technology	4
Utrecht University	3

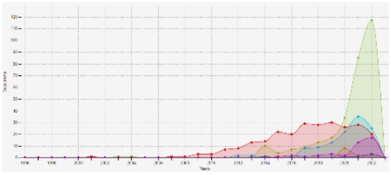
Top EU organisations	Value
Utrecht University	3
Aalborg University	2
RWTH Aachen University	1
Palermo University	1
Aalto University	1



Country	RTA
CN	1.51
EU	1.34
JP	0
KR	0
US	0

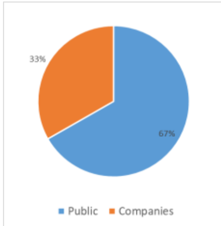
Hydrovoltaics

This concept is a variant of offshore solar power and simply combines solar photovoltaic panels with hydropower systems, typically floating on bodies of water. The primary advantage is to use the already existing hydropower infrastructure. Additional advantages are: increased efficiency of the solar panels to generate electricity (direct sun exposure + exposure to sun reflection on water), space efficiency as it optimizes land use, a cooling effect that preserves solar panel efficiency, reduced water evaporation, a smaller land footprint, and low installation costs. These advantages make hydrovoltaics an attractive and sustainable option for electricity generation, particularly in regions with abundant water resources and existing hydropower infrastructure.



Top organisations	Value
University of Catania	20
Chinese Academy Of Sciences	17
WUXI TONGCHUN NEW ENERGY TECH	16
Nanjing University of Aeronautics and Astronautics	10
City University of Hong Kong	8

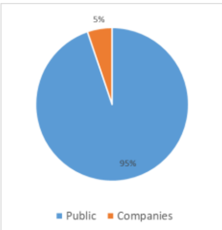
Top EU organisations	Value
University of Catania	20
Delft University of Technology	8
Upsolar Floating Srl	5
University of Naples Federico II	5
Universidad de Jaén	5



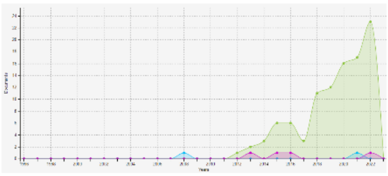
Country	RTA
CN	0.88
EU	1.07
JP	0.07
KR	2.12
US	0.34

Ternary organic photovoltaics

This type of solar cell makes use of three different active components, typically two different electron-donating organic semiconductors and one electron-accepting organic semiconductor, creating a ternary blend. This approach improves the efficiency and stability of organic solar cells by enhancing light absorption, charge generation, and charge transport. Ternary OPVs can be tuned to meet specific efficiency and stability requirements and they are suitable for a wide range of applications and device architectures (e.g. integration in tandem devices). While ternary organic photovoltaics offer several advantages, they also face some challenges, such as sub-optimal material combinations, rather low stability, and issues for scaling up production. Ongoing research in this field aims to further improve the efficiency and commercial viability for practical applications.



Country	RTA
CN	2.55
EU	0.51
JP	0
KR	3.16
US	0.56



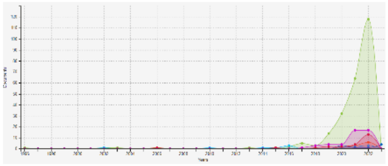
Top organisations	Value
Beijing Jiaotong University	14
National Taiwan University	10
Taishan University	9
Chinese Academy Of Sciences	9
Zhejiang University	8

Top EU organisations	Value
Information Technology	7
CNRS	4
Linköping University	3
Hasselt University	1
Cittadella Universitaria	1

2.9 Weak signals related to Renewable Fuels

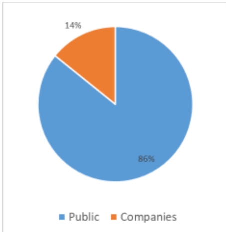
Sustainable ammonia

Produced through environmental friendly methods (e.g. sustainable reactants, integration of CCUS, renewable energy source), sustainable ammonia (NH3) is a promising clean energy carrier and energy storage product. Its advantages as clean energy carrier capabilities, hydrogen storage solution, and carbon-free agriculture enabler make it an important focus of research and development efforts towards addressing global sustainability challenges. Sustainable NH3 is also considered as a potential fuel for various transportation means e.g. heavy-duty trucks, in industrial processes, ships or trains.



Top organisations	Value
Chinese Academy Of Sciences	27
University of Oxford	11
Monash University	10
University of Electronic Science and Technology of ...	9
Tsinghua University	8

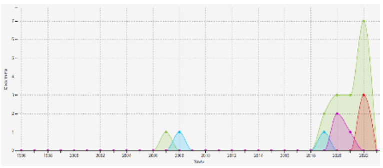
Top EU organisations	Value
Delft University of Technology	6
University of Twente	5
University of Antwerp	5
Technical University of Denmark	4
CNR	4



Country	RTA
CN	1.70
EU	0.90
JP	1.57
KR	2.04
US	0.78

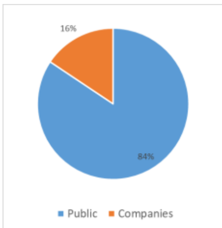
Low-temperature direct ammonia fuel cells

A promising technology that efficiently converts ammonia into electricity at low temperatures (below 100°C). It offers advantages such as high energy density, clean and carbon-free energy production, reduced heat management complexity. Ammonia is an abundant fuel source and a clean-burning fuel that does not produce carbon dioxide during combustion. These cells find applications in backup power systems, portable electronics, distributed energy generation, transportation, remote and off-grid power supply, clean propulsion systems for ships and submarines, agricultural equipment, renewable energy storage, hydrogen production, environmental monitoring, and wearable technologies. Ongoing research aims to enhance their efficiency and commercial viability for broader adoption.



Top organisations	Value
University of Delaware	4
Chinese Academy Of Sciences	4
University of Warwick	3
Monash University	3
DAJIU MANUFACTURING CO., LTD.	2

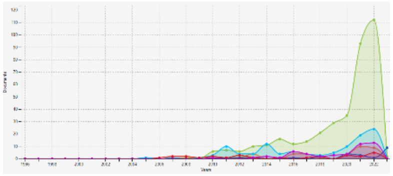
Top EU organisations	Value
Technical University of Denmark	1



Country	RTA
CN	2.82
EU	0
JP	1.65
KR	2.29
US	2.02

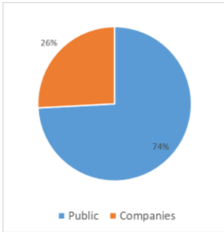
Sustainable aviation fuels

Several types of sustainable fuels are under development and testing for the aviation sector (e.g. hydroprocessed esters and fatty acids, synthetic paraffinic kerosene, fuels derived from alcohol, waste, algae or biomass), with the primary goal of reducing the carbon footprint of the aviation industry. They can be used as direct replacements for conventional aviation fuels without requiring modifications to aircraft engines or infrastructure. These fuels play a crucial role in the aviation industry's efforts to reduce its environmental impact and promote more sustainable air travel by decreasing carbon emissions.



Top organisations	Value
University of Dayton	26
Washington State University	24
Universidad de Guanajuato	24
Universidad Autónoma de Querétaro	21
National Cheng Kung University	20

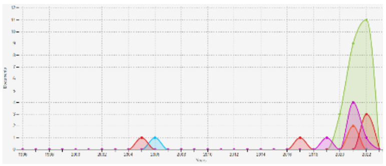
Top EU organisations	Value
Utrecht University	11
Delft University of Technology	11
University of Groningen	8
Institute of Combustion Technology	6
DEUTSCHES ZENTRUM FUR LUFT - UND RAUMFAHRT EV	6



Country	RTA
CN	1.70
EU	0.90
JP	1.57
KR	2.04
US	0.78

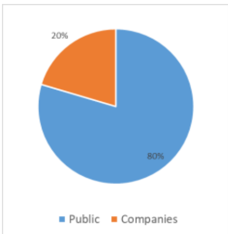
Direct seawater electrolysis

A process that uses electricity to split seawater into hydrogen and oxygen. It has recently gained interest as a method for producing H2, and it offers several advantages: abundant raw material, lower environmental impact by using renewable energy, high purity of the H2 produced, simultaneous production of O2, solution for storage of energy, integration with renewable energy sources and grid systems, applications in marine environments, potential for carbon capture. Direct seawater electrolysis faces some challenges such as energy efficiency, materials durability, and competitiveness compared to other methods.



Top organisations	Value
Technical University Berlin	4
Qingdao University of Science and Technology	2
Nankai University	2
KR INSTITUTE OF ENERGY RESEARCH	2
DAJIU MANUFACTURING CO., LTD.	2

Top EU organisations	Value
Technical University Berlin	4
University of Porto	1
Leiden University	1
Institució Catalana de Recerca i Estudis Avançats	1
ENSCM	1

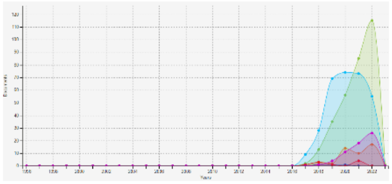


Country	RTA
CN	1.78
EU	1.13
JP	0.88
KR	2.44
US	0.90

2.10 Weak signals related to Smart Grid

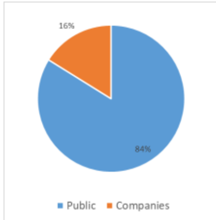
Blockchain for smart grid

Blockchain technology offers several advantages for smart grids. First, it helps integrating distributed energy resources (solar panels, wind turbines) by enabling peer-to-peer energy trading without intermediaries, promoting efficient energy use and supports the development of microgrids. It improves grid resilience by decentralizing control/coordination of grid assets, making the grid less vulnerable to failures and cyberattacks. It also facilitates billing/settlement processes by automating transactions. It provides secure and tamper-resistant data storage, which is vital for maintaining data integrity and security during operations, reducing the risk of manipulation or fraud. It also fosters interoperability among grid components and stakeholders, and enhance grid management through real-time visibility of operations and quick anomaly detection.



Top organisations	Value
Nirma University	20
North China Electric Power University	16
King Saud University	15
COMSATS University	14
Thapar Institute of Engineering and Technology	13

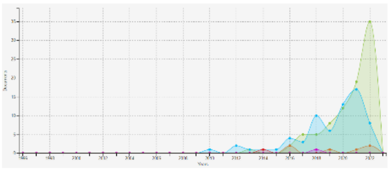
Top EU organisations	Value
University of Vaasa	8
University of Bergamo	8
University Politehnica of Bucharest	7
Universidad de Salamanca	6
Aalborg University	6



Country	RTA
CN	1.02
EU	1.01
JP	0.52
KR	1.52
US	0.64

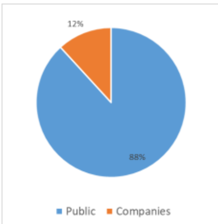
Electricity theft detection

Data analytics can identify irregular consumption patterns, potentially indicative of theft. The goal is to prevent unauthorized consumption of electrical power within a smart grid distribution network to reduce revenue losses for utility companies. The overall stability and reliability of the grid are both improved by preventing unauthorized overloads that could strain the system. It enhances safety by mitigating hazards associated with unauthorized electricity connections. Electricity theft detection contributes to better energy management, supporting energy conservation and sustainability goals while maintaining the financial health of utility companies.



Top organisations	Value
COMSATS University	25
University of Alabama	11
King Saud University	9
University of Technology Sydney	7
Chinese Academy Of Sciences	7

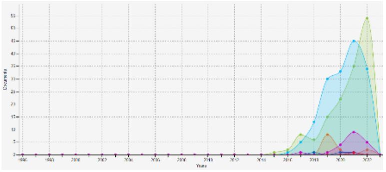
Top EU organisations	Value
Cyprus University of Technology	3
Université de Reims Champagne-Ardenne	2
Information Technology	2
RWTH Aachen University	1
Institute of Electronics and Information Technology	1



Country	RTA
CN	0.84
EU	0.44
JP	0.25
KR	1.37
US	0.81

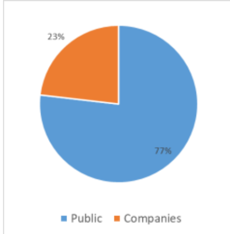
Edge computing for smart grid

This involves the processing and analysing of data locally, near its source, within the electrical distribution network. This approach enables real-time data analysis, reduces data transmission latency, enhances grid reliability, and supports localized control and decision-making, making it crucial for optimizing grid operations and facilitating the integration of distributed energy resources. Blockchain for smart grid can complement edge computing for example to secure and ensure integrity of data generated and processed at the edge.



Top organisations	Value
University of Electronic Science and Technology of China	22
STATE GRID	14
Beijing University of Posts and Telecommunications	12
CHINA SOUTHERN POWER GRID CO., LTD.	10
North China Electric Power University	7

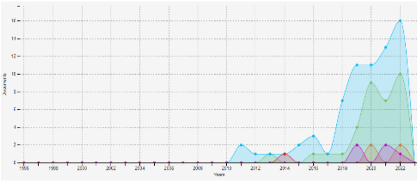
Top EU organisations	Value
CNRS	3
Information Technology	3
Instituto de Telecomunicações	3
National Institute of Telecommunications	3
University of Messina	3



Country	RTA
CN	2.20
EU	0.73
JP	0.65
KR	0.90
US	0.57

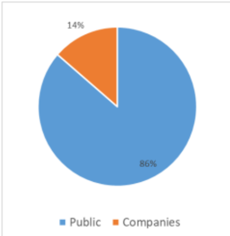
Machine learning for smart grids

Involves the use of AI tools and data analytics techniques to enhance operations and efficiency of smart grids. It plays a critical role in predicting electricity demand, optimizing load balancing, integrating renewable energy sources, detecting energy theft, identifying faults, and ensuring the optimal operation of grid components. Machine learning also supports predictive maintenance, grid resilience, cybersecurity, and customer engagement by analysing the vast quantity of data generated by sensors and meters. Harnessing the power of machine learning can improve the reliability of smart grids, reduce costs, and better accommodate renewable energy production.



Top organisations	Value
Zhejiang University	3
University of Idaho	3
Indian Institute of Technology	3
Florida International University	3
Northeastern University	2

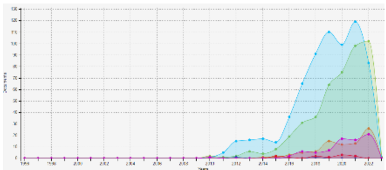
Top EU organisations	Value
Technical University of Cluj-Napoca	2
Politecnico di Milano	2
University of Aveiro	1
University College Dublin	1
LABISEN	1



Country	RTA
CN	1.24
EU	0.58
JP	0
KR	1
US	0.74

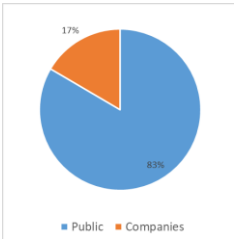
Internet of Things for smart grids

The integration of IoT devices into smart grids allows real-time monitoring and data collection about operating conditions of various grid components, which give operators a comprehensive view of the grid's status at any time, reducing time for intervention (e.g. fault detection, cyber-attack), improving reliability and reducing downtime. Data on energy consumption patterns can be collected to optimise load management and distribution, leading to more efficiency and helping reduce peak demand. It also engages consumers as they actively participate in managing their energy production/consumption through using smart meters and home automation, increasing energy efficiency and cost savings. Overall, IoT devices make smart grids more efficient, reliable, and adaptable to changing energy needs, benefiting both utility companies and consumers.



Top organisations	Value
STATE GRID	21
North China Electric Power University	17
Institute of Science and Technology	17
Chinese Academy Of Sciences	13
Islamic Azad University	12

Top EU organisations	Value
Aalto University	7
University of Cagliari	6
National Institute of Telecommunications	6
Instituto de Telecomunicações	6
Technical University of Denmark	5

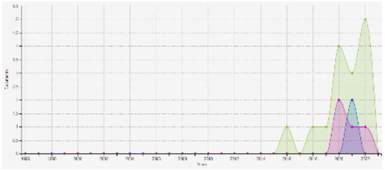


Country	RTA
CN	1.04
EU	0.70
JP	0.15
KR	1.72
US	0.40

2.11 Weak signals related to Solar Fuels

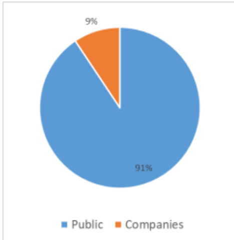
Covalent organic framework for solar fuel production

COF are promising catalysts for various applications, including the production of solar fuels. With a high surface area, they allow efficient light absorption and catalytic reactions in solar fuel production processes. Their properties can be tuned to optimize their performance for specific solar fuel production reactions. They are stable materials, able to withstand harsh conditions often associated to photochemical reactions and their catalytic activity facilitates key reactions like water splitting or CO2 reduction, essential for solar fuel production. COFs are a relatively new class of materials, promising further gains in efficiency in solar fuel production.



Top organisations	Value
Argonne National Laboratory	2
Chinese Academy Of Sciences	2
Sichuan University	2
Soochow University	2
University of Kalyani	2

Top EU organisations	Value
FUNDACIO PRIVADA INSTITUT CATALA D'INVESTIGACIO QUIMICA	2
University of Munich	1
Max Planck Institute for Solid State Research	1
Chemtrix BV	1
ACONDICIONAMIENTO TARRASENSE ASSOCIACION	1



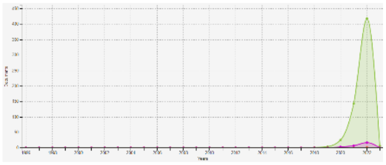
Country	RTA
CN	1.80
EU	0.53
JP	1.65
KR	4.58
US	0.67

S-scheme and Z-scheme heterojunctions

Both S-scheme and Z-scheme heterojunctions are explored in the field of photocatalysis for their potential in harnessing solar energy to drive chemical reactions, such as water splitting for hydrogen production or pollutant degradation. The terms "S-scheme" and "Z-scheme" refer to the two different mechanisms by which charge carriers (electrons and holes) are transferred between different semiconductors in the heterojunctions. The design and optimization of such heterojunctions play a crucial role in enhancing the overall efficiency of these processes.

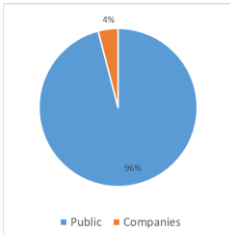
S-scheme heterojunction

In an S-scheme heterojunction, the charge carriers (electrons and holes) are transferred sequentially between the two semiconductor materials. One semiconductor absorbs light and generates electrons and holes. The electrons are then transferred to the other semiconductor, where they participate in redox reactions. The term "S" comes from the sequential nature of the charge transfer process. S-scheme heterojunctions can be used in various photocatalytic applications (e.g. water splitting, pollutant degradation) and can be tailored to specific requirements. They have a high efficiency and require less materials, which makes them greener and cost-effective photocatalysis technologies for a sustainable future.



Top EU organisations	Value
Universidad Carlos III de Madrid	3
Jagiellonian University	3
University of Antwerp	2
Lund University	2
Leibniz Institute for Catalysis	2

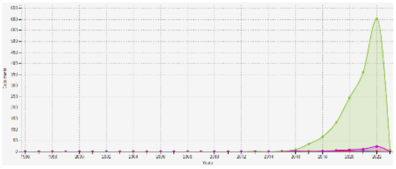
Top organisations	Value
North Minzu University	70
Zhengzhou University	42
Wuhan University of Technology	41
China University of Geosciences	32
Chinese Academy Of Sciences	28

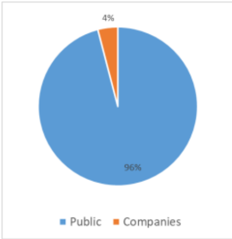


Country	RTA
CN	3.59
EU	0.17
JP	0.21
KR	0.77
US	0.11

Z-scheme heterojunction catalyst

This specialized type of catalyst mimics the natural photosynthetic process found in plants and algae. Two different semiconductor materials with distinct bandgap energies are combined to create the heterojunction. Each material is responsible for specific reactions, similar to the two photosystems in natural photosynthesis. One of the primary applications of Z-scheme heterojunction catalysts is the production of solar fuels, in particular the generation of hydrogen gas from water splitting. They can also be employed in carbon dioxide reduction, where solar energy is used to convert CO2 into organic compounds, such as hydrocarbons.





Top organisations	Value
Chinese Academy Of Sciences	68
Jiangsu University	62
Hunan University	49
Heilongjiang University	38
Nanjing University of Information Science and Technology (NUST)	37

Top EU organisations	Value
Université Paris-Saclay	3
University of Medical Sciences	3
Silesian University of Technology	3
CNRS	2
Adam Mickiewicz University	2

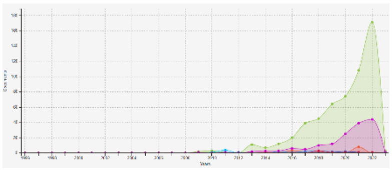
Country	RTA
CN	3.54
EU	0.14
JP	0.29
KR	0.90
US	0.18

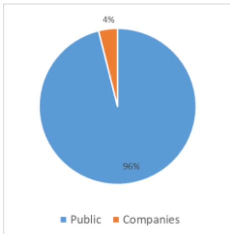
CO2 reduction to produce solar fuels

Photoelectrochemical (PEC) and Photocatalytic reduction of CO2 both make use of solar energy to convert CO2 into valuable chemicals. Yet, they differ in their mechanisms. While PEC systems involve photoelectrodes and the separation of electron-hole pairs in the semiconductor for electrochemical conversion, photocatalytic systems use photocatalysts dispersed in a solution or attached to a surface to promote photochemical reduction. That being said, they are related processes and their detection as weak signals shows the importance given by the research community to capture and utilize CO2 in industrial processes.

Photocatalytic CO2 reduction to produce solar fuels

The process makes use of photocatalysts to convert carbon dioxide into useful chemicals or fuels using sunlight or other sources of light as energy source. It is a promising technology for addressing climate change by reducing CO2 emissions and producing renewable solar fuels. Solar light is the driver of the chemical reactions, which makes it a sustainable and environmentally friendly way to mitigate CO2 emissions and create valuable energy resources. The solar fuels generated through this process can be stored and used for various applications, including electricity generation or as a substitute for fossil fuels. This technology has the potential to play a significant role in achieving a carbon-neutral or carbon-negative energy system. However, there are still challenges to overcome, such as improving the efficiency of the photocatalysts, developing scalable systems, and optimizing the overall process for practical use.





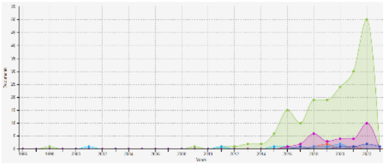
Top organisations	Value
Chinese Academy Of Sciences	62
Wuhan University of Technology	49
Fuzhou University	37
Universiti Teknologi Malaysia	36
University of Science and Technology of China	33

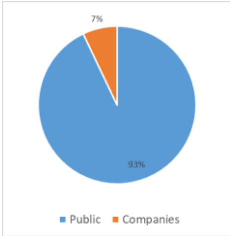
Top EU organisations	Value
Università degli Studi di Milano	4
Università degli Studi di Genova	4
IMDEA Energy	4
Ca' Foscari University	4
School of Science	3

Country	RTA
CN	2.84
EU	0.33
JP	1
KR	2
US	0.27

Photoelectrochemical CO2 reduction

This process relies on solar energy to convert CO2 into valuable chemical compounds. It involves a photoelectrochemical cell (semiconductor material), an electrolyte solution containing CO2, and sunlight. The process offers a promising way to mitigate carbon dioxide emissions, a major contributor to climate change. By using renewable energy to convert CO2 into useful products, it can help reduce the concentration of this greenhouse gas in the atmosphere. Valuable chemical compounds that can be used in various industrial processes are produced (carbon monoxide, formic acid, methane, etc.). PEC-CO2 reduction can also potentially be used to store excess solar energy by converting it into chemical energy, which can be later used. Research is ongoing to increase the efficiency of CO2 conversion, the development of more robust catalysts, and the long-term stability of photoelectrochemical cells.





Top organisations	Value
Central South University	10
University of California	9
Chinese Academy Of Sciences	9
Universiti Malaysia Pahang	7
Tokyo University of Science	7

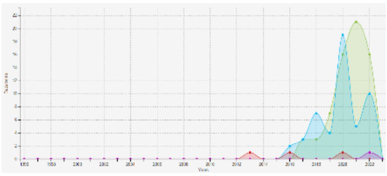
Top EU organisations	Value
Technische Universität München	4
University of Limerick	3
School of Science	3
University of Warsaw	2
SZEGEDI TUDOMANYEGYETEM	2

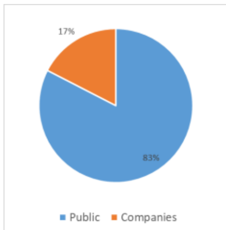
Country	RTA
CN	1.81
EU	0.64
JP	1.90
KR	4.69
US	1.17

2.12 Weak signals related to Wind Energy

Wake steering

A strategy used in wind energy management where the yaw of wind turbines is intentionally adjusted to redirect the wake generated by upstream turbines away from downstream turbines in a wind farm. Research on wake steering seeks to maximize the energy production and efficiency of wind farms by minimizing the negative impact of wake interference on downstream turbines. Wake steering also contributes to the integration of wind energy into the electrical grid, by making it more reliable and predictable. Ongoing research involves the development of advanced control algorithms and monitoring systems to optimize the wake steering process, taking into account the complex fluid dynamics of wakes. Ultimately, wake steering research is critical for improving the competitiveness and sustainability of wind farms (increased energy production without additional turbines).





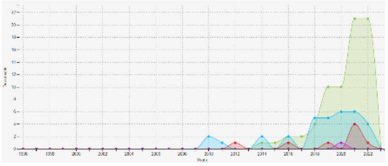
Top organisations	Value
National Renewable Energy Laboratory US	19
National Wind Technology Center US	18
Sandia National Laboratories	8
Technical University of Denmark	7
SIEMENS AG	6

Top EU organisations	Value
Technical University of Denmark	7
SIEMENS AG	6
University of Oldenburg	5
Technische Universität München	5
Delft University of Technology	5

Country	RTA
CN	0.37
EU	1.64
JP	0.90
KR	0
US	3.19

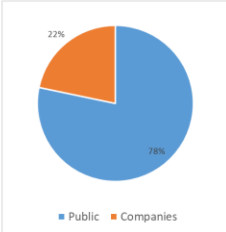
Fast frequency support in wind turbines

This refers to the combination of technologies needed to quickly adapt the functioning of wind turbines to fluctuations in the grid frequency. Control algorithms and sensor systems continuously monitor grid frequency and turbine performance which allows wind turbines to respond to variations in the grid frequency by adjusting the pitch of the blades (to capture more wind) or by changing the generator output (to balance supply and demand). These mechanisms maintain the stability of the grid, enhance the integration of renewable energy sources, and prevents power outages and disturbances.



Top organisations	Value
Universidad Politécnica de Madrid	7
Technical University of Denmark	4
Queen's University Belfast	4
Cardiff University	4
Aalborg University	4

Top EU organisations	Value
Universidad Politécnica de Madrid	7
University College Dublin	4
Technical University of Denmark	4
Aalborg University	4
Delft University of Technology	3

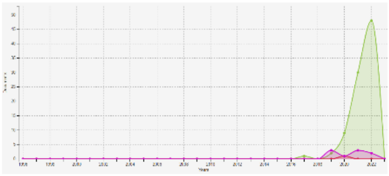


Country	RTA
CN	1.25
EU	1.84
JP	0.38
KR	0.53
US	0.55

2.13 Miscellaneous weak signals

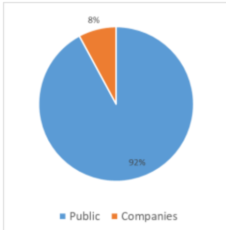
Interfacial solar evaporation

This process harnesses solar energy to evaporate a liquid at the interface between two materials. Applications are in water purification, desalination, and the concentration of brine solutions. Interfacial solar evaporation is energy efficient, environmentally friendly, has low operating costs, and is scalable and versatile. It is also a process that shows high resilience in remote areas and has high potential for solar-driven desalination, holding great promises for addressing global water and energy challenges.



Top organisations	Value
Zhejiang University	11
University of South Australia	7
Nanjing University	6
Nanjing Forestry University	6
Chinese Academy Of Sciences	6

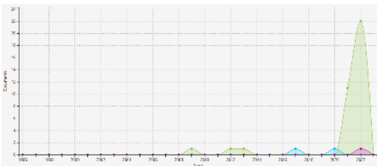
Top EU organisations	Value
Istituto Italiano di Tecnologia	2
Università Cattolica del Sacro Cuore	1
University of Bayreuth	1
Institute of Energy Technology	1
Aalto University	1



Country	RTA
CN	3.45
EU	0.23
JP	0.00
KR	0.79
US	0.35

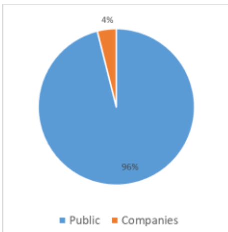
Hemispherical solar distiller

This device is used to produce pure freshwater using solar energy through distillation. The primary advantage of hemispherical solar distillers is their low-cost and sustainable purification and desalination of water (contaminants, salt and microorganisms are removed). They are ideal for remote and off-grid locations (low maintenance is needed), or for providing emergency water supply, and can be designed in various sizes to meet specific needs. Some limitations still remain, like lower water production rates compared to other water purification methods and the obvious dependence on sunlight.



Top organisations	Value
University of El Oued	29
University of Science and Technology	27
Tanta University	27
Prince Sattam Bin Abdulaziz University	11
Horus University	7

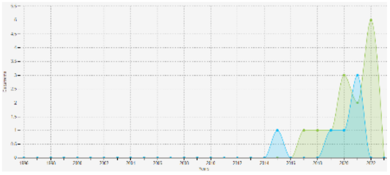
Top EU organisations	Value
Politecnico di Milano	2



Country	RTA
CN	0
EU	0
JP	0
KR	0
US	0.15

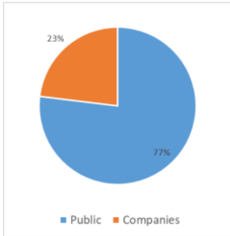
Islanded microgrid cluster

A network of interconnected microgrids operating independently from the main electrical grid, forming a self-contained resilient energy system. Each microgrid within the cluster generates, distributes, and stores electricity autonomously, incorporating renewable energy sources and energy storage technologies. In the event of a grid outage, individual microgrids can continue supplying power, ensuring uninterrupted energy supply for critical facilities and communities. The cluster allows sharing of excess energy, optimizing utilization and balancing energy loads. These clusters are particularly valuable for facilities like hospitals and emergency response centres, and represent a promising solution to enhance energy security and mitigate the impact of grid disruptions e.g. in the case of natural disasters.



Top organisations	Value
Huazhong University of Science and Technology	5
Southeast University	2
STATE GRID ZHEJIANG ELECTRIC POWER COM...	1
Islamic Azad University	1
Friedrich-Alexander-University Erlangen-Nuremberg	1

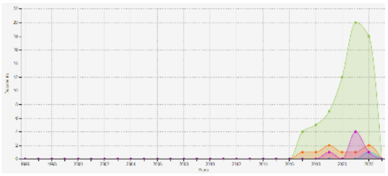
Top EU organisations	Value
Aalborg University	1
Friedrich-Alexander-University Erlangen-Nuremberg	1



Country	RTA
CN	3.23
EU	0
JP	0
KR	0
US	0.39

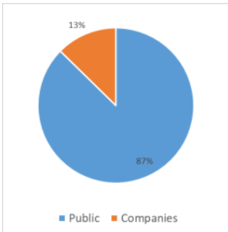
Energy injustice

This concept highlights the unequal distribution of benefits and burdens related to energy production, distribution, and consumption, particularly affecting marginalized communities. This issue has gained prominence recently due to several factors: marginalized communities are experiencing a disproportionate share of the negative impacts of energy-related activities (pollution, habitat destruction) leading to adverse health effects; disparities in access to affordable, reliable, and clean energy resources have been recognized, with an impact on education, healthcare, and economic opportunities; the impacts of climate change disproportionately affect vulnerable populations. Policy making in the field of Energy often excludes marginalized communities, leading to projects and policies that do not consider their needs and concerns. The transition to cleaner energy sources can also pose challenges, such as economic hardships in regions where coal mines and power plants are closing, necessitating just transition strategies to support affected workers and communities.



Top organisations	Value
University of Sussex	9
Aarhus University	7
University of Manchester	5
University of Cambridge	4
Cardiff University	3

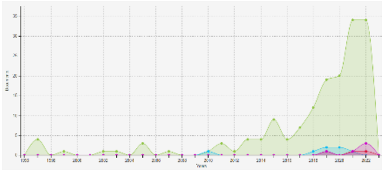
Top EU organisations	Value
Aarhus University	7
University of Twente	2
University of Tartu	2
Instituto Universitário de Lisboa	2
European University Viadrina	2



Country	RTA
CN	0.07
EU	1.77
JP	0
KR	0
US	0.72

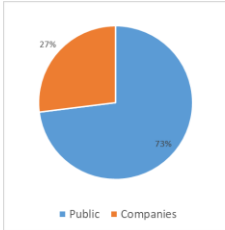
Lacustrine shale oils

These hydrocarbons are found in shale rock formations in ancient freshwater lake environments. They are one of the unconventional oil and gas resources that shows increased production in recent years, mainly due to advancements in hydraulic fracturing and horizontal drilling. Although they have economical and strategic significance, the extraction of shale oils is associated with environmental and social concerns, such as water usage and contamination, greenhouse gas emissions, and land use. It is a topic of significant debate and regulatory scrutiny. The development of new greener technologies and methods for extracting shale oils is ongoing (e.g. innovations in drilling, reservoir stimulation, and well construction techniques).



Top organisations	Value
China University of Petroleum	40
China University of Geosciences	23
Jilin University	17
SINOPEC	14
Chinese Academy Of Sciences	12

Top EU organisations	Value
RWTH Aachen University	7
Montanuniversität Leoben	4
Instituto Geológico y Minero de España	3
Universitat de Barcelona	2
Universidad Autónoma de Madrid	1



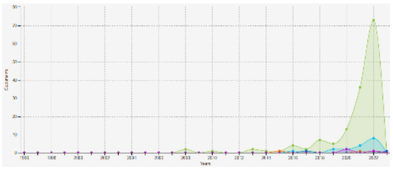
Country	RTA
CN	3.94
EU	0.13
JP	0
KR	0
US	0.40

Levelized cost of Energy

This well-known metric is used to assess and compare the lifetime costs of different energy generation methods, taking into account factors such as the initial investment, the operational and maintenance costs, and the expected energy output over the lifetime of the facility. It provides a standardized metric for evaluating the economic performance of different energy technologies. Three signals related to LCOE have been detected:

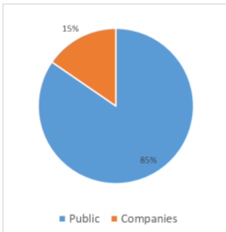
Levelized cost of hydrogen

This metric is specifically used to assess the cost of producing hydrogen over the lifetime of hydrogen production facilities. It helps hydrogen stakeholders (industry, policymakers, investors) make informed decisions about the feasibility and economic viability of hydrogen projects.

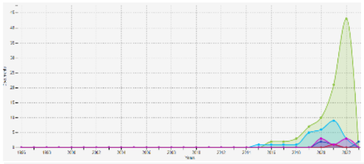


Top organisations	Value
Sharif University of Technology	7
University of Waterloo	6
Sapienza University of Rome	6
RWTH Aachen University	5
Southeast University	4

Top EU organisations	Value
Sapienza University of Rome	6
RWTH Aachen University	5
University of Naples Parthenope	4
University of Cassino and Southern Lazio	4
Technical University of Denmark	3

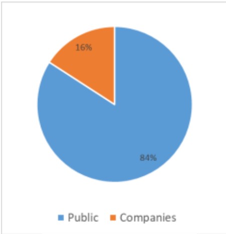


Country	RTA
CN	0.73
EU	1.77
JP	0.75
KR	2.86
US	0.38



Top organisations	Value
National Renewable Energy Laboratory US	6
Universidad Politécnica de Madrid	4
University of California	3
University of Birmingham	3
Tsinghua University	3

Top EU organisations	Value
Universidad Politécnica de Madrid	4
University of Stuttgart	2
University of Cagliari	2
TECHNISCHE UNIVERSITEIT DELFT	2
KTH Royal Institute of Technology	2



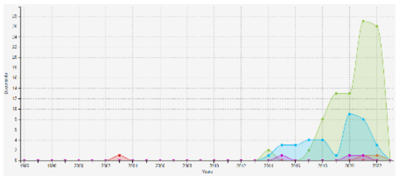
Country	RTA
CN	0.66
EU	1.24
JP	0.53
KR	0.74
US	1.42

Levelized cost of storage

The LCOE metric has also been used recently to assess the cost of energy storage over the lifetime of a storage system (expressed in €/MWh).

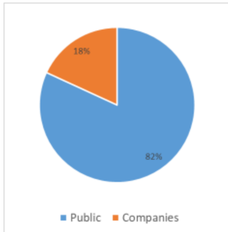
Levelized cost of heat

Similarly, LCOE metric has been used to assess and compare the cost of delivering heat from various sources and technologies over the entire lifecycle of heating systems, It allows comparing the cost-effectiveness of different heating technologies and fuel sources, helping to make informed decisions when selecting heating options for various applications, such as residential heating, industrial processes, or district heating systems. This analysis can be particularly important in the context of energy policy and investment decisions to promote efficient and cost-effective heating solutions.



Top organisations	Value
Technical University of Denmark	8
National Renewable Energy Laboratory	6
Cornell University	6
Shanghai Jiao Tong University	5
NAS of Ukraine	3

Top EU organisations	Value
Technical University of Denmark	8
University of Kassel	4
German Aerospace Center DLR	4
University of Zagreb	3
Heateon	3



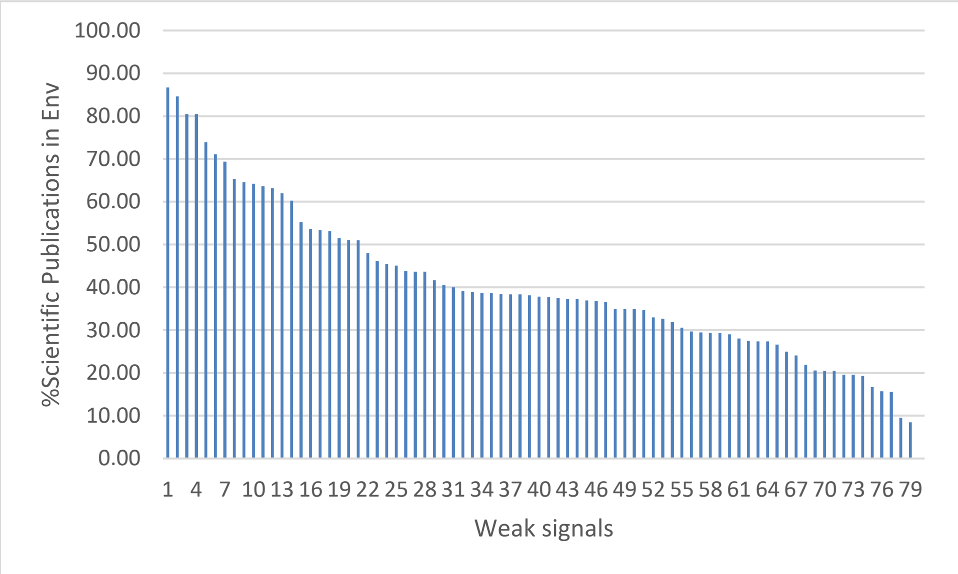
Country	RTA
CN	0.59
EU	2.03
JP	0
KR	0
US	1.20

3. Discussion

Scientific and technological fields

Environmental considerations and the transition to renewable energy sources underpins the development of most of the early stage technologies listed in this report. 37% (8.823 out of 23.945) of the scientific publications describing the weak signals are published in scientific journals classified in the journal category "Environmental Sciences" (Figure 3).

Figure 3: percentage of scientific publications in the category "Environmental Sciences" (Scopus category 21) for the weak signals, by decreasing value.



Many of the 77 early stage technologies detected build on scientific fields related to materials, as it can clearly be observed in Table 5. About 40% of the scientific publications underpinning the weak signals relate to material science, condensed matter physics, and material chemistry. The table also confirms that environmental considerations drive the development of early stage technologies in the field of energy, as reflected by the high percentage of documents in the "Renewable Energy, Sustainability and Environment" journal category.

Table 5: top 10 journal categories (ASJC) for scientific publications.

Top 10 ASCJ journal categories	%Documents
Materials Science	23%
Renewable Energy, Sustainability and the Environment	22%
Chemistry	19%
Energy Engineering and Power Technology	17%
Electrical and Electronic Engineering	14%
Chemical Engineering	10%
Condensed Matter Physics	8%
Fuel Technology	8%
Materials Chemistry	8%
Mechanical Engineering	7%

Looking at the top CPC classes for patents confirms this observation (Table 6), with 64,5% of the patents classified in the CPC class Y02E, which is the class used to flag technological inventions related to the "reduction of greenhouse gas emissions caused by the generation, transmission or distribution of energy". 50% of the patents retrieved for the 77 early stage technologies relate to batteries.

Table 6: top 10 CPC classes for patents

Top 10 CPC classes	%Patents
Y02E: REDUCTION OF GREENHOUSE GAS [GHG] EMISSIONS, RELATED TO ENERGY GENERATION, TRANSMISSION OR DISTRIBUTION	64.41%
H01M: PROCESSES OR MEANS, e.g. BATTERIES, FOR THE DIRECT CONVERSION OF CHEMICAL ENERGY INTO ELECTRICAL ENERGY	49.72%
Y02P: CLIMATE CHANGE MITIGATION TECHNOLOGIES IN THE PRODUCTION OR PROCESSING OF GOODS	10.65%
H02S: GENERATION OF ELECTRIC POWER BY CONVERSION OF INFRARED RADIATION, VISIBLE LIGHT OR ULTRAVIOLET LIGHT, e.g. USING PHOTOVOLTAIC [PV] MODULES	8.99%
B63B: SHIPS OR OTHER WATERBORNE VESSELS; EQUIPMENT FOR SHIPPING	7.37%
H02J: CIRCUIT ARRANGEMENTS OR SYSTEMS FOR SUPPLYING OR DISTRIBUTING ELECTRIC POWER; SYSTEMS FOR STORING ELECTRIC ENERGY	6.72%
C01B: NON-METALLIC ELEMENTS; COMPOUNDS THEREOF	6.01%
B82Y: SPECIFIC USES OR APPLICATIONS OF NANOSTRUCTURES	5.78%
H01G: CAPACITORS; CAPACITORS, RECTIFIERS, DETECTORS, SWITCHING DEVICES OR LIGHT-SENSITIVE DEVICES, OF THE ELECTROLYTIC TYPE	3.63%
B01J: CHEMICAL OR PHYSICAL PROCESSES, e.g. CATALYSIS OR COLLOID CHEMISTRY; THEIR RELEVANT APPARATUS	3.59%

Out of the 77 early stage technologies reported, about half of them relate to energy storage, with 18 signals directly related to batteries. Looking at the other early stage technologies, we can see that the area of photovoltaics accounts for 10 of them. This focus on energy storage technologies is most likely related to the ongoing transition to renewable energy sources. These sources of energy are characterized by intermittent output and subject to natural fluctuations. To ensure a stable and reliable energy supply, they require effective storage solutions that store energy when the production exceeds demand and release energy during high-demand periods. The decentralization of energy production also calls for the integration of technologies to store energy locally. Other factors like the electrification of mobility, the search for alternatives to lithium-based batteries, or the fight against climate change are also contributing to the ongoing intensive R&D efforts to develop new energy storage technologies.

Revealed technological advantage

Looking at the average revealed technological advantage (RTA) per category (Table 7), it can be observed that Europe shows high RTA index values for early technologies in areas such as Carbon Capture, Sequestration and Utilization, District heating and wind energy. However, Europe’s RTA is lower for early stage technologies related to batteries, geothermal energy, solar fuels, energy storage technologies and smart grids, indicating no specialization. China and South Korea have very strong RTAs in most categories, whereas Japan, and surprisingly the US, do not show high levels of specialization for many of the technologies.

Table 7: average RTA per category of weak signal (biomass and ocean energy were not considered (only one WS))

	RTA				
CETO categories	**CN**	**EU**	**JP**	**KR**	**US**
Batteries	3.03	0.59	0.72	1.32	0.58
Geothermal	2.29	0.56	0.08	0.76	0.14
Photovoltaics	1.58	1.04	1.57	3.69	0.51
Solar fuels	2.50	0.41	1.21	3.04	0.57
CCUS	0.87	1.70	0.23	1.16	0.69
District heating	0.45	2.54	0.15	0.07	0.67
Energy storage	2.35	0.59	0.40	2.09	0.57
Renewable fuel	1.28	1.11	0.90	1.68	1.14
Smart grid	1.27	0.69	0.31	1.30	0.63
Wind energy	0.81	1.74	0.64	0.27	1.87
Other	2.14	0.43	0.00	0.16	0.40

Table 8 shows the number of weak signals within each CETO category that have an RTA higher than one standard deviation above the mean value for the category, indicating strong specialization. From the table, China's leading position in most categories becomes apparent. At the same time, countries clearly display heterogeneity in their specialization patterns. While China and, to some extent, Korea seem to focus on technologies related to Batteries, Energy Storage and Photovoltaics, the EU specializes in the development of technologies related to District Heating.

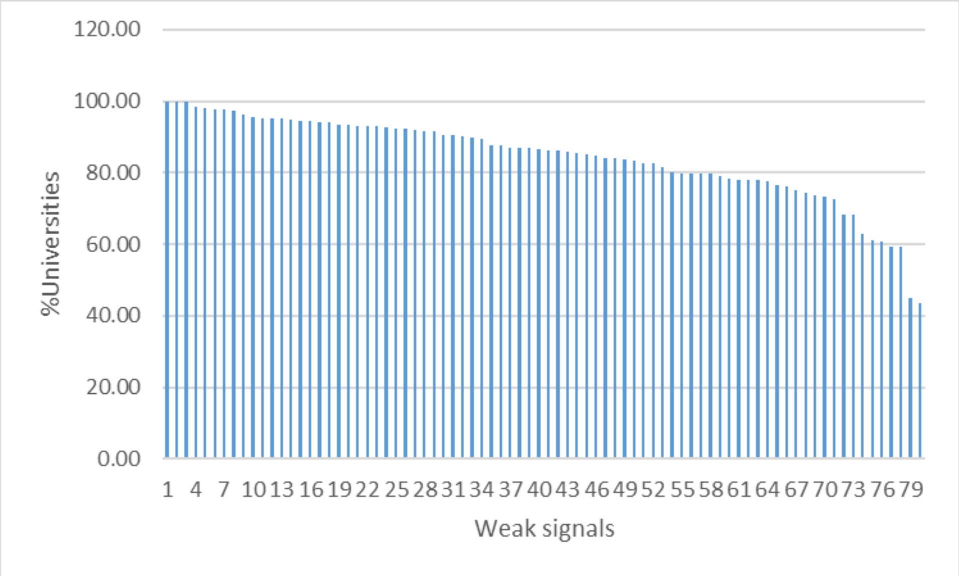
Table 8: number of weak signals with significant RTAs per country and category.

Categories	**#WS**	**Significant RTA**				
		CN	**EU**	**JP**	**KR**	**US**
Batteries	18	16.00	0	1	4	0
CCUS	3	0	1	0	1	0
District heating	4	0	4	0	0	0
Energy storage	18	12	0	0	6	1
Geothermal	3	2	0	0	1	0
Ocean energy	2	2	0	0	0	0
Other	5	3	1	0	0	0
Photovoltaics	10	2	0	3	6	0
Renewable fuels	5	2	1	1	3	1
Smart Grid	5	2	0	0	2	0
Solar fuel	5	3	0	0	3	0
Wind energy	2	0	1	0	0	1

Public and private actors

Public research institutions play a prominent role in the development of early stage technologies, before the commercialization phase. This is illustrated by Figure 4 showing the proportion of universities (among all organisations) involved in each of the weak signal.

Figure 4: proportion of universities among organisations involved in the weak signals



Patenting activity

Not surprisingly, most of the weak signals display a very low number of associated patents, reflecting the early stage of development of these technologies. At the same time, some of these early stage technologies have already entered the patenting phase, as illustrated in Figure 5, which depicts the percentage of patents among all the documents collected for each of the emerging technology. This percentage is relatively high for some of the early stage technologies (see Table 9).

Figure 5: percentage of patents retrieved for each of the weak signal.

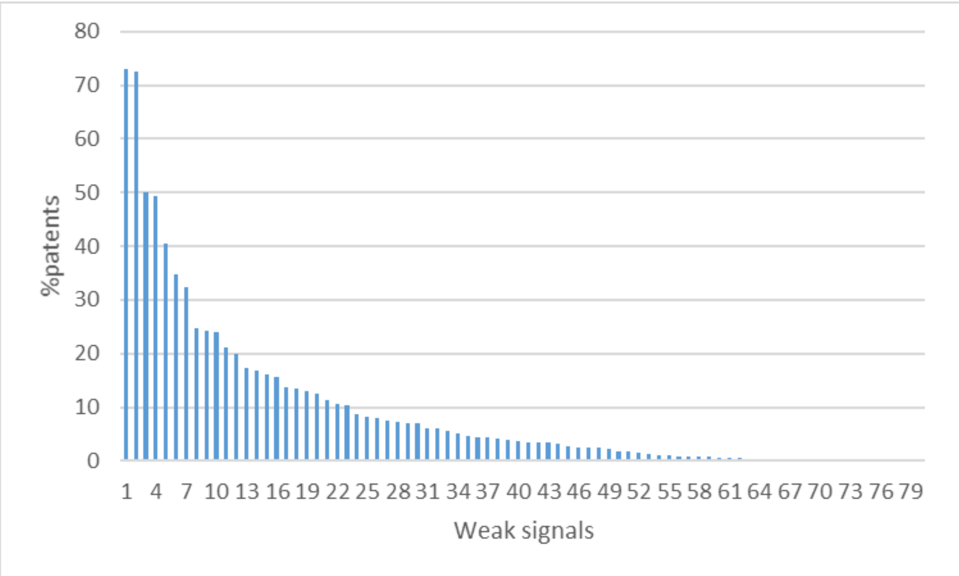
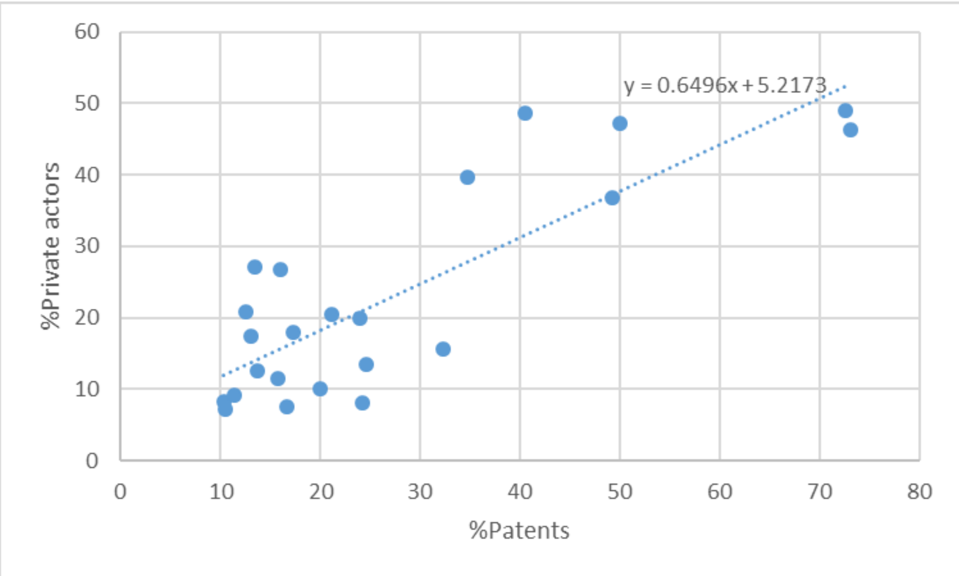


Table 9: Early stage technologies with %patent in the documents retrieved above 20%.

Weak signals	%patents
PV - offshore solar power	73
Geothermal - medium deep geothermal ener	73
energy storage - cloud energy storage	50
Batteries - retired batteries	49
energy storage - shared energy storage	40
PV - hydrovoltaics	35
Batteries - flexible Zinc ion	32
energy storage - compressed C02	25
energy storage - polyetherimide	24
batteries - Al suflur batteries	24
batteries - Organic Flow	21
Batteries - K hybrid supercapacitor	20

A correlation between the number of patents filed and the number of private actors in each weak signal can be observed (Figure 6). As technologies demonstrate commercial potential, the engagment of companies in patenting activity rises concurrently.

Figure 6: correlation between the number of patents filed for each weak signal and the number of private actors (companies and fundations), for weak signals with %patents > 10%.



Public funding

Governmental and public funding agencies are already supporting the development of most of the 77 emerging technologies reported here. Metadata from scientific literature (sourced from Scopus) allows identifying the principal funding bodies for these technologies. Table 10 shows the top 10 funding agencies mentioned in the funding section of scientific publications for the 12 different categories. It appears that the European Union, through diverse funding mechanisms like Horizon 2020 or the European Regional Development Fund, is actively funding the emerging technologies related to Biomass, CCUS, Wind Energy, Smart Grid, Renewable Fuels, and Photovoltaics.

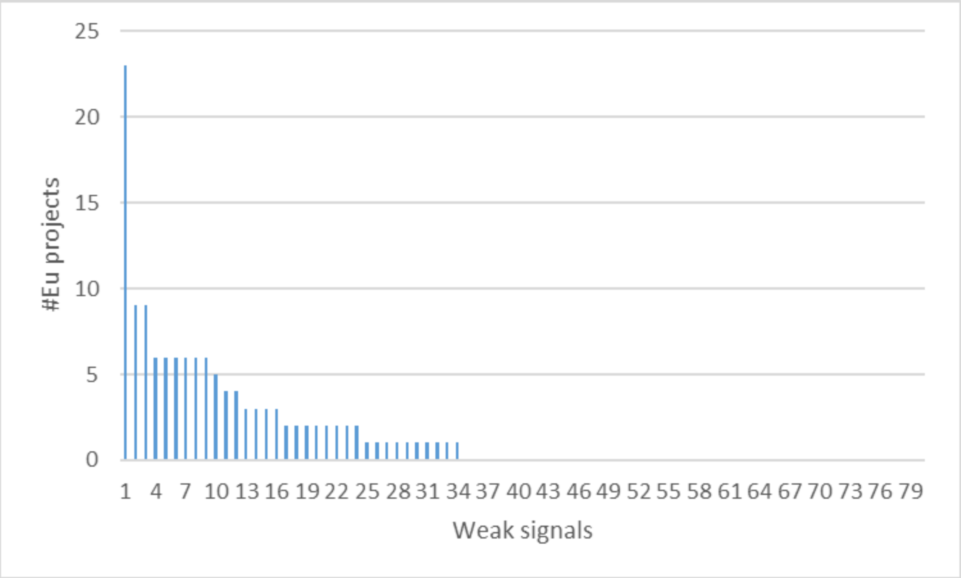
Table 10: top 10 funding agencies per category

Funding agency	#Docs	Country	Funding agency	#Docs	Country
Batteries			**Ocean Energy**		
National Science Fundation of China	6881	China	National Science Fundation of China	157	China
National Key Research and Development Program of China	1172	China	Chinese Academy of Science	47	China
National Research Fundation of Korea	400	South Korea	National Key Research and Development Program of China	23	China
Chinese Academy of Science	383	China	Beijing Municipal Science and Technology Commission	15	China
Ministry of Education	364	South Korea	National Research Fundation of Korea	11	South Korea
National Science Foundation	284	USA	China Scholarship Council	7	China
U.S. Department of Energy	282	USA	Chongqing University	7	China
China Scholarship Council	247	China	Ministry of Science and Technology Taiwan	6	Taiwan
Ministry of Science and Technology Taiwan	245	Taiwan	U.S. Department of Energy	5	USA
Australian Research Council	240	Australia	Engineering & Physical Sciences Research Council	5	UK
Biomass			**Photovoltaics**		
National Science Fundation of China	54	China	National Science Fundation of China	1113	China
National Key Research and Development Program of China	9	China	National Key Research and Development Program of China	235	China
Chinese Academy of Science	5	China	National Research Fundation of Korea	118	South Korea
European Commission	5	European Union	Ministry of Science, ICT and Future Planning	78	South Korea
Spanish Ministry of Science, Innovation and Universities	5	Spain	Ministry of Science and Technology Taiwan	74	China
National Research Foundation Singapore	4	Singapore	National Science Foundation	72	USA
Agencia Estatal de Investigación	4	Spain	European Commission	69	European Union
European Regional Development Fund	3	European Union	Ministry of Education of Taiwan	68	Taiwan
Central South University	3	China	U.S. Department of Energy	63	USA
Deutsche Forschungsgemeinschaft	3	Germany	Ministry of Trade, Industry and Energy	53	Korea
Carbon Capture, Utilization and Sequestration			**Renewable Fuels**		
National Science Fundation of China	42	China	National Natural Science Foundation of China	223	China
European Commission	21	European Union	U.S. Department of Energy	96	USA
National Key Research and Development Program of China	8	China	European Commission	70	European Union
National Research Fundation of Korea	8	South Korea	U.S. Federal Aviation Administration	62	USA
Fundação para a Ciência e a Tecnologia	8	Portugal	Engineering and Physical Sciences Research Council	42	UK
China Scholarship Council	7	China	National Key Research and Development Program of China	35	China
Ministry of Science, ICT and Future Planning	7	South Korea	Fundamental Research Funds for the Central Universities	35	China
Natural Sciences and Engineering Research Council of Canada	6	Canada	National Research Foundation of Korea	33	South Korea
U.S. Department of Energy	6	USA	National Science Foundation	30	USA
Ministério da Ciência, Tecnologia e Ensino Superior	6	Portugal	China Postdoctoral Science Foundation	30	China
District heating			**Smart Grid**		
U.S. Department of Energy	56	USA	National Science Fundation of China	187	China
European Commission	30	European Union	European Commission	91	European Union
National Science Fundation of China	26	China	National Research Fundation of Korea	49	South Korea
National Science Foundation	18	USA	National Science Foundation	49	USA
Engineering and Physical Sciences Research Council	12	UK	National Key Research and Development Program of China	44	China
National Renewable Energy Laboratory US	12	USA	Conselho Nacional de Desenvolvimento Científico e Tecnológico	28	Brasil
Natural Sciences and Engineering Research Council	10	Canada	Ministy of Education	26	South Korea
UFE switzerland	8	Switzerland	Ministry of Science, ICT and Future Planning	21	South Korea
National Research Fundation of Korea	8	South Korea	European Regional Development Fund	20	European Union
Federal Ministry for Economic Affairs and Energy	7	Germany	Qatar National Research Fund	20	Qatar
Energy storage			**Solar fuels**		
National Science Fundation of China	1537	China	National Science Fundation of China	1775	China
National Research Fundation of Korea	240	South Korea	National Key Research and Development Program of China	204	China
National Key Research and Development Program of China	184	China	National Research Fundation of Korea	96	South Korea
Ministry of Education of Taiwan	143	Taiwan	Priority Academic Program Development	83	China
Ministry of Science, ICT and Future Planning	137	South Korea	Ministy of Education	78	South Korea
Department of Science and Technology	81	India	Chinese Academy of Science	59	China
China Scholarship Council	62	China	Ministry of Science, ICT and Future Planning	54	South Korea
U.S. Department of Energy	62	USA	Ministry of Science and Technology Taiwan	46	Taiwan
National Science fundation USA	61	USA	National Science Foundation	40	USA
ZJNSF	58	China	Ministry of Science and Technology	36	India
Geothermal			**Wind energy**		
National Science Fundation of China	42	China	U.S. Department of Energy	68	USA
National Key Research and Development Program of China	13	China	National Science Foundation	25	USA
CRECU, MLR	7	China	National Renewable Energy Laboratory US	24	USA
Engineering & Physical Sciences Research Council	7	UK	European Commission	21	European Union
China Scholarship Council	6	China	National Science Fundation of China	20	China
Chinese Academy of Science	5	China	Wind Energy Technologies Office	10	USA
European Commission	3	European Union	Engineering & Physical Sciences Research Council	9	UK
Ministry of Science and Technology Taiwan	3	Taiwan	National Key Research and Development Program of China	8	China
Chinese Government Scholarship	3	China	Science Foundation Ireland	5	Ireland
Deanship of Scientific Research	2	Saudi Arabia	Federal Ministry for Economic Affairs and Energy	5	Germany
Others					
National Science Fundation of China	195	China			
National Key Research and Development Program of China	34	China			
Commonwealth Scholarship Commission in the UK	19	UK			
Australian Research Council	14	Australia			
European Commission	13	European Union			
KHHK	10	China			
CUP	9	China			
Chinese Academy of Science	8	China			
Ministry of Science and Technology	7	Bangladesh			
Ministry of Education Taiwan	7	Taiwan			

The alignment of EU's financial support with the Revealed Technological Advantages (RTAs) is evident for Biomass, CCUS, and Wind Energy. However, this is not the case for technologies in the categories Smart Grids, Photovoltaics and Renewable Fuels, which do not display any strong relative specialization despite receiving significant public funding from EU mechanisms. Public funding by European Institutions in Batteries, Energy Storage, and Ocean Energy significantly lags behind contributions from Chinese and Korean public bodies, reflecting the disparity noted above in the RTA analysis.

The EU's commitment to support to the development of emerging technologies in the field of energy is further confirmed by looking at the documents retrieved from the CORDIS database, which contains EU funded research projects (Figure 7). One technology in particular, "sustainable aviation fuel", received significant funding by research funding programmes of the EU, with 23 EU projects.

Figure 7: number of EU projects collected from the Cordis database for each weak signal.



We do not observe any increase of private entity engagement in weak signals supported by EU funding. Indeed, the average participation of private entity for weak signals supported by EU funding and weak signals not (yet) funded by any EU research programme remains consistent at around 18%.

4. Conclusions

The JRC's methodology for detecting emerging technologies through the application of text mining techniques on document corpuses allowed to identify 77 emerging technologies in the field of Energy.

The results of the analysis suggest that environmental considerations and the transition to renewable energy sources drive the development of most of these emerging technologies, many of which are directly related to energy storage and to photovoltaics. The crucial role of public research organisations and governmental bodies in the development of these early stage technologies is confirmed, as evidenced by the prominent participation of public research organisations in fundamental research and by the numerous funding agencies already providing financial support. At the same time, the engagement of private companies increases for those technologies that have already entered the patenting phase. When it comes to relative specialization, Europe appears to be more specialized in areas such as carbon capture, sequestration and utilization, district heating and wind energy, while it lags behind other major economies in technologies related to batteries, geothermal energy, solar fuels, energy storage and smart grids. China and South Korea, on the contrary, distinctly emerge as leaders in most categories, with specialization indexes consistently above one. Finally, Japan, and, surprisingly, the US, do not show high levels of specialisation for many of the early stage technologies in any category (low RTA).

Looking ahead, the detection of emerging technologies using text mining techniques is likely to see continued advancements, ultimately contributing to better informed decision-making. The text mining methodology used here could be improved by refining the keyword extraction techniques to reduce the inherent noise associated to semantic-based methods. This would minimize the human effort required for cleaning raw signals. Overall, text mining and natural language processing techniques will continue to advance, and so too will the ability to extract insights from large volumes of technology related documents. The integration of artificial intelligence and machine learning algorithms with text mining techniques is anticipated to bolster technology detection capabilities. This could lead to the creation of more automated and adaptable systems capable of continuously identifying and monitoring emerging technologies in real-time. Moreover, combining scientific document corpuses, such as patents or scientific publications, with other data sources like social media, industry reports, and market data, could offer a more comprehensive and holistic view of emerging technologies and their potential impact.

5. List of acronyms

CETO – Clean Energy Technology Observatory

TIM – Technology Innovation monitoring, a suite of tools developed by JRC for technogical foresight and technology monitoring

TFIDF - Term Frequency–Inverse Document Frequency

RTA – Revealed Technology Advantage

ASJC – All Sciences Journal Classification

CCUS – Carbon Capture, Utilisation, and Storage

CPC – Cooperative Patent Classification

6. Annexes

Annex 1: List of weak signals with search query

Dataset Category- signal	Search query	Act 20-23
Geothermal - hybrid nanofluid	topic:("hybrid nanofluid"~2 AND geothermal)	100.00
PV- s scheme heterojunction cat	topic:("s scheme heterojunction"~2)	99.20
Batteries - Zn CO2	topic:("Zinc CO2 battery"~1 OR "Zn CO2 battery"~1 OR "zinc carbon dioxyde battery"~2)	94.83
other - interfacial solar evaporation	topic:("interfacial solar evaporation"~1)	94.00
batteries - quasi-solid-state Li-Metal	topic:("quasi-solid-state lithium metal batteries"~2 OR "pseud-osolid-state lithium metal batteries"~2)	93.33
district heating - 5th generation	topic:("5th generation district heating"~3)	92.31
district heating - digital twin	topic:("digital twin" AND "district heating"~2)	90.91
CCUS - Blue h2	topic:("blue hydrogen")	90.67
energy storage - Znhybrid supercapacitor	topic:("zinc hybrid supercapacitor"~2 OR "zn-ion hybrid supercapacitor"~2)	90.09
other - hemispherical solar distiller	topic:("hemispherical solar distiller"~1 OR "hemispherical solar still"~1)	89.74
Solar fuel - Direct seawater electrolysi	topic:("Direct seawater electrolysis"~2 OR "direct sea water electrolysis"~2)	89.19
Batteries - aqueous zinc	topic:("aqueous zinc battery"~1)	88.43
PV - indoor organic PV	topic:("indoor organic photovoltaic"~2 OR "indoor organic PV"~2)	88.41
PV - Agrivoltaics	topic:(agrivoltaics OR "agri-photovoltaics" OR "agri-PV" OR agrophotovoltaics)	87.63
Batteries - K hybrid capacitor	topic:("potassium hybrid capacitor"~2)	86.51
RenewFuel - sustainable ammonia	topic:("sustainable ammonia" OR "green ammonia")	85.84

Solar Fuel - covalent organic framework	topic:("covalent organic framework" AND "solar fuel")	85.71
energy storage - polyetherimide	topic:("energy storage" AND polyetherimide)	85.48
Batteries - K metal	topic:("K metal battery"~2 OR "Potassium metal battery"~2)	85.23
CCUS - green hydrogen	topic:("green hydrogen" AND "carbon capture") NOT topic:("blue hydrogen" OR "grey hydrogen")	83.67
Solar fuel - z scheme heterojunction cat	topic:("z scheme heterojunction"~2)	82.97
RenewFuel - levelized cost of hydrogen	topic:("levelized cost of hydrogen")	82.08
energy storage - levelized cost storage	topic:("levelized cost of storage"~1)	82.03
Batteries - flexible Zinc ion	topic:("flexible zinc ion battery"~2)	81.25
energy storage - aqueous hybrid supercap	topic:("aqueous hybrid supercapacitor"~2 AND "energy storage") NOT (topic:"non-aqueous hybrid supercapacitor"~2)	80.56
Batteries - K hybrid supercapacitor	topic:("potassium hybrid supercapacitor"~2 OR "K hybrid supercapacitor"~2)	80.00
energy storage - mxene supercapacitors	topic:(supercapacitor AND Mxene AND "energy storage")	79.48
RenewFuel - cold direct ammonia fuel cel	topic:((("low temperature" OR "room temperature") AND "direct ammonia"~1 AND "fuel cell") OR "cold ammonia direct fuel cell"~2)	79.17
Geothermal - medium deep geothermal ener	topic:("medium deep geothermal energy"~2)	78.43
energy storage - h2 in aquifers	topic:("hydrogen aquifer storage"~5 OR ("H2 storage aquifer"~5 AND hydrogen))	78.26
Ocean - osmotic energy conversion	topic:("osmotic energy conversion"~2)	78.23
energy storage - electrochromic	topic:("electrochromic energy storage"~1)	77.24
PV - tin perovskite solar cells	topic:("tin perovskite solar cells"~2)	77.15
smart grid - blockchain	topic:("smart grids" AND blockchain)	76.29

batteries - small molecule organic cath	topic:("small molecule organic cathode"~2 OR "Low-Molecular-Weight Organic Cathode"~2 OR "Low-Mass Organic Cathode"~2 OR "Small Organic Material Cathode"~2 OR ("organic cathode" AND "small molecule"))	76.00
energy storage - shared energy storage	topic:("shared energy storage")	75.71
PV - bifacial perovskite solar cell	topic:("bifacial perovskite solar cell"~2)	75.61
Batteries - Zinc graphite	topic:("zinc graphite battery"~2 OR "Zn graphite battery"~2 OR ("zinc battery"~2 AND "graphite cathode"~1))	75.00
batteries - human-robot recycling	topic:(human AND robot AND battery AND recycling)	75.00
Batteries - retired batteries	topic:("retired batteries")	74.25
Wind - wake steering	topic:("wake steering" AND wind AND turbine)	74.17
other - energy injustice	topic:("energy injustice"~1)	74.07
batteries - dendrite-free	topic:("dendrite free")	74.07
other - microgrid island clusters	topic:("microgrid island clusters"~2)	73.68
smart grid - edge computing	topic:("smart grid" AND "edge computing")	72.94
RenewFuel - geological H2 storage	topic:("geological hydrogen storage"~2 OR "underground hydrogen storage"~2 OR "hydrogen geo storage"~2 OR "geological H2 storage"~2 OR "underground H2 storage"~2 OR "H2 geo storage"~2)	72.57
energy storage - compressed C02	topic:("compressed carbon dioxide energy storage"~2 OR "compressed CO2 energy storage"~2 OR "CO2 energy storage"~1 OR "compressed air energy storage with CO2"~1) NOT (emm_year:[2017 TO 2017] AND source:patstat) NOT emm_year:[1996 TO 2010]	72.39
PV - vehicle integrated PV	topic:("vehicle integrated photovoltaic"~2 OR "vehicle integrated PV"~2)	71.88
energy storage -ultrahigh energy storage	topic:("ultrahigh energy storage")	71.43
energy storage - MOF-based suprcapacitor	topic:(("metal organic framework" OR "metal-organic-framework" OR MOF) AND supercapacitor AND "energy storage")	71.04

Batteries - multivalent ion	topic:("multivalent ion battery"~2)	68.31
Ocean - triboelectric nanogenerator	topic:(("wave energy"~1 OR "ocean energy"~1) AND "triboelectric nanogenerator"~1)	68.10
district heating - levelized cost heat	topic:("levelized cost of heat"~2)	67.67
Biomass - chemical looping gasification	topic:("biomass chemical looping gasification"~3)	67.39
PV - Perovskite/silicon tandem sol cells	topic:("Perovskite silicon tandem solar cells"~2)	66.87
Geothermal - deep borehole heat exchange	topic:("deep borehole heat exchanger"~3)	66.67
smart grid - electricity theft detection	topic:(("electricity theft" AND "smart grid") OR "Smart Grid Revenue Protection"~2)	66.05
Batteries - Li CO2	topic:("Li CO2 battery"~2 OR "Lithium CO2 battery"~2)	65.22
Wind - fast frequency support	topic:(("fast frequency support"~2 OR "fast frequency response"~2) AND wind)	64.91
batteries - dual ion	topic:("dual ion batteries"~2)	64.65
smart grid - machine learning	topic:("smart grid machine learning"~5)	64.60
district heating - urban building energy	topic:("urban building energy modeling"~2)	63.94
energy storage - cloud energy storage	topic:("cloud energy storage"~2) NOT topic:"cloud computing"	63.77
Solar Fuel - photocatalytic CO2 reductio	topic:(("photocatalytic CO2 reduction"~1 OR "solar driven CO2 reduction"~1 OR "visible-light-driven CO2 reduction"~2 OR "CO2 photoreduction"~1) AND "fuel")	63.47
PV - offshore solar power	topic:("offshore solar power"~2 OR "offshore photovoltaics")	62.76
batteries - Al suflur batteries	topic:("aluminum sulfur batteries"~2 OR "AlS batteries"~2) NOT topic:("grammatical" OR "amyotrophic" OR "intrathecal" OR "generalizability")	62.67
energy storage - nanoencap phs chang mat	topic:("nano encapsulated phase change material"~2 AND (cooling OR energy OR heating))	61.76

energy storage - mobile energy storage	topic:("mobile energy storage")	61.25
energy storage - aqueous supercap	topic:("aqueous supercapacitor"~1 AND "energy storage") NOT topic:("non-aqueous")	61.16
PV - hydrovoltaics	topic:("hydrovoltaics" OR "aquavoltaics" OR "water voltaics" OR "floating PV" OR "floating photovoltaics")	60.55
RenewFuel - Sustainable aviation fuel	topic:("sustainable aviation fuel"~1 OR "renewable jet fuel"~1 OR "renewable aviation fuel"~1 OR "sustainable jet fuel"~1)	60.06
batteries - Zn air	topic:("zinc air batteries"~1 OR "ZN air batteries"~1)	59.67
energy storage - liquid organic h2 carr	topic:("Liquid Organic Hydrogen Carriers"~2)	59.25
Batteries - Mg Sulfur	topic:("Magnesium sulfur battery"~2 OR "Mg S battery"~2)	57.69
batteries - Lithium Argyrodite	topic:("lithium argyrodite")	57.33
batteries - Organic Flow	topic:("Organic Flow Batteries"~3)	56.90
Solar fuel - PEC CO2	topic:("photoelectrochemical CO2 reduction"~2 OR "PEC CO2 reduction"~2)	56.52
energy storage - metal foam phas chng ma	topic:("metal foam"~1 AND "energy storage" AND "phase change materials"~1)	56.30
CCUS - deep eutectic solvents	topic:("deep eutectic solvent"~1 AND ("carbon capture"~2 OR "CO2 capture"~2 OR "carbon sequestration"~2 OR "CO2 sequestration"~2))	55.56
energy storage - shell-and-tube thermal	topic:("shell-and-tube thermal energy storage"~3)	55.49
PV - ternary organic photovoltaics	topic:("ternary organic photovoltaics"~2)	54.72
other - lacustrine shale oil	topic:("lacustrine shale oil"~2)	54.49
smart grid - IoT	topic:("smart grid") AND title:(IOT OR "internet of things")	53.26

Annex 2: List of all raw weak signals reconstructed in TIM Technology

Potential weak signal	Query	#Doc	Act 20-23
Geothermal - hybrid nanofluid	topic:("hybrid nanofluid"~2 AND geothermal)	16	100.00
other - s scheme heterojunction cat	topic:("s scheme heterojunction"~2)	625	99.20
Batteries - Zn CO2	topic:("Zinc CO2 battery"~1 OR "Zn CO2 battery"~1 OR "zinc carbon dioxyde battery"~2)	58	94.83
other - interfacial solar evaporation	topic:("interfacial solar evaporation"~1)	100	94.00
batteries - quasi-solid-state Li-Metal	topic:("quasi-solid-state lithium metal batteries"~2 OR "pseud-osolid-state lithium metal batteries"~2)	30	93.33
other - H2 geological storage	topic:("hydrogen geo storage"~2 OR "hydrogen geological storage"~2)	40	92.50
district heating - 5th generation	topic:("5th generation district heating"~3)	26	92.31
district heating - digital twin	topic:("digital twin" AND "district heating"~2)	11	90.91
CCUS - Blue h2	topic:("blue hydrogen")	150	90.67
energy storage - Znhybrid supercapacitor	topic:("zinc hybrid supercapacitor"~2 OR "zn-ion hybrid supercapacitor"~2)	212	90.09
other - hemispherical solar distiller	topic:("hemispherical solar distiller"~1 OR "hemispherical solar still"~1)	39	89.74
Solar fuel - Direct seawater electrolysi	topic:("Direct seawater electrolysis"~2 OR "direct sea water electrolysis"~2)	37	89.19
Batteries - aqueous zinc	topic:("aqueous zinc battery"~1)	2092	88.43
PV - indoor organic PV	topic:("indoor organic photovoltaic"~2 OR "indoor organic PV"~2)	69	88.41
PV - Agrivoltaics	topic:(agrivoltaics OR "agri-photovoltaics" OR "agri-PV" OR agrophotovoltaics)	299	87.63
Batteries - K hybrid capacitor	topic:("potassium hybrid capacitor"~2)	126	86.51

other - sustainable ammonia	topic:("sustainable ammonia" OR "green ammonia")	346	85.84
Solar Fuel - covalent organic framework	topic:("covalent organic framework" AND "solar fuel")	21	85.71
energy storage - polyetherimide	topic:("energy storage" AND polyetherimide)	62	85.48
Batteries - K metal	topic:("K metal battery"~2 OR "Potassium metal battery"~2)	88	85.23
CCUS - green hydrogen	topic:("green hydrogen" AND "carbon capture") NOT topic:("blue hydrogen" OR "grey hydrogen")	49	83.67
Other - z scheme heterojunction cat	topic:("z scheme heterojunction"~2)	1521	82.97
other - levelized cost of hydrogen	topic:("levelized cost of hydrogen")	173	82.08
energy storage - levelized cost storage	topic:("levelized cost of storage"~1)	128	82.03
Batteries - flexible Zinc ion	topic:("flexible zinc ion battery"~2)	96	81.25
energy storage - aqueous hybrid supercap	topic:("aqueous hybrid supercapacitor"~2 AND "energy storage") NOT (topic:"non-aqueous hybrid supercapacitor"~2)	72	80.56
Batteries - K hybrid supercapacitor	topic:("potassium hybrid supercapacitor"~2 OR "K hybrid supercapacitor"~2)	20	80.00
energy storage - mxene supercapacitors	topic:(supercapacitor AND Mxene AND "energy storage")	614	79.48
other - cold direct ammonia fuel cell	topic:((("low temperature" OR "room temperature") AND "direct ammonia" AND "fuel cell") OR "cold ammonia direct fuel cell"~2)	24	79.17
Geothermal - medium deep geothermal ener	topic:("medium deep geothermal energy"~2)	51	78.43
energy storage - h2 in aquifers	topic:("hydrogen aquifer storage"~5 OR ("H2 storage aquifer"~5 AND hydrogen))	23	78.26
Ocean - osmotic energy conversion	topic:("osmotic energy conversion"~2)	124	78.23
energy storage - electrochromic	topic:("electrochromic energy storage"~1)	145	77.24

PV - tin perovskite solar cells	topic:("tin perovskite solar cells"~2)	407	77.15
smart grid - blockchain	topic:("smart grids" AND blockchain)	734	76.29
other - small molecule organic cathode	topic:("small molecule organic cathode"~2 OR "Low-Molecular-Weight Organic Cathode"~2 OR "Low-Mass Organic Cathode"~2 OR "Small Organic Material Cathode"~2 OR ("organic cathode" AND "small molecule"))	25	76.00
energy storage - shared energy storage	topic:("shared energy storage")	247	75.71
PV - bifacial perovskite solar cell	topic:("bifacial perovskite solar cell"~2)	41	75.61
Batteries - Zinc graphite	topic:("zinc graphite battery"~2 OR "Zn graphite battery"~2 OR ("zinc battery"~2 AND "graphite cathode"~1))	20	75.00
batteries - human-robot recycling	topic:(human AND robot AND battery AND recycling)	12	75.00
other - blockchain for smart grid	topic:(("smart grid" OR "smart energy" OR "smart electricity") AND blockchain)	794	74.69
Batteries - retired batteries	topic:("retired batteries")	365	74.25
Wind - wake steering	topic:("wake steering" AND wind AND turbine)	120	74.17
other - energy injustice	topic:("energy injustice"~1)	81	74.07
other - dendrite-free	topic:("dendrite free")	2071	74.07
other - microgrid island clusters	topic:("microgrid island clusters"~2)	19	73.68
smart grid - edge computing	topic:("smart grid" AND "edge computing")	340	72.94
energy storage - compressed CO2	topic:("compressed carbon dioxide energy storage"~2 OR "compressed CO2 energy storage"~2 OR "CO2 energy storage"~1 OR "compressed air energy storage with CO2"~1) NOT (emm_year:[2017 TO 2017] AND source:patstat) NOT emm_year:[1996 TO 2010]	134	72.39
PV - vehicle integrated PV	topic:("vehicle integrated photovoltaic"~2 OR "vehicle integrated PV"~2)	64	71.88

energy storage -ultrahigh energy storage	topic:("ultrahigh energy storage")	140	71.43
energy storage - MOF-based suprcapacitor	topic:(("metal organic framework" OR "metal-organic-framework" OR MOF) AND supercapacitor AND "energy storage")	777	71.04
RenewFuel - geological H2 storage	topic:("geological hydrogen storage"~2 OR "underground hydrogen storage"~2)	219	70.32
Wind - fast frequency support	topic:(("fast frequency support" OR "fast frequency response") AND wind)	104	69.23
Biomass - chemical looping gasification	topic:("biomass chemical looping gasification"~2)	78	69.23
district heating - levelized cost heat	topic:("levelized cost of heat"~1)	126	69.05
other - lacustrine shale oil	topic:("lacustrine shale oil"~1)	103	68.93
other - cloud energy storage system	topic:("cloud energy storage"~1)	118	68.64
Battery - multivalent ion	topic:("multivalent ion battery"~2)	183	68.31
Ocean - triboelectric nanogenerator	topic:(("wave energy"~1 OR "ocean energy"~1) AND "triboelectric nanogenerator"~1)	210	68.10
RenewFuel - e-NH3	topic:((("e-NH3" OR "e-ammonia" OR "electrochemical ammonia"~2 OR "electrochemical NH3"~2 OR "synthetic ammonia" OR "electro ammonia" OR "electro NH3") AND ("renewable fuel"~2 OR "advanced fuel"~2 OR "synthetic fuel"~2 OR biofuel OR "green fuel"~2)) OR "electrochemical ammonia synthesis"~1) NOT topic:("i e NH3" OR "i e ammonia" OR "i e ch4" OR "i e methane")	224	67.41
Batteries - Li CO2	topic:("Li CO2 battery"~1 OR "Lithium CO2 battery"~1)	233	66.95
PV - Perovskite/silicon tandem sol cells	topic:("Perovskite silicon tandem solar cells"~2)	335	66.87
RenewFuel - MOF	topic:("metal organic framework" AND "renewable fuel")	24	66.67
Geothermal - flash binary geothermal	topic:("flash binary geothermal"~2)	60	66.67

Geothermal - deep borehole heat exchange	topic:("deep borehole heat exchanger"~3)	156	66.67
smart grid - electricity theft detecton	topic:("electricity theft" AND "smart grid")	162	66.05
batteries - Na CO2	topic:("na CO2 batteries"~2 OR "sodium CO2 batteries"~2 OR "sodium carbon dioxide batteries"~2)	50	66.00
district heating - urban building energy	topic:("urban building energy modeling"~1)	189	65.61
solar fuel - dry reforming	topic:("dry reforming"~2 AND "solar fuel")	20	65.00
other - nano encapsultd phase change mat	topic:("nano encapsulated phase change material"~2)	136	63.97
Solar Fuel - photocatalytic CO2 reductio	topic:("photocatalytic CO2 reduction"~1 OR "solar driven CO2 reduction"~1 OR "visible-light-driven CO2 reduction"~2 OR "CO2 photoreduction"~1)	3339	63.94
hydropower - gravitational water vortex	topic:("gravitational water vortex power plant"~2 OR "gravitational vortex turbine"~2 OR ("vortex turbine" AND (hydropower OR hydro?power OR hydroelectric OR hydro?electric)))	66	63.64
batteries - Al suflur batteries	topic:("aluminum sulfur batteries"~1 OR "AlS batteries"~1)	74	63.51
other - bidirectional EV charging	topic:("bidirectional Electric Vehicle charger"~2)	41	63.41
PV - offshore solar power	topic:("offshore solar power"~2 OR "offshore photovoltaics")	145	62.76
smart grid - machine learning	topic:("smart grid" AND "machine learning")	1327	62.62
energy storage - Dielectric energy stora	topic:("Dielectric energy storage")	361	62.60
batteries - Al Na	topic:("Aluminum-Sodium Batteries"~2 OR "Al-Na Batteries"~2)	8	62.50
other - multi-energy systems	topic:("multi-energy systems" OR "multigeneration power"~1 OR "polygeneration power"~1)	1316	61.32
CCUS - Electrochemically Mediated Adsorp	topic:(("electrochemical mediated"~2 OR "electrochemistry") AND ("carbon capture"~1 OR "CO2 capture"~1 OR "carbon sequestration"~1 OR "CO2 sequestration"~1))	93	61.29

energy storage - mobile energy storage	topic:("mobile energy storage")	640	61.25
energy storage - aqueous supercapacitor	topic:("aqueous supercapacitor"~1 AND "energy storage") NOT topic:("non-aqueous")	242	61.16
PV - hydrovoltaics	topic:("hydrovoltaics" OR "aquavoltaics" OR "water voltaics" OR "floating PV" OR "floating photovoltaics")	730	60.55
Solar fuel - metal organic framework	topic:(("metal organic framework" OR MOF) AND "solar fuel")	81	60.49
RenewFuel - Sustainable aviation fuel	topic:("sustainable aviation fuel"~1 OR "renewable jet fuel"~1 OR "renewable aviation fuel"~1 OR "sustainable jet fuel"~1)	621	60.06
Batteries - supercabattery	topic:(supercabattery)	20	60.00
AdvBiof - lignin derived bio-oil	topic:("lignin derived bio oil"~2 OR "lignin-based bio?oil"~2 OR "lignin bio-crude"~2 OR "biomass lignin oil"~2) AND topic:(fuel or biofuel OR biodiesel OR diesel OR engine)	25	60.00
other - hybrid solid state transformer	topic:("hybrid solid state transformer"~2)	15	60.00
ocean - vortex induced vibrations	topic:(("Vortex Induced Vibrations"~1 OR vivace) AND ("ocean energy" OR "blue energy"))	15	60.00
energy storage - pseudocapacitive	topic:("pseudocapacitive energy storage"~2)	142	59.86
PV - colored PV module	topic:("colored photovoltaic"~2)	77	59.74
AdvBiof - hydrothermal Carbonization	topic:("Hydrothermal Carbonization" AND (biofuel OR bioenergy))	269	59.48
energy storage - liquid organic h2 carr	topic:("Liquid Organic Hydrogen Carriers"~2)	584	59.25
smart grid - multi energy microgrid	topic:("multi energy" AND "microgrid")	666	59.16
other - humanitarian energy	topic:("humanitarian energy"~2)	22	59.09
batteries - Organic Flow	topic:("Organic Flow Batteries"~2)	430	58.84
Wind - vernier generator	topic:("permanent magnet vernier generator"~2 OR "axial-flux vernier generator"~2 OR "magnetic flux vernier generator"~2)	34	58.82

Batteries - Mg S	topic:("Magnesium sulfur battery"~2 OR "Mg S battery"~2)	156	57.69
other - Lithium Argyrodite	topic:("lithium argyrodite")	75	57.33
other - hygroelectricity	topic:(hygroelectricity OR "Spontaneous electricity generator"~2 OR "electricity generation from ambient humidity"~2)	30	56.67
energy storage - Relaxor ferroelectr cer	topic:("Relaxor ferroelectric ceramic"~3 AND "energy storage")	53	56.60
Solar fuel - PEC CO2	topic:("photoelectrochemical CO2 reduction"~2 OR "PEC CO2 reduction"~2)	230	56.52
RenewFuel - Alcohol to Jet	topic:("Alcohol to Jet") AND topic:(fuel OR biofuel)	132	56.06
energy storage - self-healing storage	topic:("self healing energy storage"~7)	86	55.81
CCUS - deep eutectic solvents	topic:("deep eutectic solvent"~1 AND ("carbon capture"~2 OR "CO2 capture"~2 OR "carbon sequestration"~2 OR "CO2 sequestration"~2))	171	55.56
district heating - predictive maintenanc	topic:("predictive maintenance" AND "district heating")	9	55.56
energy storage - shell-and-tube thermal	topic:("shell-and-tube thermal energy storage"~3)	173	55.49
other - hybrid electric aircraft	topic:("hybrid electric aircraft"~1)	411	55.47
batteries - sodium selenium batteries	topic:("sodium selenium batteries"~1 OR "Na Se batteries"~1)	74	55.41
Geothermal - phase change materials	topic:("phase change material" AND geothermal)	116	55.17
batteries - Zn air	topic:("zinc air batteries"~1)	2991	55.03
energy storage - O3 ceramics	topic:(("O3ceramics" OR "O3 ceramics") AND "energy storage"~1)	151	54.97
smart grid - IoT	topic:("smart grid" AND IOT)	1978	54.95
PV - ternary organic photovoltaics	topic:("ternary organic photovoltaics"~2)	106	54.72
energy storage – liquid air	topic:("liquid air energy storage"~2)	410	54.63

energy storage - solid polymer electroly	topic:("energy storage" AND "solid polymer electrolyte")	272	54.41
hydropower - floating hydropower	topic:("floating hydropower"~3 OR "floating hydro?power" OR "floating hydro generator"~2 OR "floating photovoltaics")	587	54.00
energy storage - homopolar inductor flyw	topic:("homopolar inductor" AND flywheel)	26	53.85
Solar fuel - photocatalytic hydrogen pro	topic:(("photocatalytic h2"~2 OR "photocatalytic hydrogen"~2) AND "solar fuel")	143	53.85
other - extreme fast charging station	topic:("extreme fast charging station"~2 OR "super fast charging station"~2 OR "high-power charging stations"~2)	84	53.57
energy storage - plastic crystal	topic:("plastic crystal") AND topic:("energy storage")	58	53.45
other - virtual synchronous machine grid	topic:("virtual synchronous machine" AND grid)	586	53.07
Wind - super-twisting sliding	topic:("super-twisting sliding mode"~1 AND "wind turbine")	36	52.78
Batteries - Zn MnO2	topic:("Zinc-Manganese Dioxide Batteries"~1 OR "Zn-MnO2 batteries"~1)	457	52.74
energy storage - long duration storage	topic:("long duration energy storage"~2 OR "long term energy storage"~2)	624	52.40
biomass - biomass electrodes	topic:("biomass electrode"~2 OR "biomass cathode"~2 Or "biomass anode"~2)	104	51.92
CCUS - photoelectrochemical CO2 convers	topic:("photoelectrochemical CO2 conversion" OR "photoelectrochemical CO2 reduction" OR "photoelectrochemical carbon dioxide conversion"~2 OR "photoelectrochemical carbon dioxide reduction"~2)	168	51.79
energy storage - film capacitor	topic:("energy storage" AND "film capacitor")	487	51.75
AdvBiof - brewer spent grains	topic:(("brewer spent grain"~2 OR "spent malt"~2 OR "spent brewing grain"~2 OR "brewed grain residue"~2 OR "spent barley") AND (fuel OR biofuel))	70	51.43
energy storage - metal foam	topic:("metal foam"~1 AND "energy storage")	371	51.21

district heating - ultra low temperature	topic:("ultra low temperature" AND "district heating")	43	51.16
energy storage - thermo chemical	topic:("thermo chemical energy storage"~2 OR "thermochemical energy storage"~2)	1080	51.11
energy storage - antiferroelectrics	topic:("antiferroelectrics energy storage"~5)	210	50.95
batteries - LiTiS2	topic:("Lithium Titanium Sulfide Batteries"~3 OR (LiTiS2 OR "Li TiS2" AND batteries))	10	50.00
Geothermal - heated bridge	topic:("heated bridge"~2 AND geothermal)	16	50.00
energy storage - virtual synchronous gen	topic:("virtual synchronous generator" AND "energy storage")	411	49.88
energy storage - Gravity storage	topic:("gravity energy storage"~1 OR "gravitational energy storage"~1) OR topic:("gravitational potential energy storage"~1) OR (topic:(("gravity energy storage"~3 AND rail) OR ("rail energy storage"~3 AND gravity) OR "rail energy storage")) OR topic:("pumped hydro storage")	867	49.71
Batteries - battery recycling	topic:("battery recycling")	1958	49.28
energy storage - residential batteries	topic:("energy storage" AND "residential batteries")	67	49.25
district heating - 4th generation	topic:("4th generation district heating"~3)	120	49.17
Bioenergy - waste to bioenergy	topic:("waste bioenergy"~2)	332	49.10
RenewFuel - e-fuels	topic:(("e-fuel" OR "electro fuel" OR electrofuel)) NOT topic:("i e fuel")	515	48.74
energy storage - heat pump	topic:("heat pump energy storage integration"~10)	39	48.72
batteries - lithium silicon Ti nitrides	topic:("Lithium-Sulfur" AND "Titanium Nitride" AND batteries)	56	48.21
batteries - Li Sb	topic:("lithium antimony batteries"~3 OR "li Sb batteries"~3)	27	48.15
Energy storage - integration PV with ES	topic:("integration photovoltaics energy storage"~3 OR "hybrid photovoltaics energy storage"~3 OR "combination photovoltaics energy	162	48.15

	storage"~3 OR "inter connection photovoltaics energy storage"~3)		
Wind - type IV wind turbine	topic:("type IV wind turbine"~2 OR "type 4 wind turbine"~2) NOT topic:("type 3" OR "type III")	129	48.06
CCUS - mineral carbonation	topic:("mineral carbonation CO2"~2 OR "mineral carbonation carbon dioxide"~2 OR ("carbon mineralisation"~2 OR "carbon mineralization"~2) AND ("CO2 capture" OR "carbon capture"~2))	96	47.92
PV - hybrid offshore wind solar	topic:("hybrid offshore wind solar"~3 OR "hybrid offshore wind PV"~3 OR "hybrid wind offshore photovoltaics"~3 OR "combined offshore wind solar"~3 OR "combined offshore wind PV"~3 OR "combined offshore wind photovoltaics"~3 OR "integrated offshore wind solar"~3 OR "integrated offshore wind PV"~3 OR "integrated offshore wind photovoltaics"~3 OR "offshore wind solar"~1)	67	47.76
Geothermal - abandonned well	topic:("abandoned well" AND geothermal)	80	47.50
hydropower - underground pumped storage	topic:(("underground pumped storage" AND (hydropower OR hydro?power)) OR "Underground Pumping Storage Hydroelectricity" OR "underground hydro energy storage"~2 OR ("underground energy reservoir"~2 AND (hydropower OR hydro?power)) OR "underground pumped hydro"~2 OR "underground pumped hydropower storage"~2 OR "Hybrid Pumped Hydro Storage"~2)	76	47.37
PV - Bifacial solar panel	topic:("bifacial solar panel"~2 OR "bifacial PV panel"~2)	96	46.88
Geothermal - multilateral well	topic:(("multilateral well"~1 OR "multi-branch well"~2) AND geothermal)	47	46.81
energy storage - Relaxor ferroelect poly	topic:("Relaxor ferroelectric"~2 AND polymer AND "energy storage")	45	46.67
energy storage - supercapacitors	topic:("energy storage supercapacitors"~2)	1206	46.60
Biomass - Hydrothermal liquefaction	topic:("Hydrothermal liquefaction biomass"~2)	211	46.45
energy storage - high-temperature	topic:("high-temperature energy storage"~1)	722	46.26

other - flexible hybrid electronics	topic:("flexible hybrid electronics"~2 AND ("energy harvesting"~2 OR "energy scavenging"~2 OR "power harvesting"~2))	13	46.15
AdvBiof - biogas upgrading to biomethane	topic:("biogas upgrading to biomethane"~2)	167	45.51
energy storage - flexible supercapacitor	topic:("flexible supercapacitor")	2619	45.21
Wind - anti icing coating	topic:("wind turbine"~2 AND (icing OR frosting) AND coating)	102	45.10
others - clean heating	topic:("clean heating")	671	45.01
other - reversible solid oxide cell	topic:("reversible solid oxide cell"~2)	494	44.94
Solar fuel - liquid solar fuel	topic:("liquid solar fuel")	18	44.44
CCUS - offshore cavern	topic:(("offshore cavern"~2 OR "salt cavern"~2 OR "salt dome") AND (carbon OR CO2) AND (capture OR sequestration OR storage OR abatement OR disposal))	135	44.44
hydropower - hydrostatic pressure machin	topic:("hydrostatic pressure machine")	9	44.44
AdvBiof - hydothermal liquefaction	topic:("Hydrothermal Liquefaction" AND (biofuel OR bioenergy))	652	44.33
PV - transparent photovoltaics	topic:("transparent photovoltaics")	467	43.90
other - superconducting pipeline	topic:("superconducting pipeline"~1)	92	43.48
hydropower - bio inspired turbines	topic:("Bio-inspired Turbine"~2 OR "biomimetic turbine"~2 OR "bio mimetic turbine"~2 OR "Bio-inspired blade"~2 OR "biomimetic blade"~2 OR "bio mimetic blade"~2 OR "Bio-inspired rotor"~2 OR "biomimetic rotor"~2 OR "bio mimetic rotor"~2)	53	43.40
AdvBiof - thermo catalytic reforming	topic:(("Thermo-Catalytic Reforming"~2 OR "pyrolysis reforming"~2) AND biofuel)	30	43.33
batteries - Mg Air	topic:("magnesium air batteries"~2 OR "Mg air batteries"~2)	397	43.32
RenewFuel - on site H2 production	topic:("on-site hydrogen production"~1 OR "on-site H2 production"~1)	146	43.15

district heating - flexibility / demand	topic:(("flexibility demand"~3 OR "flexibility response"~2) AND "district heating")	65	43.08
AdvBiof - hydrothermal processing	topic:("hydrothermal processing" AND (Biofuel OR bioenergy))	119	42.86
energy storage - seasonal storage	topic:("seasonal energy storage"~2)	619	42.49
RenewFuel - artificial photosynthesis	topic:(("renewable fuel" OR biofuel) AND ("artificial photosynthesis" OR photocatalysis))	142	42.25
energy storage - rail storage	topic:(("gravity energy storage"~3 AND rail) OR ("rail energy storage"~3 AND gravity) OR "rail energy storage" OR "rail based energy storage"~2 OR ("mobile energy storage"~2 AND rail) OR (("railway energy storage"~2 OR "train energy storage"~2) AND (brake OR traction OR transport)) OR ("energy storage system" AND (rail OR railway OR train) AND (transport OR traction OR brake)))	621	41.38
PV - singlet fission solar cell	topic:("singlet fission solar cell"~2)	29	41.38
other - salinity gradient energy harvest	topic:("salinity gradient energy harvesting"~2 OR "salinity gradient power"~1)	405	41.23
other - power sharing islanded microgrid	topic:("power sharing islandic microgrid"~4)	211	41.23
district heating - renewab district heat	topic:("renewable district heating"~2)	68	41.18
other - turquoise hydrogen	topic:("turquoise hydrogen"~2 OR ("hydrogen production"~1 AND ("natural gas cracking"~1 OR "methane cracking"~1 OR "pyrolysis natural gas"~1 OR "pyrolysis methane"~1)))	124	41.13
district heating - SMR	topic:("small modular reactor" AND "district heating")	22	40.91
energy storage - modular multilevel conv	topic:("modular multilevel converter" AND (("energy storage" AND photovoltaics) OR (hybrid AND "energy storage") OR "grid integration"~3))	159	40.88
PV - waste	topic:("photovoltaic waste"~2 OR "PV waste"~2 OR "solar waste"~1 OR "photovoltaic recycling"~2 OR "PV recycling"~2)	1156	40.48
RenewFuel - Sabatier reaction	topic:("Sabatier reaction" AND (fuel OR biofuel OR "carbon capture" OR "energy storage"~1 OR "methane production"~2 OR "CO2" OR "carbon dioxide"))	206	40.29

RenewFuel - renew fuel additives	topic:("renewable fuel additives"~3)	55	40.00
Wind - funnel wind turbine	topic:("invelox wind turbine"~2 OR "funnel wind turbine"~2 OR "wind funnel generator"~2) NOT topic:aircraft	30	40.00
district heating - booster heat pumps	topic:("booster heat pumps"~2)	35	40.00
AdvBiof - microbial cell factories	topic:(("microbial cell factories"~1 OR "microbial bioproduction systems"~1 OR "microbial production platforms"~1 OR "microbial cell systems"~1 OR "microbial biomanufacturing"~1 OR "microbial bioprocessing units"~1 OR "microbial fermentation facilities"~1) AND (biofuel OR fuel))	455	39.34
batteries - Li Selenium	topic:("lithium selenium batteries"~1 OR "Li Se batteries"~1)	324	39.20
AdvBiof - hydrothermal gasification	topic:("Hydrothermal Gasification" AND (biofuel OR bioenergy))	46	39.13
Ocean - floating oscillating column	topic:("floating oscillating column"~2)	113	38.94
CCUS - clinker	topic:((clinker OR concrete OR cement) AND ("carbon capture"~2 OR "CO2 capture"~2 OR "carbon sequestration"~2 OR "CO2 sequestration"~2))	1883	38.93
hydropower - pico hydropower	topic:("pico hydropower" OR "pico hydro?power" OR "pico hydroelectric" OR"pico hydro?electric")	185	38.92
CCUS - MOF	topic:(("carbon capture"~1 OR "CO2 capture"~1 OR "carbon sequestration"~2 OR "CO2 sequestration"~2) AND ("metal organic framework" OR MOF))	1528	38.22
district heating - smart district heatin	topic:("smart district heating"~2)	63	38.10
CCUS - hydrate based CC	topic:("hydrate carbon capture"~4 OR "hydrate CO2 capture"~4)	195	37.95
other - direct hydrazine fuel cell	topic:("direct hydrazine fuel cell"~2)	124	37.90
energy storage - compressed-air	topic:("compressed-air energy storage"~2)	3011	37.70

Solar fuel - cyanobacterial chassis	topic:(("cyanobacterial chassis" OR "cyanobacterial factories"))	32	37.50
ocean - Reverse Electrodialysis	topic:("Reverse Electrodialysis")	928	37.39
district heating - district energy plann	topic:("district energy planning"~3)	43	37.21
district heating - thermal storage	topic:("district heating" AND "thermal storage")	264	37.12
district heating - system integration	topic:("district heating" AND "system integration")	49	36.73
CCUS - quadgeneration	topic:(("quad generation"~2 AND (heating OR cooling OR electricity)) OR quadgeneration)	11	36.36
AdvBiof - biomass torrefaction	topic:("biomass torrefaction"~2 AND (biofuel OR bioenergy))	61	36.07
Wind - vortex/bladeless wind turbines	topic:("vortex wind turbine"~2 OR "bladeless wind turbine"~2)	158	34.81
district heating - low temperature	topic:("low temperature" AND "district heating") NOT topic:ultra	628	34.39
AdvBiof - lignin derived phenols	topic:("lignin phenols"~2 AND (biofuel OR fuel))	181	34.25
Advbiof - Green Diesel	topic:("green diesel")	579	34.20
AdvBiof - bisabolene	topic:((biofuel OR fuel) AND bisabolene)	41	34.15
AdvBiof - hydroprocessed renewab jet	topic:("hydroprocessed renewable jet fuel"~2 OR "hydro processed renewable jet fuel"~2 OR "hydro treated renewable jet fuel"~2 OR (HRJ AND (biofuel OR fuel) AND (jet OR aviation)) OR (HEFA AND (biofuel OR fuel) AND (jet OR aviation)) OR ("Hydroprocessed Esters and Fatty Acids" AND (biofuel OR fuel) AND (jet OR aviation)))	277	33.94
hydropower - archimedes turbine	topic:("archimedes turbine" OR "screw turbine" OR "Archimedes screw generator"~1 OR "Archimedes screw turbine"~1 OR "archimedean hydro turbine" OR "hydrodynamic screw")	174	33.91
ocean - Capacitive Mixing	topic:("Capacitive Mixing" AND (ocean OR salinity))	59	33.90
RenewFuel - Microbial electrolysis cel	topic:("microbial electrolysis cells"~2 AND (biofuel OR "hydrogen production"~2 OR biohydrogen OR "methane production"~2 OR "renewable fuel"~1 OR "energy production"~1))	754	33.82

AdvBiof - microbial lipid production	topic:("microbial lipid production"~2 OR "microbial oil" OR "microbial triglycerides production"~2) AND topic:(biofuel OR fuel)	210	33.81
PV - Infrastructure-integrated	topic:("Solar-Powered Infrastructure"~2 OR "Infrastructure-Embedded Photovoltaics"~2 OR "PV-Inclusive Infrastructure"~2 OR "Photovoltaics Inclusive Infrastructure"~2 OR "Infrastructure-Embedded Solar"~2 OR "Integrated Solar Infrastructure"~2 OR "Solar-Embedded Infrastructure"~2 OR "Building-Integrated Photovoltaics"~2 OR "infrastructure integrated photovoltaics"~3 OR "infrastructure integrated PV"~3 OR (IIPV AND infrastructure AND photovoltaics))	3031	33.72
Geothermal - induced earthquakes	topic:(("induced earthquakes" OR "induced seismicity") AND geothermal)	629	33.70
district heating - waste heat	topic:("district heating waste heat"~5)	116	33.62
Geothermal - vertical earth-air heat exc	topic:("earth air heat exchanger"~3)	595	33.45
CCUS – ionic liquids	topic:("ionic liquid" AND ("carbon capture"~1 OR "CO2 capture"~1 OR "carbon sequestration"~1 OR "CO2 sequestration"~1))	1388	33.43
Wind - ultrasonic de icing	topic:((Ultrasonic OR ultrasound) AND icing AND "wind turbine"~2)	39	33.33
hydropower - VLH turbines	topic:("VLH turbine"~1 OR "very low head turbine"~1)	27	33.33
solar fuels - plasmonic photocatalysis	topic:("plasmonic photocatalysis" AND "solar fuel")	6	33.33
other - smart local energy system	topic:("smart local energy system" OR ("smart technologies" AND "energy systems" AND local) OR "intelligent decentralized energy system"~1 OR "advanced microgrid system"~1 OR "intelligent distributed energy network"~2 OR "smart microgrid")	1183	33.22
CCUS - photobioreactor	topic:(("carbon capture"~2 OR "CO2 capture"~2 OR "carbon sequestration"~2 OR "CO2 sequestration"~2) AND (photobioreactor OR "bio?sequestration" OR biosequestration))	353	33.14
other - radiative cooling paint	topic:("cooling paint")	76	32.89

Geothermal - transcritical co2	topic:(("transcritical co2" OR "supercritical CO2") AND geothermal)	199	32.66
hydropower - variable speed turbines	topic:(("variable speed turbine"~2) AND (hydropower OR hydro?power OR hydroelectric OR hydro?electric))	34	32.35
energy storage - composite system	topic:("composite energy storage material"~2 OR "composite energy storage system"~2)	493	32.25
AdvBiof - Bio-dimethyl ether	topic:(("bio-dimethyl ether" OR "bio-DME" OR "renewable dimethyl ether"~2 OR "sustainable dimethyl ether"~2 OR "Bio-di methyl ether" OR "renewable di methyl ether"~2 OR "sustainable di methyl ether"~2 OR bioether OR "green dimethyl ether"~2 OR "green DME" OR "renewable DME"~2 "sustainable DME"~2 OR "eco friendly dimethyl ether"~2 OR "bio-based DME"~2 OR "biogenic dimethyl ether"~2 OR "biogenic DME"~2 OR "environmental* friendly dimethyl ether"~2 OR "organic dimethyl ether"~2 OR "organic DME"~2 OR "eco-DME") AND (fuel OR biofuel))	60	31.67
district heating - microgrids	topic:(microgrid AND "district heating")	51	31.37
other - fuel cell hybrid train	topic:("fuel cell hybrid train"~3)	55	30.91
AdvBiof - hydroprocessing	topic:(Hydroprocessing AND (biofuel))	233	30.90
energy storage - hydrogen storage in MOF	topic:("hydrogen storage metal materials"~2 OR "hydrogen storage MOF"~2)	86	30.23
CCUS - mineral carbonation 3	topic:((("mineral carbonation" OR "carbon mineralisation"~2 OR "carbon mineralization"~2 OR "CO2 mineralisation"~2 OR "carbon mineralization"~2 OR "reactive basalt rock") AND ("CO2 capture" OR "carbon capture" OR "CO2 sequestration" OR "carbon dioxide sequestration"~2)))	604	30.13
AdvBiof - kluyveromyces marxianus	topic:("kluyveromyces marxianus" AND (biofuel OR fuel))	87	29.89
other - solar pavement	topic:("solar pavement"~2) NOT topic:("cool pavement")	125	29.60
district heating - district cooling	topic:("district cooling")	741	29.42

Biomass - trigeneration	topic:(biomass AND ("combined cooling heating power"~2 OR trigeneration))	243	29.22
batteries - zinc bromine	topic:("zinc bromide batteries"~2 OR "zinc bromine batteries"~2 OR "Zn Br batteries"~2 OR "ZnBr batteries"~2 OR "zn bromide batteries"~2)	327	28.75
AdvBiof - biomass sorghum	topic:(("sorghum biomass"~2 OR "broomcorn biomass"~2) AND (biofuel OR fuel))	131	28.24
district heating - sensors	topic:("district heating" AND sensor)	142	28.17
AdvBiof - synthetic biology	topic:("synthetic biology" AND (biofuel OR fuel))	859	27.82
other - Heterojunction composites	topic:(("heterojunction composites" OR "heterojunction materials") AND ("production electricity"~1 OR "energy production"~1 OR power))	78	26.92
hydropower - water wheels	topic:((hydropower OR hydro?power OR hydroelectric OR hydro?electric) AND ("water wheel" OR "overshot wheel" OR "breast?shot wheel" OR "undershot wheel"))	286	26.57
Advbiof - Renewable diesel	topic:("renewable diesel")	644	26.55
hydropower - micro and low head	topic:("micro hydropower" OR "micro hydro?power" OR "low head hydropower" OR "low head hydro?power")	1032	26.55
Wind - ice detection	topic:(("ice detection"~2 OR "ice sensing"~2) AND "wind turbine")	87	26.44
AdvBiof - xylo oligosaccharides	topic:((biofuel OR fuel) AND ("xylo oligosaccharides"~2 OR xylooligosaccharides~2 OR "xylo oligomer"~1 OR "xylan-based oligosaccharides"~2 OR (xylan AND oligosaccharides)))	176	26.14
CCUS - mineral carbonation 2	topic:("mineral carbonation")	1106	25.95
batteries - lithium sulfur graphene	topic:("Lithium Sulfur Batteries graphene"~5)	150	25.33
PV - bio solar cell	topic:("bio solar cell" OR "biosolar cell" OR "living solar cell")	76	25.00
AdvBiof - clostridium beijerinckii	topic:((biofuel OR fuel OR biobutanol) AND "clostridium beijerinckii")	184	25.00

CCUS - thermochemical splitting CO2	topic:("thermochemical splitting CO2"~1 OR "thermochemical splitting carbon dioxide"~2)	42	23.81
district heating - control strategies	topic:("district heating control"~3)	108	23.15
energy storage - flywheel	topic:("flywheel" AND "energy storage")	4762	22.55
hydropower - fish friendly turbines	topic:("fish friendly turbine"~3 OR "environmentally enhanced turbine"~3 OR "fish safe turbine"~2 OR "fish passage turbine" OR "fish-friendly hydropower technology" OR "hydrokinetic turbine with fish protection"~3 OR "Alden turbine" OR "MGR turbine" OR "Natel Energy turbine")	71	22.54
AdvBiof - oligosaccharides	topic:((biofuel OR fuel) AND oligosaccharides)	372	22.31
AdvBiof - proteomics	topic:(proteomics AND (biofuel OR fuel))	702	21.79
ocean - Pressure Retarded Osmosis	topic:("Pressure Retarded Osmosis"~1)	922	21.69
X RenewFuel - Methanol route	topic:(("Methanol route" OR "Methanol based Biofuels"~2 OR "Methanol to Fuels" OR "Methanol Pathway"~2 OR "Biomass-to-Methanol" OR "Methanol Biomass Conversion"~2 OR "Methanol Bioconversion"~1 OR "Bio-Methanol Production"~2 OR "Methanol Biofuel Synthesis"~1) AND (biodiesel OR biofuel OR fuel)) OR topic:("renewable methanol")	1426	21.32
district heating - intgrtd ele-heatg sys	topic:("integrated electricity heating systems"~2 OR "combined heat and power" OR "cogeneration systems")	15560	21.03
CCUS - depleted oil and gas fields	topic:(("depleted oil field"~2 OR "depleted gas field"~2 OR "depleted oil reservoir"~2 OR "depleted gas reservoir"~2 OR "disused oil field"~2 OR "disused gas field"~2 OR "disused oil reservoir"~2 OR "disused gas reservoir"~2) AND ("carbon capture"~2 OR "CO2 capture"~2 OR "carbon sequestration"~2 OR "CO2 sequestration"~2))	468	20.73
AdvBiof - isopentanol	topic:((isopentanol OR isoamyl OR isopentyl OR "3-Méthylbutan-1-ol" OR "Isoamyl alcohol" OR Isobutylcarbinol OR "3-Methyl-1-butanol" OR "1-Hydroxy-3-methylbutane" OR "3-Methylbutanol" OR "Isopentan-3-ol" OR "3-Methylbutan-1-ol" OR "Isopentan-1-ol" OR "Isopentyl carbinol") AND (biofuel OR fuel))	249	18.07

CCUS – ocean storage	topic:(("ocean storage" AND ("carbon capture"~2 OR "CO2 capture"~2 OR "carbon sequestration"~2 OR "CO2 sequestration"~2)) OR "ocean storage CO2"~1 OR "ocean storage carbon dioxide"~2)	52	17.31
battery - Li air	topic:("Li air battery"~1 OR "Lithium air battery"~1)	2610	17.24
CCUS - saline aquifers	topic:(("saline aquifer") AND ("carbon capture"~2 OR "carbon sequestration"~2 OR "carbon storage"~2 OR "carbon abatement"~2 OR "carbon disposal"~2 OR "CO2 capture"~2 OR "CO2 sequestration"~2 OR "CO2 storage"~2 OR "CO2 abatement"~2 OR "CO2 disposal"~2))	1905	16.90
energy storage – superconducting magneti	topic:("superconducting magnetic energy storage")	1964	16.75
batteries - NaMCl2	topic:("namcl2 batteries"~2 OR "naCucl2 batteries"~2 OR "nanicl2 batteries"~2 OR "naFecl2 batteries"~2 "sodium metal chloride batteries"~2 OR "sodium nickel chloride batteries"~2 OR "sodium iron chloride batteries"~2 OR "sodium copper chloride batteries"~2)	162	16.67
district heating - geothermal	topic:("geothermal district heating"~2)	234	16.67
biomass - biomass gasification	topic:(("gasification biomass"~1 AND "synthesis gas") OR "biomass gasified synthesis gas"~2)	222	16.67
Geothermal - cooling	topic:("geothermal air conditioning"~2 OR "geothermal cooling")	296	14.19
Solar fuel - transparent electrodes	topic:("transparent electrodes"~2 AND "solar fuel")	8	12.50
CCUS - supercritical CO2 injection	topic:("supercritical CO2 injection" AND ("carbon capture" OR "carbon sequestration" OR "mineralisation"))	16	12.50
hydropower - oil-free turbine	topic:(("oil-free turbine"~2 OR "self-lubricating turbine"~2 OR "water-lubricated turbine"~2 OR "auto-venting turbine"~2))	35	11.43
district heating - cogeneration	topic:("district heating cogeneration"~3)	98	10.20

Annex 3 - RTA by country for weak signals (by CETO categories)

Weak signals	RTA				
	CN	EU	JP	KR	US
batteries - Al suflur batteries	2.81	0.62	0.64	0.00	0.26
Batteries - aqueous zinc	3.58	0.16	0.34	1.28	0.36
batteries - dendrite-free	3.55	0.23	0.42	1.78	0.57
batteries - dual ion	2.93	0.42	1.30	1.13	0.43
Batteries - flexible Zinc ion	3.60	0.15	0.00	0.64	0.57
batteries - human-robot recycling	2.05	0.71	0.00	0.00	0.90
Batteries - K hybrid capacitor	3.83	0.37	0.52	0.72	0.05
Batteries - K hybrid supercapacitor	3.82	0.61	0.00	0.00	0.00
Batteries - K metal	3.26	0.44	0.78	1.08	1.35
Batteries - Li CO2	3.49	0.05	1.50	1.38	0.48
batteries - Lithium Argyrodite	1.69	1.41	3.39	4.70	0.97
Batteries - Mg Sulfur	1.61	1.50	0.33	0.93	0.82
Batteries - multivalent ion	2.60	0.39	0.66	3.36	0.81
batteries - Organic Flow	1.27	1.19	0.12	2.95	1.23
batteries - quasi-solid-state Li-Metal	3.50	1.10	0.00	4.07	0.00
Batteries - retired batteries	3.19	0.43	0.00	0.74	0.40
batteries - small molecule organic cath	3.46	0.00	1.39	0.00	0.85
Batteries - Zinc graphite	3.01	1.41	1.76	0.00	0.36
batteries - Zn air	3.45	0.27	0.72	1.64	0.38
Batteries - Zn CO2	3.95	0.40	0.50	0.00	0.81
average	3.03	0.59	0.72	1.32	0.58
	CN	EU	JP	KR	US
Geothermal - deep borehole heat exchange	3.12	0.77	0.25	0.00	0.41

Geothermal - hybrid nanofluid	0.00	0.53	0.00	2.29	0.00
Geothermal - medium deep geothermal ener	3.74	0.39	0.00	0.00	0.00
Average	2.29	0.56	0.08	0.76	0.14
	CN	EU	JP	KR	US
other - energy injustice	0.07	1.77	0.00	0.00	0.72
other - hemispherical solar distiller	0.00	0.00	0.00	0.00	0.15
other - interfacial solar evaporation	3.45	0.23	0.00	0.79	0.35
other - lacustrine shale oil	3.94	0.13	0.00	0.00	0.40
other - microgrid island clusters	3.23	0.00	0.00	0.00	0.39
Average	2.14	0.43	0.00	0.16	0.40
	CN	EU	JP	KR	US
PV - Agrivoltaics	0.27	1.60	0.96	2.37	1.31
PV - bifacial perovskite solar cell	1.46	1.09	0.85	3.55	1.04
PV - hydrovoltaics	0.88	1.07	0.07	2.12	0.34
PV - indoor organic PV	1.42	0.39	0.48	16.66	0.49
PV - offshore solar power	1.51	1.34	0.00	0.00	0.00
PV - Perovskite/silicon tandem sol cells	1.25	1.58	1.92	2.83	0.39
PV - ternary organic photovoltaics	2.55	0.51	0.00	3.16	0.56
PV - tin perovskite solar cells	2.21	0.48	4.32	2.22	0.35
PV - vehicle integrated PV	0.63	2.21	6.89	3.19	0.47
PV- s scheme heterojunction cat	3.59	0.17	0.21	0.77	0.11
Average	1.58	1.04	1.57	3.69	0.51
	CN	EU	JP	KR	US
Solar Fuel - covalent organic framework	1.80	0.53	1.65	4.58	0.67
Solar fuel - PEC reduction of CO2	1.81	0.64	1.90	4.69	1.17

Solar Fuel - photocatalytic CO2 reductio	2.84	0.33	1.00	2.00	0.27
Solar fuel - z scheme heterojunction cat	3.54	0.14	0.29	0.90	0.18
Average	2.50	0.41	1.21	3.04	0.57
	CN	EU	JP	KR	US
CCUS - Blue h2	0.35	1.51	0.41	1.70	1.00
CCUS - deep eutectic solvents	1.38	1.24	0.29	0.80	0.35
CCUS - green hydrogen	0.86	2.34	0.00	0.96	0.71
Average	0.87	1.70	0.23	1.16	0.69
	CN	EU	JP	KR	US
district heating - 5th generation	0.17	3.18	0.00	0.00	0.00
district heating - digital twin	0.41	2.97	0.00	0.00	0.00
district heating - levelized cost heat	0.59	2.03	0.00	0.00	1.20
district heating - urban building energy	0.62	1.98	0.60	0.28	1.50
Average	0.45	2.54	0.15	0.07	0.67
	CN	EU	JP	KR	US
Biomass - chemical looping gasification	2.81	1.13	0.88	0.00	0.27
	CN	EU	JP	KR	US
energy storage - aqueous hybrid supercap	3.33	0.37	1.82	2.53	0.00
energy storage - aqueous supercap	3.06	0.32	0.73	2.02	0.45
energy storage - cloud energy storage	2.82	0.17	0.00	1.44	0.74
energy storage - compressed C02	3.26	0.50	0.00	2.70	0.56
energy storage - electrochromic	2.82	0.21	0.27	5.92	0.27
energy storage - h2 in aquifers	0.48	0.75	0.00	0.00	0.95
energy storage - levelized cost storage	0.66	1.24	0.53	0.74	1.42

energy storage - liquid organic h2 carr	0.90	1.58	0.43	6.49	0.34
energy storage - metal foam phas chng ma	1.83	0.95	0.00	0.26	0.66
energy storage - MOF-based suprcapacitor	2.65	0.21	0.64	4.39	0.35
energy storage - mxene supercapacitors	2.68	0.48	0.40	2.99	0.59
energy storage - nanoencap phs chang mat	0.88	0.81	0.63	0.87	0.39
energy storage - polyetherimide	3.62	0.20	0.00	0.00	1.28
energy storage - shared energy storage	3.00	0.38	0.00	1.32	0.53
energy storage - shell-and-tube thermal	1.97	0.84	0.00	0.76	0.45
energy storage - Znhybrid supercapacitor	3.61	0.42	0.88	1.02	0.15
Average	2.35	0.59	0.40	2.09	0.57
	CN	EU	JP	KR	US
RenewFuel - cold direct ammonia fuel cel	2.82	0.00	1.65	2.29	2.02
RenewFuel - Direct seawater electrolysi	1.78	1.13	0.88	2.44	0.90
RenewFuel - geological H2 storage	0.40	1.61	0.16	0.22	0.53
RenewFuel - levelized cost of hydrogen	0.73	1.77	0.75	2.86	0.38
RenewFuel - sustainable ammonia	1.70	0.90	1.57	2.04	0.78
RenewFuel - Sustainable aviation fuel	0.25	1.26	0.38	0.21	2.21
Average	1.28	1.11	0.90	1.68	1.14
	CN	EU	JP	KR	US
smart grid - blockchain	1.02	1.01	0.52	1.52	0.64
smart grid - edge computing	2.20	0.73	0.65	0.90	0.57
smart grid - electricity theft detection	0.84	0.44	0.25	1.37	0.81
smart grid - IoT	1.04	0.70	0.15	1.72	0.40
smart grid - machine learning	1.24	0.58	0.00	1.00	0.74
Average	1.27	0.69	0.31	1.30	0.63

	CN	EU	JP	KR	US
Wind - fast frequency support	1.25	1.84	0.38	0.53	0.55
Wind - wake steering	0.37	1.64	0.90	0.00	3.19
Average	0.81	1.74	0.64	0.27	1.87

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