

Supporting information: Uncovering collaboration and knowledge areas in lithium-ion battery recycling

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9 S1 Patent extraction and filtering methodology

10 As described in Section 3.1, the initial patent extraction was performed using a keyword
11 search. This search targeted the “CTB” field (revised title, abstract, and claims) in the
12 Derwent World Patents Index. The keywords were derived from a bibliometric analysis
13 of recycling methods for spent LIBs¹, with manual standardisation of battery-related
14 search terms to ensure comprehensive retrieval and address inconsistencies (e.g.
15 consistently pairing “li-ion” and “lithium-ion”). To ensure reasonable initial capture, the
16 list of search terms (shown in Table S1) was intentionally kept broad. Wildcard
17 truncation (“*”) captures alternate word forms. Logical operators, Boolean logic, and
18 field restrictions used for the Derwent search exactly match the query structure shown
19 in Table S1. The search was not restricted by language, as Derwent provides reliable
20 English translations, nor by specific CPC codes to preserve downstream analysis. All
21 patents from January 1, 1990 (AD>=(19900101)) onward were included.

22 Table S1: Complete list of search terms used in this study. The search yielded **63,109** patent families.

23 **CTB**=((li-ion ADJ batter*) OR (lithium-ion ADJ cell*) OR (li-ion ADJ cell*) OR (lithium-ion ADJ power
24 ADJ batter*) OR (li-ion ADJ power ADJ batter*) OR (lithium-ion ADJ secondary ADJ batter*) OR (li-ion
25 ADJ secondary ADJ batter*) OR LIB OR (ternary ADJ batter*) OR (lithium-ion ADJ rechargeable ADJ
26 batter*) OR (li-ion ADJ rechargeable ADJ batter*) OR LiFePO4 OR LiCoO2 OR NMC OR LiMn2O4 OR
27 (li-ion ADJ accumulator*) OR (lithium-ion ADJ accumulator*)) **AND** **CTB**=(recycl* OR circular* OR
28 (circular ADJ economy) OR recover* OR regenerat* OR reclaim* OR reus* OR separat* OR synthesiz*
29 OR remanufactur* OR reproduc* OR repair* OR renovat* OR remediat* OR reviv* OR determinat* OR
30 purify* OR detect* OR measur* OR characteriz* OR refunction* OR regain* OR repurpos* OR
31 hydrothermal OR hydrometallurg* OR leach* OR bioleach* OR prepar* OR fabricat* OR produc* OR
32 extract OR precipitat* OR co-precipitat* OR dissolv* OR electrolysis OR electroosmosis OR
33 electrodialysis OR electrodeposit OR electrowinning OR pyrometallurg* OR roast* OR calcinat* OR bak*
34 OR flotation OR mechanochemical OR pyrolysis OR sinter* OR heat-treat* OR disassembl* OR crush*
35 OR pretreat* OR scrap* OR discharg* OR shred* OR fragment* OR comminut* OR smash) **AND**
36 **AD**>=(19900101)

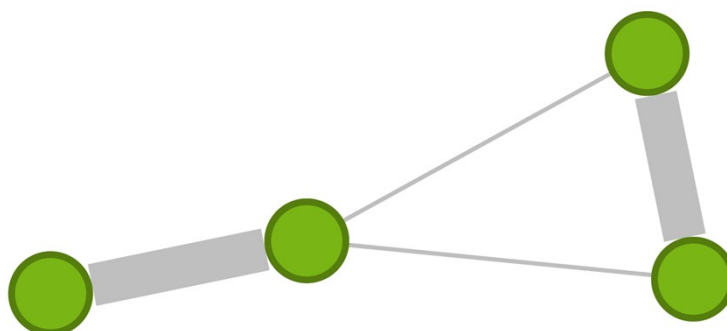
37 In a subsequent step, the scope was narrowed in the Python script to include only
38 those patents containing the term “recycl” in the abstract, title, or claims. This captured
39 all derivatives due to Python substring matching. Further data pre-processing steps,
40 including other filtering procedures, may be found in the accompanying code on
41 GitHub, where patents were deduplicated based on application number, entries with
42 missing core data fields (priority date, priority region, CPC code, assignee) were
43 excluded, and fields were normalised to lowercase. Quantitatively, our initial query

44 yielded 63,109 patent families, which were reduced to 1,233 patent families after
45 applying the described clean-up and “recycl” filtering as the final analytical dataset.

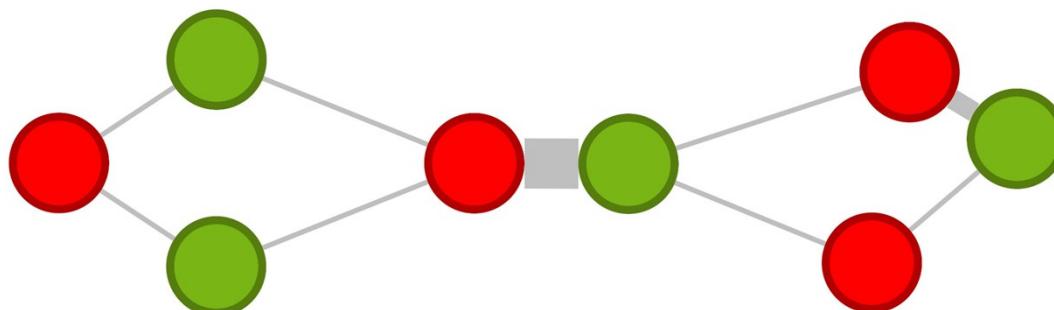
46 **S2. Example networks**

47 As referenced in Chapter 3.2.1., Figure S1 features two sample networks. Panel a)
48 shows a simple weighted one-mode network containing a single node class, while
49 panel b) displays a weighted two-mode network with two different node classes. As is
50 a characteristic of this type of network, nodes of the same class are never directly
51 connected to each other. Instead, nodes can only be interconnected to nodes of the
52 opposite class.

a)



b)



53

54 Figure S1: a) Example of a weighted one-mode network. b) Example of a weighted two-mode network

55

56 **S3. Corresponding descriptions of the top 20 most frequent CPC-** 57 **classes in the patent dataset**

58 Table S2 features the full descriptions of the top 20 most frequent Cooperative Patent
59 Classification (CPC) classes in the patent dataset as found in Espacenet².

60 Table S2: Overview of the top 20 most frequent CPC classes in the patent dataset. Words in “[]” are
61 added based on the descriptions of higher corresponding CPC codes to increase clarity.

CPC-Symbol	CPC-Description
Y02W 30/84	Recycling of batteries or fuel cells
H01M 10/54	Reclaiming serviceable parts of waste accumulators
Y02E 60/10	Energy storage using batteries
H01M 10/0525	Rocking-chair batteries, i.e. batteries with lithium insertion or intercalation in both electrodes; Lithium-ion batteries
Y02P 10/20	Recycling
C22B 26/12	Obtaining lithium
H01M 4/525	of mixed oxides or hydroxides containing iron, cobalt or nickel for inserting or intercalating light metals, e.g. LiNiO ₂ , LiCoO ₂ or LiCoOxFy
H01M 4/505	of mixed oxides or hydroxides containing manganese for inserting or intercalating light metals, e.g. LiMn ₂ O ₄ or LiMn ₂ OxFy
C22B 7/006	Wet processes
C22B 7/007	by acid leaching
H01M 2004/028	Positive electrodes
H01M 10/052	Li-accumulators
H01M 4/5825	Oxygenated metallic salts or polyanionic structures, e.g. borates, phosphates, silicates, olivines
C22B 47/00	Obtaining manganese
Y02P 70/50	Manufacturing or production processes characterised by the final manufactured product
C01D 15/08	Carbonates; Bicarbonates [Lithium compounds]
C01P 2006/40	Electric properties [of inorganic compounds]
C01P 2002/72	[crystal structural characteristics] by d-values or two theta-values, e.g. as X-ray diagram

H01M 4/131	Electrodes based on mixed oxides or hydroxides, or on mixtures of oxides or hydroxides, e.g. LiCoOx
C01P 2006/80	Compositional purity [of inorganic compounds]

62

63 **S4 Term frequency-inverse document frequency (TF-IDF)**

64 **hyperparameters**

65 The TF-IDF analysis was performed using the *TfidfVectorizer* module from the *scikit-*
66 *learn* (version 1.5.0) library³. All hyperparameters were set to default values, as
67 summarised in Table S3. The choice to use defaults reflects a focus on established
68 and easily reproducible settings. The `stop_words` parameter was set to “None” since
69 stopwords were already removed during preprocessing. The key hyperparameters,
70 their default values, and relevant implications for the analysis are detailed below.

71 Table S3: Overview and implications of key TF-IDF hyperparameters used in this study.

Parameter	Default value	Description	Implications
<code>ngram_range</code>	(1, 1)	Only single words (unigrams) are considered as features	Key phrases (e.g. “lithium ion”) not detected as a unit
<code>min_df</code>	1	Terms must appear in ≥ 1 document to be included	All non-stopword terms included, even very rare ones
<code>max_df</code>	1.0	Terms may appear in all documents	Terms common across all clusters are not filtered out
<code>max_features</code>	None	No upper limit on the number of features	Complete vocabulary included; most relevant terms extracted
<code>stop_words</code>	None	No stopwords removed by vectorizer—filtered during preprocessing with <i>nltk</i>	Allows full control over standard and domain stopwords
<code>token_pattern</code>	<code>\b\w\w+\b</code>	Tokens are ≥ 2 alphanumeric chars	Single-letter tokens are ignored
<code>norm</code>	<code>l2</code>	Each cluster’s TF-IDF vector is scaled to unit Euclidean norm	Ensures keyword scores are comparable within clusters
<code>use_idf</code>	True	Weights penalise terms common across the corpus	Reduces influence of highly generic terms

smooth_idf	True	Adds 1 to document frequencies for IDF calculation	Avoids division by zero and stabilises weights
sublinear_tf	False	Raw term frequencies used; no logarithmic scaling	Terms are counted linearly with their frequency
lowercase	True	Converts all text to lowercase	Is redundant with preprocessing, but has no drawbacks for results
binary	False	If True, all nonzero term counts are set to 1 (only presence or absence is considered); frequency is ignored.	Term frequency is considered, so more frequent words receive higher TF-IDF scores.

72

73 **S5. Supplementary patent assignee co-occurrence networks**

74 To complement Figure 7 of the manuscript, this section depicts the full patent assignee
75 co-occurrence network labelled completely (Figure S2) and the corresponding
76 unlabelled network (Figure S3).

77

SONY GROUP CORP

POSCO HOLDINGS INC. (F/K/A POSCO LTD)

SNAMPROGETTI SPA

SANMARU KAGAKU KK

RESEARCH INSTITUTE OF INDUSTRIAL SCIENCE & TECHNOLOGY

SIEMENS VAI

ENI SPA

CANADA CHEM CORP

SWISS FEDERAL INSTITUTE OF TECHNOLOGY ZURICH

PRATSINIS SOTIRIS E.

KOBE STEEL LTD.

EXXONMOBIL CORP

Legend:

- KR (Green circle)
- NL (Cyan circle)
- TW (Magenta circle)
- US (Pink circle)
- No country found (Grey circle)
- ROW (Dark grey circle)

Entities and connections:

- UNIV PICARDIE (NL) connected to CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE (NL)
- CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE (NL) connected to SHENZHEN ZHENHUA NEW MATERIAL CO LTD (US)
- SHENZHEN ZHENHUA NEW MATERIAL CO LTD (US) connected to GUIZHOU ZHENHUA NEW MATERIALS CO LTD (US)
- GUIZHOU ZHENHUA NEW MATERIALS CO LTD (US) connected to LI X (US)
- LI X (US) connected to XU JUN (US)
- LI X (US) connected to LEI JUN - NING JING (US)
- LEI JUN - NING JING (US) connected to LIU JING - HUA (US)
- LIU JING - HUA (US) connected to CHANGZHOU XIANGYU RESOURCE RECYCLING TEC (US)
- CHANGZHOU XIANGYU RESOURCE RECYCLING TEC (US) connected to UNIV JIANGSU TECHNOLOGY (US)
- UNIV JIANGSU TECHNOLOGY (US) connected to CPC CORPORATION (US)
- CPC CORPORATION (US) connected to AMT INT INC (US)
- AMT INT INC (US) connected to TAKASAGO KOGYO KK (US)
- TAKASAGO KOGYO KK (US) connected to NATIONAL INSTITUTE FOR INDUSTRIAL SCIENCE AND TECHNOLOGY (US)
- TOYOTA MOTOR CORP (KR) connected to ZEON CORP. (KR)
- ZEON CORP. (KR) connected to BATTERY ASSOC JAPAN (KR)
- BATTERY ASSOC JAPAN (KR) connected to COVALENT MATERIALS CORPORATION (KR)
- COVALENT MATERIALS CORPORATION (KR) connected to UCB SA (US)
- UCB SA (US) connected to YERANDE S (US)
- YERANDE S (US) connected to SAMSUNG SDI CO., LTD. YONGIN-SI KR (KR)
- SAMSUNG SDI CO., LTD. YONGIN-SI KR (KR) connected to SAMSUNG SDI CO LTD (KR)
- SAMSUNG SDI CO LTD (KR) connected to BOSCH (ROBERT) GMBH (US)
- BOSCH (ROBERT) GMBH (US) connected to ZHEJIANG NEW ENERGY TECHNOLOGY CO LTD (US)
- ZHEJIANG NEW ENERGY TECHNOLOGY CO LTD (US) connected to UNIV WUHAN (US)
- UNIV WUHAN (US) connected to ASCEND ELEMENTS INC (US)
- ASCEND ELEMENTS INC (US) connected to WORCESTER POLYTECHNIC INSTITUTE (WPI) (US)
- WORCESTER POLYTECHNIC INSTITUTE (WPI) (US) connected to HON HAI PRECISION INDUSTRY CO., LTD.(ALSO KNOWN AS FOXCONN) (TW)
- HON HAI PRECISION INDUSTRY CO., LTD.(ALSO KNOWN AS FOXCONN) (TW) connected to TSINGHUA UNIVERSITY (US)
- TSINGHUA UNIVERSITY (US) connected to AKZO NOBEL N.V. (NL)
- AKZO NOBEL N.V. (NL) connected to SEERDEN J P G (NL)
- SEERDEN J P G (NL) connected to BEIQI FOTON MOTOR CO LTD (US)
- BEIQI FOTON MOTOR CO LTD (US) connected to UNIV BEIJING TECHNOLOGY (US)

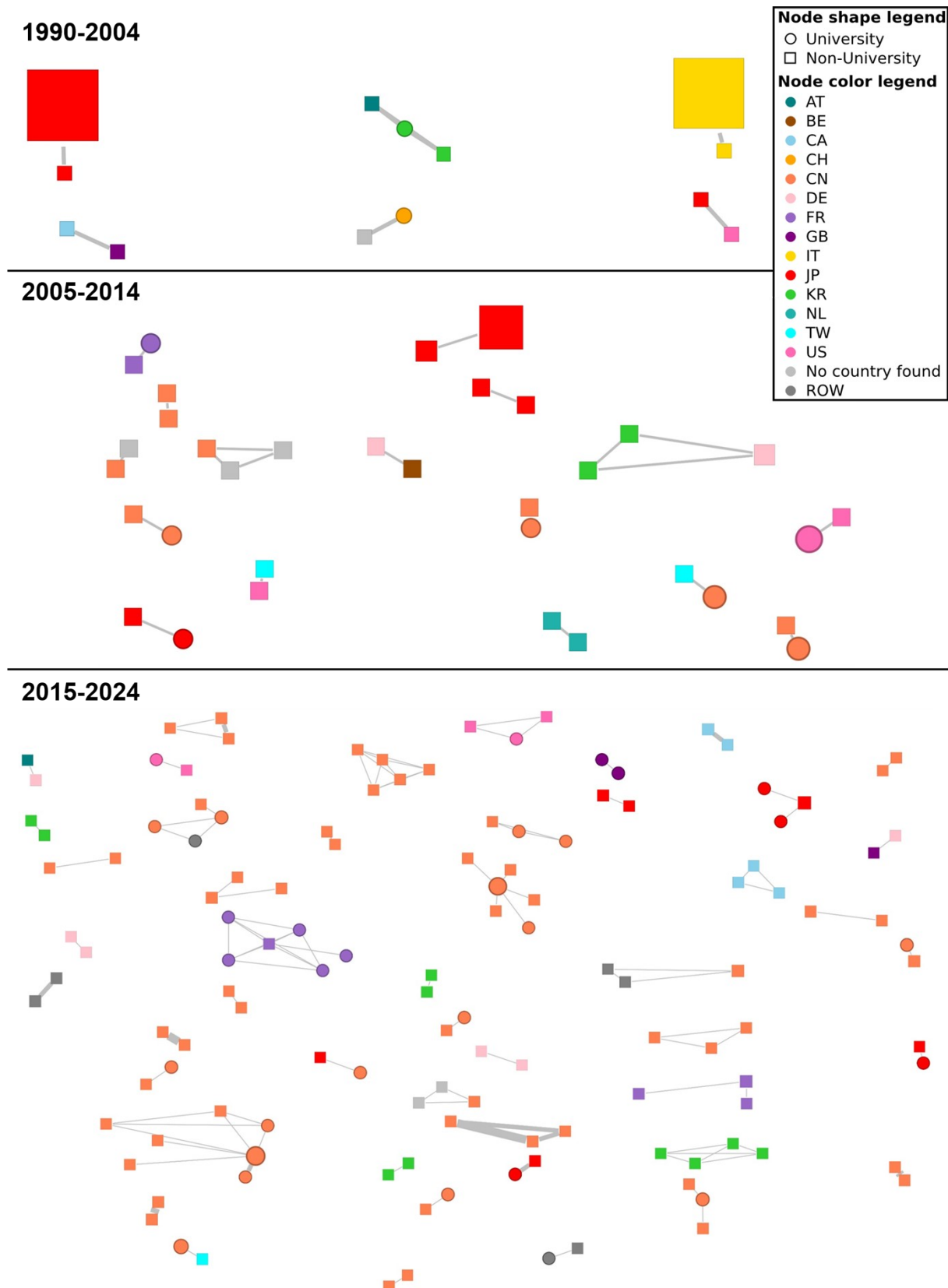
The diagram illustrates a global network of clean energy stakeholders, primarily Chinese companies and institutions, interconnected by a complex web of relationships. The nodes are color-coded and labeled with company names, while the edges represent the connections between them. The network is dense, with many nodes having multiple connections, suggesting a highly integrated industry. The layout is roughly circular, with many nodes connected to a central hub or to each other in a complex web. The nodes are color-coded, with many in shades of blue, green, and orange. The edges are thin lines connecting the nodes. The overall impression is one of a highly interconnected global network of clean energy stakeholders.

Key entities and connections include:

- Top Section:** GUANGXI YINXI ADVANCED MATERIAL CO LTD, GUANGXI TENKFEI HYDRO MATERIAL CO LTD, GUANGXI YINXI HIGH-TECH RES & DEV CO LTD, SHANGHAI CENAT NEW ENERGY CO LTD, NANZHANG KANAI NEW ENERGY CO LTD, JIANGSU CAREN NEW ENERGY CO LTD, GUANGXI KANAI NEW ENERGY CO LTD, NANJING CENAT NEW ENERGY TECHNOLOGY DEV, SORTERA TECHNOLOGIES INC, SORTERA MEMOIRS INC, BATTELLE MEMORIAL INSTITUTE, HYDRO-QUEBEC, TRANSFERTEC PLUS SEC, HENAN HAIIRI INTELLIGENT TECHNOLOGY GROUP CO LTD, GONGYI RECYCLE ENVIRONMENTAL PROTECTION.
- Left Section:** SCHOLZ RECYCLING GMBH, ANDRITZ AG, PRINCETON UNIVERSITY, PRINCETON ENERGY INC, GUANGZHOU SAYIDI NEW ENERGY TECHNOLOGY, UNIV SOUTH CHINA NORMAL, UNIV MACAU, UNIV MOGALAY, UNIV NANCHANG, UNIV NANCHANG HANGKONG, UNIV ANHUI AGRIC, HONDA MOTOR CO LTD, HONDA GIKEN KOGYO KK, JAPAN METALS, CHEM CO LTD, KYUSHU UNIVERSITY, TOYOTA MOTOR CORP, NENAN HAIIRI INTELLIGENT TECHNOLOGY GROUP CO LTD, GONGYI RECYCLE ENVIRONMENTAL PROTECTION.
- Bottom Section:** WEICK & POLLER HOLDING GMBH, WKS TECH GMBH, NORTHVOLT REVOLT AB, NORTHVOLT AB, YINGNAIWEI ZHEJIANG NEW ENERGY TECHNOLOGY, ZHEJIANG CHANGXING CHINA RUSSIA NEW ENER, HUNAN CHANGYUAN LICO CO LTD, JINCHI ENERGY MATERIALS CO LTD, UNIV HEFEI TECHNOLOGY, HEFEI YUANXIN RECYCLING TECHNOLOGY CO, ANHUI CHAOYUE ENVIRONMENTAL PROTECTION, ANHUI HUIHONG TECHNOLOGY CO LTD, UNIV BEIJING SCIENCE & TECHNOLOGY, LANGFANG GREEN IND TECHNOLOGY SERVICE, SOUTHERN MARINE SCIENCE ENG GUANGDONG LAB, CHINESE ACADEMY OF SCIENCE, ZHENGZHOU INST EMERGING IND TECHNOLOGY, GUANGDONG JIANA ENERGY TECHNOLOGY CO LTD, QINGYUAN JIAZHI NEW MATERIALS RES INST, TSINGHUA UNIVERSITY, HON HAI PRECISION INDUSTRY CO LTD (ALSO KNOWN AS FOXCONN), TIANMA MICROELECTRONICS CO LTD, CAL-CHINA AVIATION LITHIUM BATTERY, BEIJING INST TECHNOLOGY, BEIJING LIGONG XINYUAN INFORMATION TECHNI, CONSEJO NACIONAL DE INVESTIGACIONES CIENTIFICAS Y TECNICAS, UNIV NACIONAL CUYO.
- Right Section:** UNIV LIVER, CONOPCO INC, AG HYDROMETALLURGY SERVICES INC, XPS EXPERT PROCESS SOLUTIONS-GLENCORE, FRONTIER LITHIUM INC, ZHEJIANG NARADA POWER SOURCE CO LTD, JIESHOU NANDU HUAYU POWER CO LTD, HARBIN INSTITUTE OF TECHNOLOGY, STATE GRID CORP OF CHINA, PT GEM INDONESIA NEW ENERGY MATERIALS, GEN CO LTD, QINGMEIBANG NEW ENERGY MATERIALS CO LTD, XIAN JIATONG UNIVERSITY, HUNAN DESAY BATTERY CO LTD, WP HOLDING GMBH DE, WKS TECH GMBH DE, NALON BATTERY, SHENZHEN CO LTD, QIANTAI TECHNOLOGY, SHENZHAN SPECIAL CO, SHENZHEN QIANTAI ENERGY REGENERATION TEC, TANAKA HOLDINGS CO LTD, YOKOHAMA NATIONAL UNIVERSITY, COMMISSARIAT A L'ENERGIE ATOMIQUE, ORANO SA (FORMERLY NEW AREVA), SEO HYUN SEUNG, HONG KWANHEE, JANG WOOSEONG, SONG JAE HA, SHANGHAI FEIKANG MACHINERY ELECTRIC APPL, CHINA UNIVERSITY OF MINING & TECHNOLOGY, HUMAN KEYING RECYCLING TECHNOLOGY CO, JIANGSU HUAHONG TECHNOLOGY CO LTD.

79 Figure S2: Overview of full labelled patent assignee co-occurrence networks over three periods.

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82 Figure S3: Overview of full unlabelled patent assignee co-occurrence networks over three periods.

83

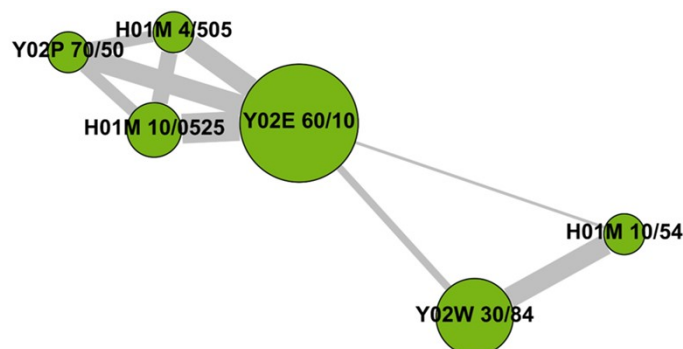
84 S6. Supplementary CPC co-occurrence and clustered CPC co- 85 occurrence networks

86 To complement Figure 8 of the manuscript, this section first presents the fully labelled
87 CPC co-occurrence networks filtered to include only nodes with a weight of 5 or more
88 (Figure S4), followed by the completely unfiltered and unlabelled networks used in the
89 CPC co-occurrence analysis (Figure S5).

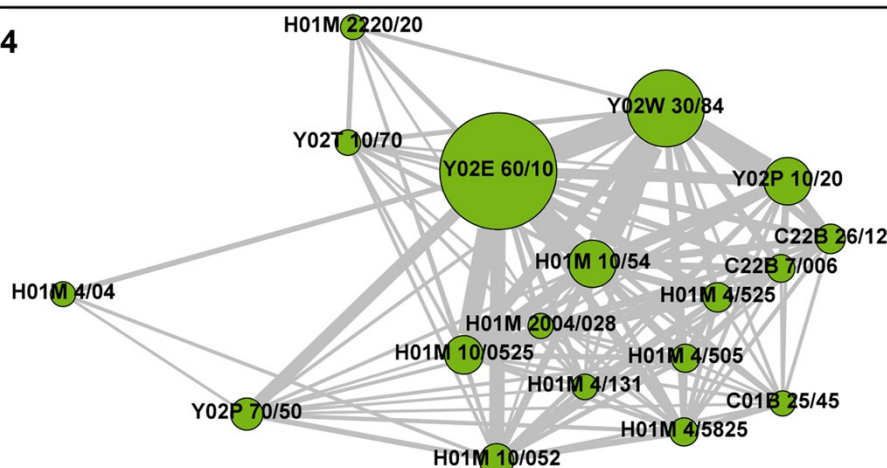
90 To complement Figure 9, it then features the fully labelled clustered CPC co-
91 occurrence networks filtered to nodes with a weight of 5 or more (Figure S6), and
92 finally, the completely unfiltered and unlabelled clustered CPC co-occurrence networks
93 (Figure S7).

94

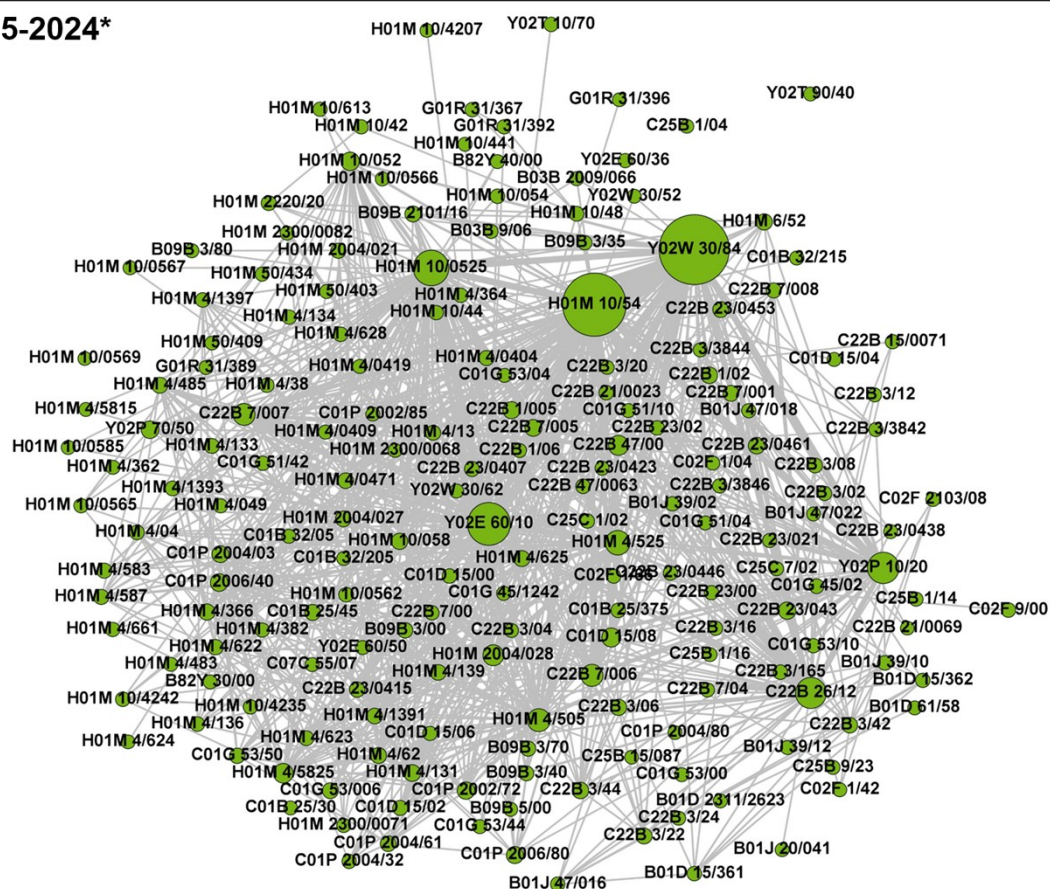
1990-2004



2005-2014



2015-2024*



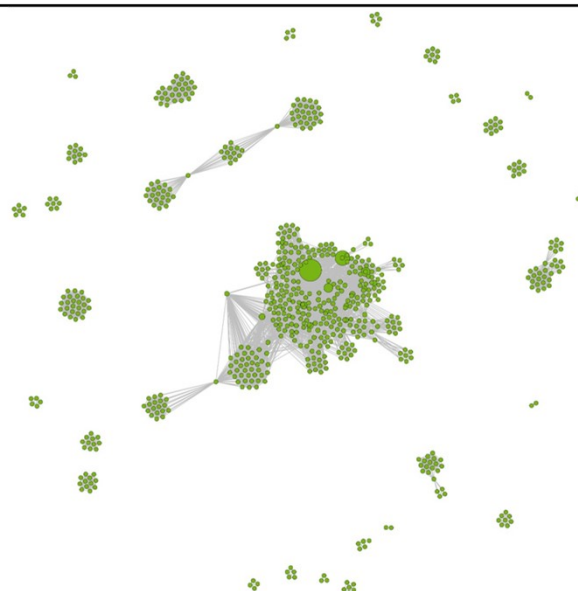
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96 Figure S4: Overview of CPC co-occurrence networks for three periods. Only nodes with weight ≥ 5 are
 97 shown. *To increase readability, edges with weights below five are filtered out.

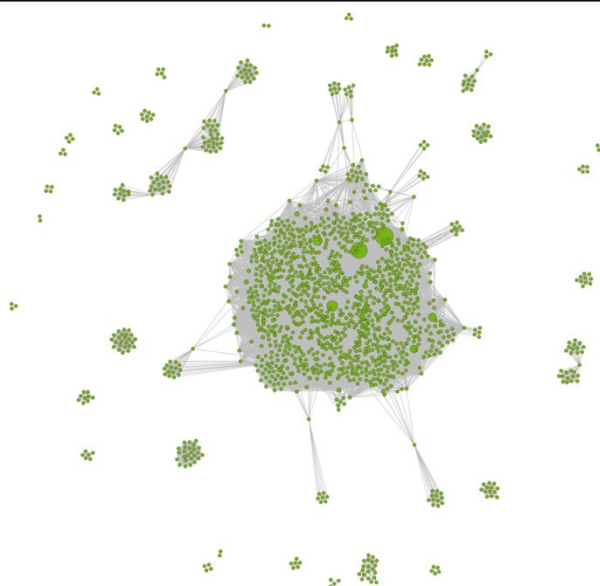
1990-2004



2005-2014



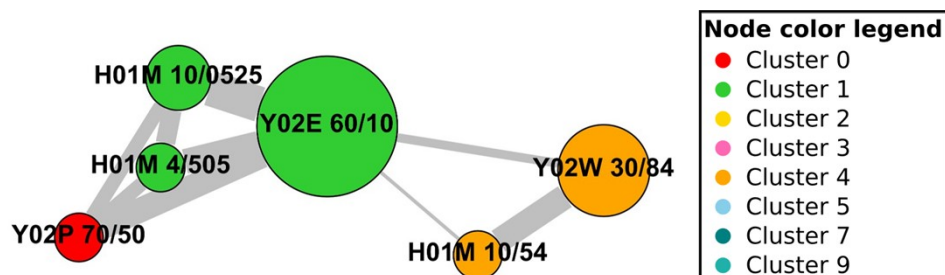
2015-2024



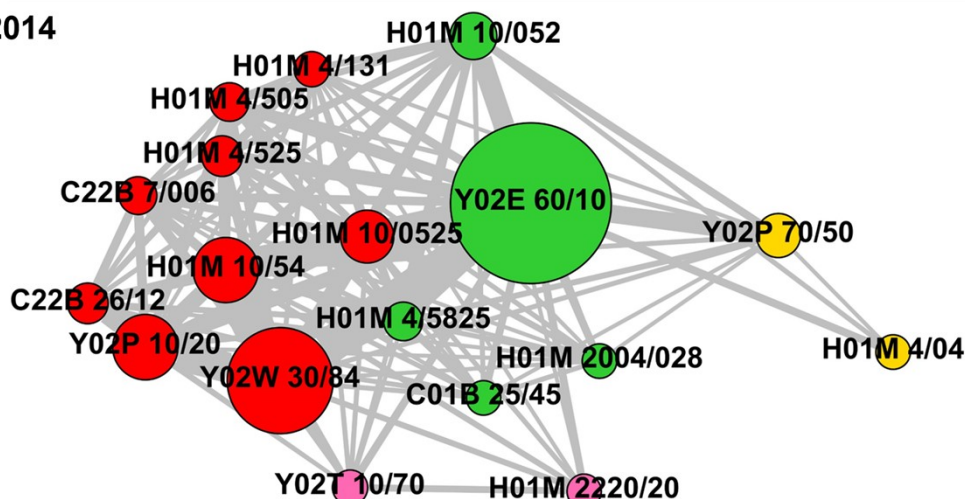
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99 Figure S5: Overview of full CPC co-occurrence networks over three periods.

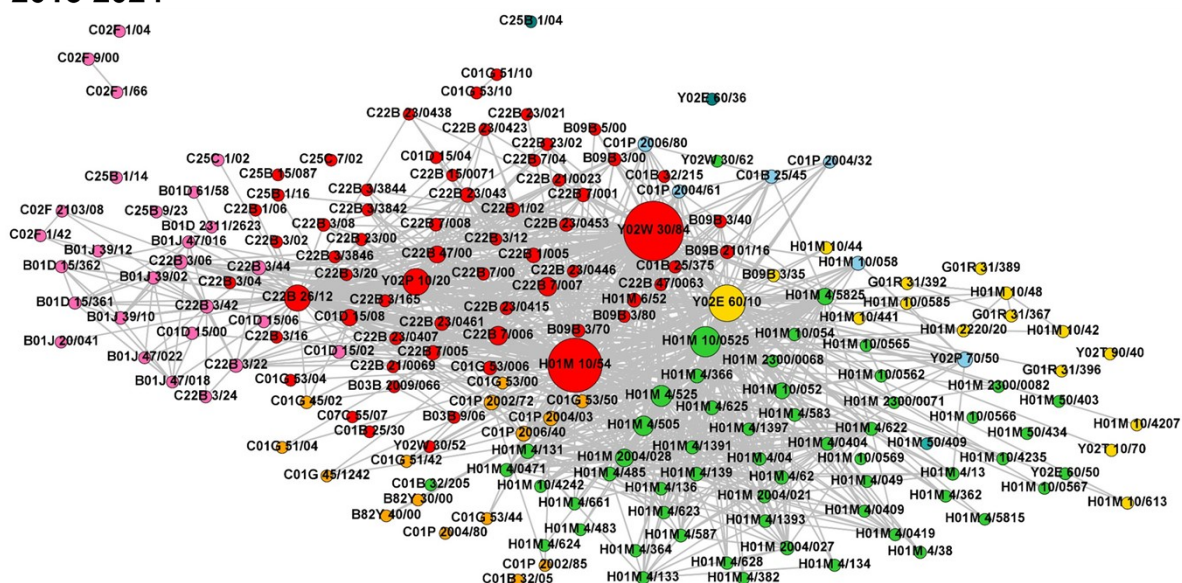
1990-2004



2005-2014



2015-2024*

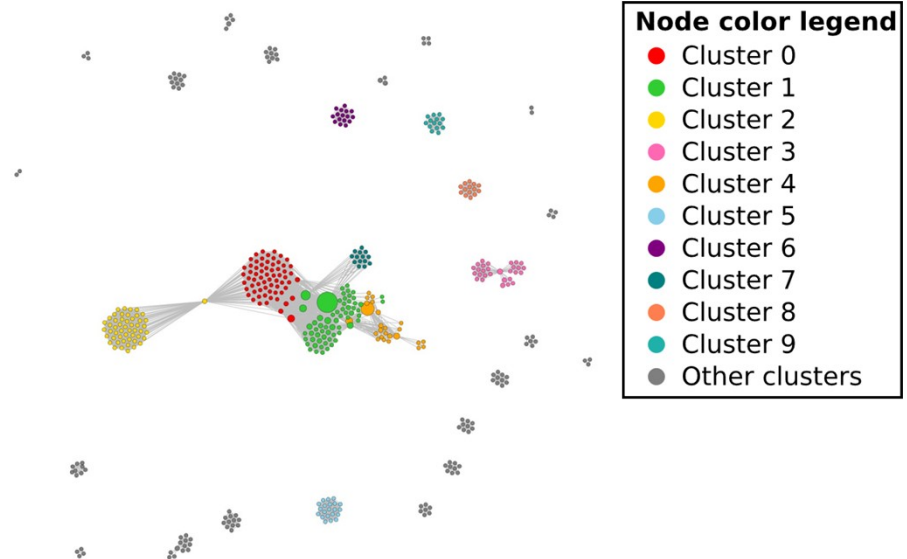


100

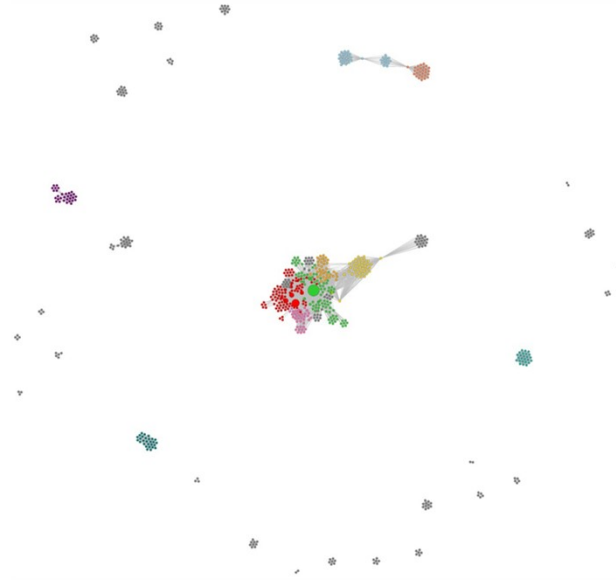
101 Figure S6: Overview of clustered CPC co-occurrence networks for three periods. Only nodes with weight
 102 ≥ 5 are shown. Only the 10 nodes with the highest weights are labelled. *To increase readability, edges
 103 with weights below five are filtered out.

104

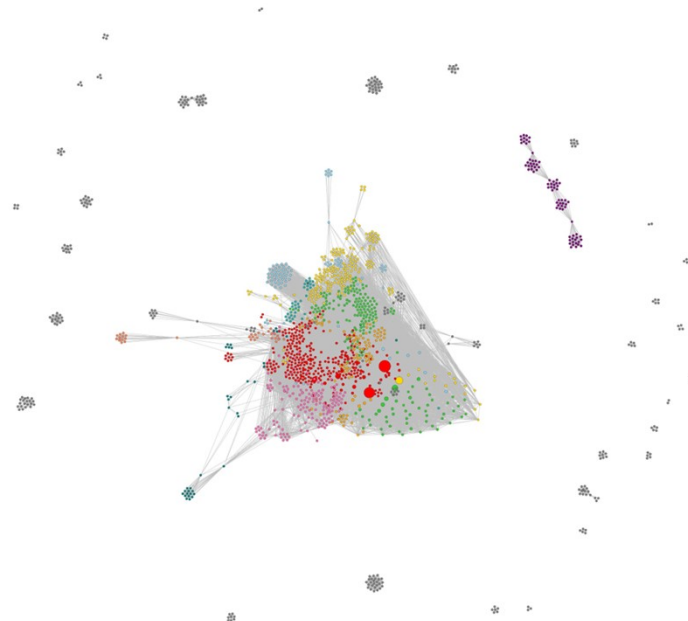
1990-2004



2005-2014



2015-2024



105

106 Figure S7: Overview of full clustered CPC co-occurrence networks over three periods.

107 S7. Full lists of keywords describing the clusters

108 Tables S4 to S6 present the top ten keywords for each cluster across all periods. These
 109 keywords were extracted using the TF-IDF methodology. In some clusters, fewer than
 110 ten keywords were identified because certain clusters are so small that their
 111 corresponding CPC class descriptions contain fewer than ten words. Consequently,
 112 TF-IDF analysis was not essential for these smallest and least significant clusters.

113 Table S4: Overview of the top ten extracted keywords for each cluster from 1990 to 2004.

Cluster-ID	Central Keywords
0	['oxides', 'thereof', 'salts', 'oxide', 'final', 'manufactured', 'nanometer', 'manufacturing', 'production', 'product']
1	['batteries', 'energy', 'storage', 'oxides', 'electrodes', 'hydroxides', 'mixed', 'inserting', 'intercalating', 'intercalation']
2	['catalysts', 'plates', 'catalytically', 'step', 'product', 'fuel', 'gases', 'feed', 'active', 'cells']
3	['ligands', 'groups', 'containing', 'carbon', 'separation', 'hydroxy', 'including', 'bonds', 'comprising', 'catalysts']
4	['recycling', 'cells', 'batteries', 'fuel', 'accumulators', 'reclaiming', 'serviceable', 'waste', 'parts', 'processes']
5	['joined', 'joining', 'several', 'parts', 'form', 'articles', 'least', 'ir', 'reciprocating', 'welding']
6	['work', 'film', 'separating', 'apparatus', 'plastics', 'single', 'subclass', 'part', 'recycling', 'means']
7	['manufacture', 'processes', 'inorganic', 'diluent', 'nanobatteries', 'electrolytes', 'impregnation', 'solution', 'paste', 'electrode']
8	['meth', 'acrylate', 'containing', 'polyethylene', 'glycol', 'moiety', 'alcohol', 'treatment', 'methoxy', 'acrylic']
9	['filter', 'ultraviolet', 'filtrate', 'measuring', 'flow', 'devices', 'membrane', 'filters', 'rate', 'irradiation']
10	['groups', 'hydroxy', 'primary', 'containing', 'hydroxyl', 'ether', 'bound', 'group', 'carbon', 'without']
11	['carboxylic', 'acids', 'acid', 'halides', 'isomers', 'conversion', 'salts', 'part', 'anhydrides', 'derivatives']
12	['compositions', 'derivatives', 'compounds', 'epoxy', 'polyesters', 'resins', 'polymers', 'according', 'chemical', 'thereof']

13	['means', 'receptacle', 'additional', 'raising', 'vertical', 'like', 'assisting', 'tipping', 'keeping', 'lengthwise']
14	['polymers', 'compounds', 'dicarboxylic', 'dihydroxy', 'one', 'compositions', 'macromolecular', 'aromatic', 'unsaturated', 'containing']
15	['hydrocarbons', 'containing', 'ring', 'alumina', 'naphthalene', 'preparation', 'none', 'hydrocarbon', 'propyltoluene', 'vinyltoluene']
16	['unspecified', 'rubbers', 'characterised', 'moulding', 'undesirable', 'residual', 'monomers', 'degassing', 'centrifugal', 'fluidised']
17	['one', 'radical', 'aliphatic', 'double', 'homopolymers', 'copolymers', 'bond', 'carboxyl', 'unsaturated', 'ester']
18	['discovery', 'potential', 'user', 'area', 'limitation', 'expansion', 'scope', 'consultation', 'announcement', 'among']
19	['atms', 'operations', 'within', 'handling', 'housing', 'dispensing', 'accessories', 'automatic', 'teller', 'machines']
20	['resulting', 'excipient', 'pure', 'drug', 'agglomerate', 'optionally', 'containing', 'antivirals', 'drugs', 'nutrients']
21	['comprising', 'electrodialysis', 'sorbents', 'binder', 'aggregated', 'agglomerated', 'granulated', 'products', 'forming', 'provided']
22	['ptfe', 'polytetrafluorethylene', 'helical', 'teeth', 'screw', 'carter', 'arrangements', 'admission', 'discharge', 'working']
23	['flow', 'outlet', 'liquid', 'gas', 'intersecting', 'jets', 'deflecting', 'central', 'towards', 'peripheral']
24	['dispersed', 'adsorbents', 'absorbents', 'selection', 'liquid', 'materials', 'removing', 'organic', 'compounds']
25	['quinone', 'imines', 'imino', 'unsaturated', 'ring', 'groups', 'compounds', 'containing']
26	['air', 'sterile', 'surgical', 'table', 'application', 'units', 'peltier', 'effect', 'clean', 'stations']
27	['pressure', 'cookers', 'fryers', 'steam', 'water']
28	['esters', 'amino', 'hydrolysis', 'formation', 'halides', 'amides', 'carboxyl', 'purification', 'separation', 'reactions']

115 Table S5: Overview of the top ten extracted keywords for each cluster from 2005 to 2014.

Cluster-ID	Central Keywords
0	['batteries', 'recycling', 'fuel', 'cells', 'reclaiming', 'serviceable', 'waste', 'lithium', 'hydroxides', 'parts']
1	['storage', 'batteries', 'energy', 'active', 'phosphates', 'silicates', 'polyanionic', 'borates', 'oxygenated', 'metallic']
2	['final', 'manufactured', 'product', 'manufacturing', 'processes', 'characterised', 'production', 'manufacture', 'electrodes', 'form']
3	['batteries', 'battery', 'controller', 'systems', 'data', 'state', 'electromobility', 'transfer', 'several', 'sequentially']
4	['alloys', 'si', 'based', 'electrodes', 'metals', 'silicon', 'solutes', 'making', 'battery', 'electrolyte']
5	['gasification', 'removing', 'carbon', 'water', 'recovery', 'cogeneration', 'pressure', 'dioxide', 'distributors', 'electrolysis']
6	['hydroxy', 'aromatic', 'amino', 'carbon', 'groups', 'ring', 'rings', 'bound', 'skeleton', 'atom']
7	['nitrogen', 'ligands', 'atom', 'complexing', 'least', 'one', 'ring', 'comprising', 'ruthenium', 'complexes']
8	['treatment', 'biological', 'waste', 'anaerobic', 'sewage', 'processes', 'water', 'temperature', 'alcohol', 'sludge']
9	['portion', 'mould', 'moulding', 'preform', 'runner', 'injected', 'flange', 'variable', 'components', 'two']
10	['microorganisms', 'yeasts', 'multiple', 'halogen', 'biofuels', 'substrate', 'cellulosic', 'cellulase', 'action', 'carbohydrase']
11	['magnetic', 'employing', 'electric', 'reactors', 'properties', 'processes', 'energy', 'characterised', 'mixing', 'spinels']
12	['cells', 'adapted', 'heat', 'interconnectors', 'protecting', 'keeping', 'batteries', 'exchange', 'shape', 'solid']
13	['fluid', 'bearings', 'sealing', 'cooling', 'gas', 'means', 'propulsion', 'aircraft', 'gaseous', 'lubricant']
14	['sulfides', 'selenides', 'tellurides', 'licofy', 'hydroxides', 'halogenides', 'compounds', 'electrodes', 'inorganic', 'based']
15	['substance', 'separated', 'constructional', 'screening', 'surfaces', 'screens', 'matrix', 'cleaning', 'acting', 'details']

16	['gasoline', 'boiling', 'range', 'oil', 'diesel', 'naphtha', 'well', 'fluids', 'cos', 'hcn']
17	['oxidoreductases', 'donors', 'leucine', 'acceptor', 'dehydrogenase', 'acting', 'group', 'acids', 'alanine', 'isoleucine']
18	['means', 'locks', 'locking', 'striker', 'data', 'safes', 'vaults', 'remotely', 'controlled', 'clothing']
19	['used', 'acids', 'thermoplastic', 'elastomer', 'fibers', 'biodegradable', 'polyurethanes', 'grafted', 'rubbers', 'epoxide']
20	['solvents', 'used', 'oils', 'solvent', 'single', 'extractive', 'sheets', 'extraction', 'refining', 'applications']
21	['atoms', 'carbon', 'hydrogen', 'unsaturation', 'five', 'four', 'saturated', 'dehydration', 'acyclic', 'double']
22	['ammonia', 'separation', 'liquors', 'without', 'moving', 'inside', 'vapours', 'sulfuric', 'absorbents', 'reactors']
23	['load', 'demand', 'response', 'shedding', 'peak', 'shaving', 'transactions', 'systems', 'energy', 'trading']
24	['acids', 'esters', 'starting', 'intermediate', 'peroxy', 'moiety', 'unreacted', 'precursors', 'ester', 'atom']
25	['crystalline', 'molecular', 'sieves', 'cracking', 'catalytic', 'oxides', 'steps', 'according', 'step', 'absence']
26	['wheels', 'wheel', 'disc', 'mounting', 'axle', 'mount', 'roller', 'skates', 'hubs', 'arrangement']
27	['technologies', 'arrangements', 'water', 'consumption', 'aiming', 'efficiency', 'home', 'appliances', 'induction', 'cooking']
28	['like', 'paper', 'ribs', 'flanges', 'framed', 'panels', 'spaced', 'wood', 'chips', 'vegetable']
29	['electronically', 'readable', 'memory', 'parts', 'cartridges', 'cartridge', 'attachment', 'positioning', 'regulation', 'connecting']
30	['reactive', 'dyes', 'colouring', 'agents', 'disazo', 'directly', 'heterocyclic', 'system', 'attached', 'mixtures']
31	['compositions', 'paints', 'varnishes', 'lacquers', 'coating', 'inorganic', 'diluent', 'nature', 'pastes', 'effects']
32	['water', 'industrial', 'household', 'valves', 'relating', 'pumps', 'supply', 'used', 'details', 'cooling']
33	['rings', 'unspecified', 'carbocyclic', 'hetero', 'radicals', 'condensed', 'heterocyclic', 'substituted', 'ring', 'oxygen']
34	['assessing', 'vulnerabilities', 'evaluating', 'computer', 'security', 'domains', 'executing',

	'restricted', 'sandbox', 'secure']
35	['collapsible', 'foldable', 'bottles', 'wall', 'structure']
36	['systems']
37	['emission', 'atmospheric', 'pm', 'smoke', 'microparticles', 'smog', 'aerosol', 'quality', 'improvement', 'preservation']

116

117 Table S6: Overview of the top ten extracted keywords for each cluster from 2015 to 2024.

Cluster-ID	Central Keywords
0	['recycling', 'serviceable', 'reclaiming', 'fuel', 'batteries', 'accumulators', 'cells', 'parts', 'waste', 'obtaining']
1	['batteries', 'electrodes', 'hydroxides', 'oxides', 'inserting', 'intercalating', 'mixed', 'intercalation', 'insertion', 'lithium']
2	['batteries', 'storage', 'energy', 'cells', 'battery', 'testing', 'systems', 'measuring', 'circuits', 'arrangements']
3	['solutions', 'inorganic', 'salt', 'processes', 'hydroxides', 'oxides', 'filtration', 'generated', 'extraction', 'exchangers']
4	['li', 'diagram', 'sem', 'electric', 'two', 'obtained', 'properties', 'type', 'oxides', 'hydroxides']
5	['manufactured', 'micrometer', 'compositional', 'purity', 'final', 'product', 'manufacturing', 'production', 'metal', 'characterised']
6	['catalysts', 'one', 'least', 'atoms', 'compounds', 'type', 'hydroxy', 'ring', 'addition', 'groups']
7	['electrolysis', 'water', 'sources', 'production', 'hydrogen', 'gases', 'hydride', 'catalysts', 'containing', 'carbon']
8	['screens', 'separator', 'devices', 'screen', 'denying', 'egress', 'oversize', 'disintegrating', 'mechanisms', 'screening']
9	['diaphragms', 'membranes', 'characterised', 'material', 'separators', 'waste', 'processing', 'separation', 'choice', 'metal']
10	['saturated', 'carboxyl', 'groups', 'acids', 'esters', 'rings', 'carboxylic', 'containing', 'group', 'bound']
11	['cnhm', 'column', 'gas', 'stream', 'feed', 'separation', 'refrigeration', 'natural', 'gaseous', 'refinery']
12	['made', 'piece', 'contact', 'surface', 'one', 'paper', 'shape', 'discrete', 'locating', 'articles']
13	['oligosaccharides', 'five', 'saccharide', 'glycosidic', 'linkages', 'sugar', 'active', 'three',

	'radicals', 'attached']
14	['boring', 'cutting', 'stream', 'moving', 'cleaning', 'fluid', 'devices', 'conveyor', 'jet', 'conjunction']
15	['polymers', 'vinyl', 'derivatives', 'cellulose', 'co', 'acrylic', 'powder', 'particles', 'inorganic', 'thereof']
16	['reforming', 'step', 'monoxide', 'reaction', 'gasifying', 'carbon', 'vapour', 'hydrocarbons', 'containing', 'water']
17	['one', 'metallic', 'gaseous', 'electrode', 'power', 'exfoliation', 'photovoltaic', 'sensitive', 'attaching', 'trailing']
18	['memory', 'space', 'call', 'system', 'message', 'queues', 'buffers', 'shared', 'considering', 'execution']
19	['ammonium', 'fluorides', 'sulfates', 'sulfate', 'fluoride', 'sulfite', 'orthophosphates', 'calcium', 'fertilisers', 'preparing']
20	['networks', 'proprietary', 'networking', 'environments', 'medical', 'sensor', 'metering', 'transactions', 'measuring', 'variables']
21	['compositions', 'epoxy', 'polycarbonates', 'homopolymers', 'copolymers', 'resins', 'derivatives', 'compounds', 'polyesters', 'dicarboxylic']
22	['signals', 'cleaning', 'vehicles', 'acoustic', 'singals', 'ir', 'integral', 'tracks', 'spray', 'cleaned']
23	['liquid', 'effluents', 'oil', 'slurries', 'subject', 'circulatory', 'ascending', 'instrument', 'suspended', 'introduced']
24	['necks', 'bottles', 'apertures', 'held', 'together', 'slits', 'articles', 'packaging', 'containers', 'formed']
25	['constructions', 'cardboard', 'sachet', 'toiletty', 'cosmetic', 'adhesive', 'perfumes', 'labels', 'badges', 'releasability']
26	['carbonic', 'haloformic', 'carbonates', 'dehydration', 'amides', 'rare', 'earths', 'nitriles', 'dioxide', 'carboxylic']
27	['fluorine', 'hx', 'containing', 'compound', 'stabilisation', 'halogenated', 'halides', 'hydrocarbons', 'distillation', 'purification']
28	['ring', 'amines', 'indane', 'aromatisation', 'position', 'amino', 'condensed', 'skeleton', 'substitution', 'reduction']
29	['waste', 'heat', 'controlling', 'channels', 'recuperated', 'condensates', 'reclaiming', 'efficiency', 'media', 'distribution']
30	['form', 'elements', 'walls', 'wood', 'dismantled', 'concrete', 'recoverable', 'beams',

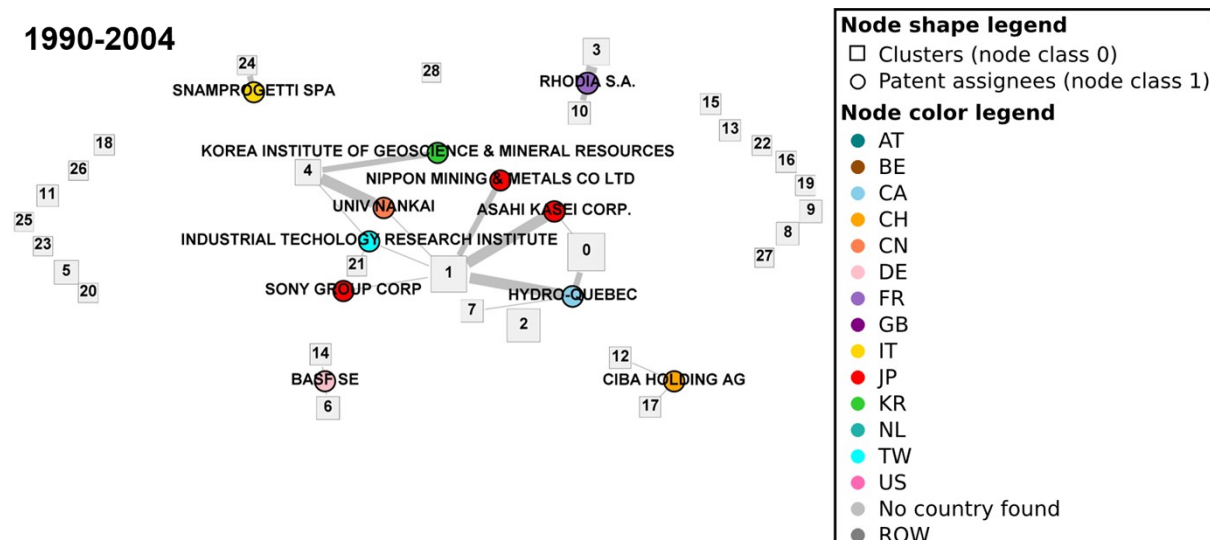
	'erection', 'shuttering']
31	['scrap', 'metal', 'consolidating', 'briquettes', 'strainers', 'briquetting', 'cars', 'compacting', 'permeable', 'casings']
32	['light', 'controlling', 'adapted', 'specially', 'omnidirectional', 'bulb', 'intensity', 'retrofit', 'led', 'colour']
33	['dynamics', 'cad', 'force', 'fluid', 'adapted', 'specially', 'equations', 'cfd', 'entry', 'interfaces']
34	['arrangements', 'fluent', 'means', 'liquid', 'material', 'excess', 'independently', 'preventing', 'deposits', 'blockage']
35	['spindles', 'elastic', 'twist', 'hollow', 'due', 'rather', 'twisting', 'fixing', 'backtwisting', 'imparting']
36	['management', 'power', 'computing', 'low', 'processors', 'configuring', 'program', 'initiating', 'registry', 'files']
37	['containing', 'dissolved', 'specified', 'removing', 'nitrogen', 'oxygen', 'compounds']
38	['effect', 'cooled', 'garments', 'peltier', 'means']
39	['nitro', 'atoms', 'groups', 'stabilisation', 'rings', 'substitution', 'bound', 'aromatic', 'purification', 'separation']
40	['government', 'public', 'services', 'certifying', 'business', 'benchmarking', 'key', 'indicator', 'kpi', 'performance']
41	['controllers', 'data', 'control', 'programme', 'numerical', 'employing', 'traffic', 'historical', 'logic', 'speed']
42	['situ', 'removing', 'surface', 'treatment', 'devices', 'material']
43	['parallelly', 'network', 'generators', 'transformers', 'converters', 'converting', 'feeding', 'batteries', 'arrangements', 'single']

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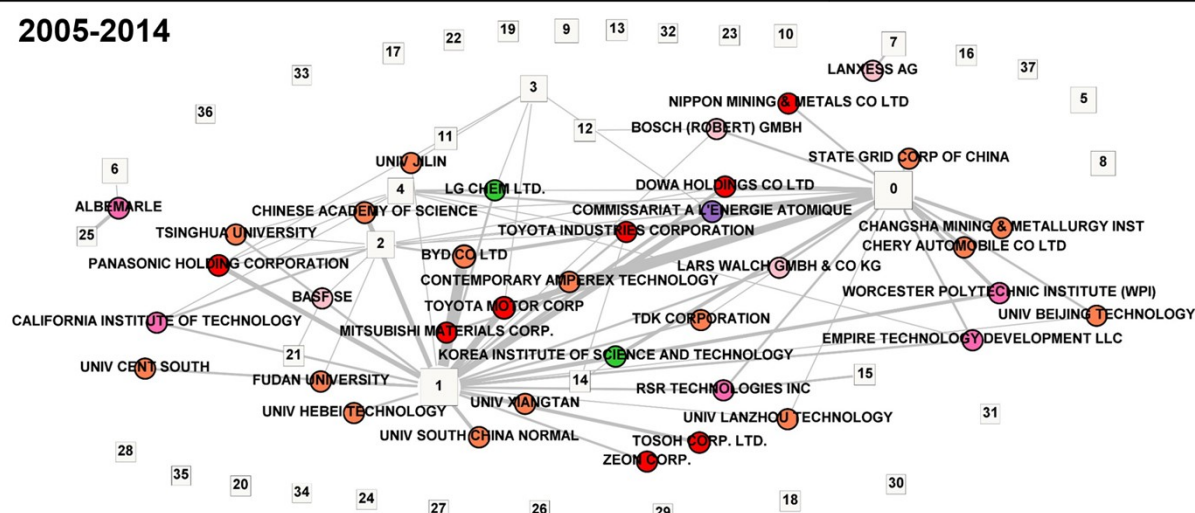
119 **S8. Supplementary two-mode networks**

120 To complement the two-mode networks shown in Figure 10, this section first presents
121 the fully labelled two-mode networks filtered to include only nodes with a weight of 2
122 or more (Figure S8), followed by the completely unfiltered two-mode networks
123 (Figure S9), in which only the clusters are labelled.

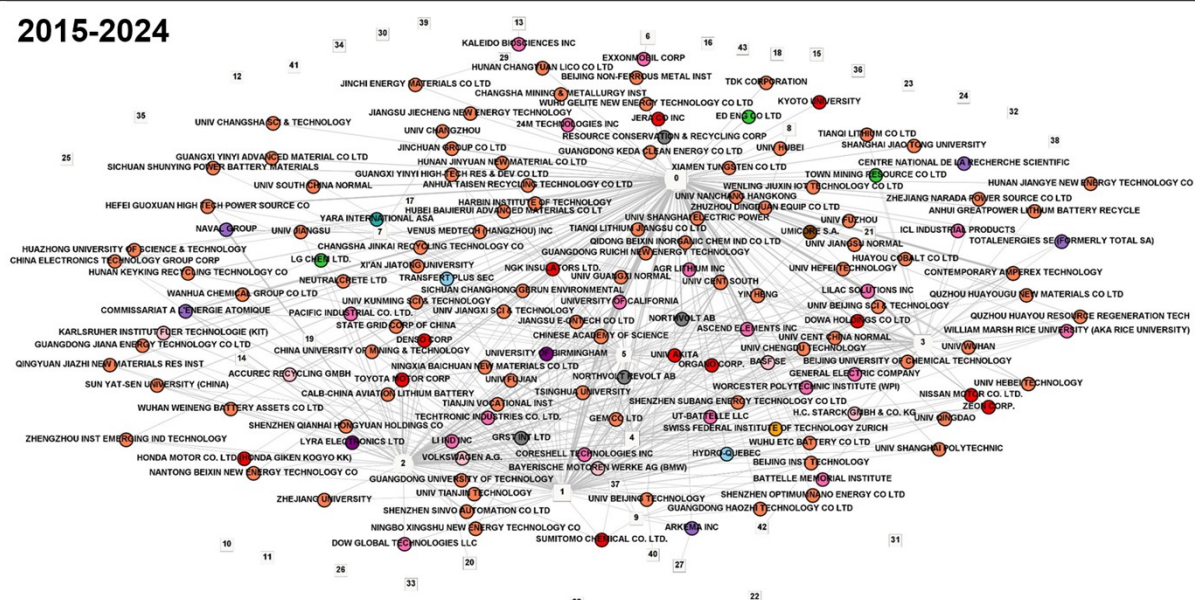
1990-2004



2005-2014



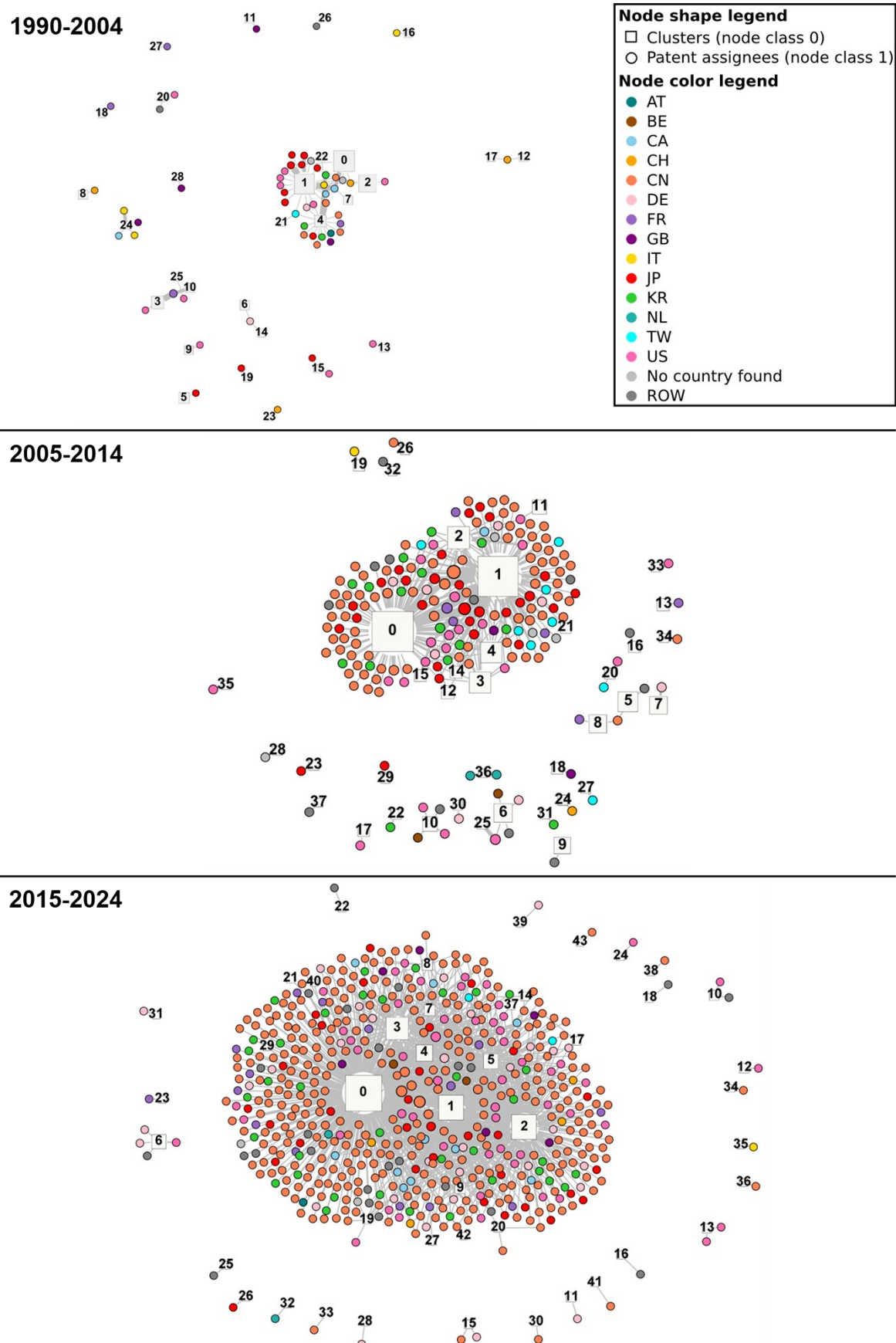
2015-2024



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125 Figure S8: Overview of two mode networks (Knowledge areas and patent assignees) over three
126 periods. Only nodes with a weight of ≥ 2 are displayed and labelled.

127



128

129 Figure S9: Overview of full two-mode networks (knowledge areas and patent assignees) over three
 130 periods. Patent assignees are not labelled.

131 **S9. References**

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137 [learn.org/stable/modules/generated/sklearn.feature_extraction.text.TfidfVectorizer](https://scikit-learn.org/stable/modules/generated/sklearn.feature_extraction.text.TfidfVectorizer.html)

138 [.html](https://scikit-learn.org/stable/modules/generated/sklearn.feature_extraction.text.TfidfVectorizer.html), accessed 5 September 2024.

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