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Monitoring scientific collaboration trends in wind energy components

Bibliometric analysis of scientific articles based on TIM

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Contents

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Executive summary

Since many years, research and innovation in wind energy have focused on lowering the technology cost, an objective that seems to be accomplished as evidenced by the falling bid prices in the latest offshore wind auctions in Europe. Yet, recent developments of the IRPWind/EERA research and innovation agenda suggest that the sector is moving besides pure cost reduction through up-scaling (e.g. 10MW+ turbines and longer blades) towards new wind markets such as floating wind farms[1].

These innovations become even more relevant as the European Commission's 'Clean Energy for All Europeans' package addresses wind energy in its key aim 'Achieving global leadership in renewable energies'. Moreover the EC's renewable energy directive foresees that by 2030 32% of the energy consumed in the EU will come from renewables, a development that could be seen as an incentive by countries and their research organisations to intensify efforts in wind energy.

For the offshore wind market, there is an ongoing debate between wind energy industry requesting a foreseeable pipeline of wind energy projects and policy trying to set up regulatory frameworks that ensure high market compatibility without neglecting market signals. To ensure a stable growth of the European offshore wind market the industry players are claiming for an annual deployment of European offshore installations of at least 4 GW/year. As a consequence of the industry needs and the ambitious renewable energy targets in the EU, offshore wind will have to adapt the technology to new marine environments (e.g. Baltic Sea, Mediterranean Sea) characterised by steeper coastlines and changed climatic conditions.

The recent EC Communication on a renewed European Agenda for Research and Innovation points out that Europe is relatively strong in adding or sustaining value for existing products, services and processes, known as incremental innovation. But Europe needs to do better at generating disruptive and breakthrough innovations[2]. Thus, the agenda encourages cooperation between research teams across countries and disciplines, supporting them to make breakthrough discoveries. Also countries outside the EU have put policies in place (e.g. China's 12th Five Year Plan) explicitly focussing on technology innovation in the sector of onshore and offshore wind[3].

Within this context, this analysis uses the JRC's Tools for Innovation Monitoring (TIM) software developed by the JRC to retrieve bibliometric data on blades (a component more benefitting from incremental innovations) and offshore wind support structures (a relatively new research field in which disruptive innovations like floating power plants might become breakthrough innovations) to

- measure the publication and collaboration activity,
- identify leading organisations and new entrants,
- identify the main areas of publications of the leading players and
- identify the leading countries and country collaboration patterns.

The bibliometric results obtained are then contrasted with data for research funding on wind energy from the Horizon 2020 Research and Innovation programme, to analyse the thematic focus of publication and funding activity. Results are also complemented with recent information from the wind industry and research news on the latest developments in the investigated areas. Thus, this study can support policies aiming for prioritisation and alignment of European research efforts within the wind energy topic.

Our analysis finds that, for both blades and offshore support structures, co-publication networks are growing following the trend of the wind industry towards larger blade designs and innovative offshore support structure solutions. For both components the

[1] IRPWind/EERA Joint Programme Wind R&D Conference, Amsterdam, 25-26 September 2017 [63]
[2] COM(2018) 306 [64]
[3] 12th Five Year Plan for National Strategic Emerging Industries [44]

EU28 shows a significant higher publication activity than its strongest competitors from China and the United States. Between 1996 and 2016 the entire EU28 top up the United States and China in publication counts on blades and offshore support structures by 40% and 130%, respectively. Over this timeframe publication activity of all leading countries seems to follow their clean energy policies and wind energy deployment.

Using TIM to analyse the co-publication networks between organisations on blade research unveils European (DTU, TU Delft, Aalborg University) and US organisation (NREL, Sandia) in the lead, a result that is underpinned through strong ties to industry and significant investments in test facilities. Blade research mainly focuses on the aerodynamic effects, new solutions in O&M and load impacts and thus rather incremental innovations within this component. The identified co-publication networks on blades show that European organisations are forming collaborations across the world whereas US organisations tend to collaborate more with partners inside the US. This pattern can also be observed in recent US collaborations with the blade industry on additive manufacturing such as in the case of the collaboration between Sandia and the blade manufacturer TPI Composites. Given its current dominance DTU is seen to maintain its leadership position in blade research, however lately more and more Chinese players can be found among the top publishing organisations incentivised by ambitious clean energy policies implemented in the country.

Publication activity of European organisations is found to be even stronger in offshore wind support structures than on blade-related topics. Only NREL is found among the Top 5 organisations stemming from outside the EU. For European institutions, our TIM-based searches detected strong publication activity on grounded support structures and floating devices, whereas for NREL most publications were found on floating support structures. With respect to grounded support structures this seems to follow Europe's role as a frontrunner in offshore wind deployment as almost all capacity deployed since 2001 uses this foundation type.

With more and more countries engaging in offshore wind research, floating offshore becomes increasingly interesting as it allows countries with steep coastlines to venture into offshore wind. Recent increased publication activity by new players such as Universidade de Lisboa from Portugal confirms this trend, as floating devices give the country an option to enter an emerging market. Notably with the NER300-funded 25 MW Windfloat project, Portugal is also home of a promising floating offshore wind concept.

Thus, this potentially disruptive technology attracts many industrial players (e.g. Ørsted[4], Equinor[5]), a trend also visible in the detected co-publication networks by TIM. All leading organisations share a strong industrial research environment. As an example, the Norwegian energy utility Equinor encourages research by European research institutes, and also builds on NREL's capabilities in floating offshore in order to develop software tools for the 30 MW Hywind floating concept.

Contrasting the EU research funding with the thematic focus of our bibliometric searches unveils that the research areas in blades and offshore support structures addressed by the current EU research funding are generally well represented in our results. Even more, funding programmes such as Horizon 2020 show a broader scope in research on blades and offshore support structures addressing innovative topics such as advanced materials for blades or innovative and hybrid concepts and installation and lifting operations for offshore wind support structures.

[4] Formerly Dong Energy
[5] Formerly Statoil

1 Introduction

1.1 Policy and technology context

The European Union is setting the new policy framework for the clean energy transition in line with its 2020 and 2030 targets, including research and innovation initiatives to support EU's ambition to become a global leader in renewables [1]. Upstream R&D, inventions and patents as well as breakthrough technologies and new business models are key elements all along the value chain to gain new market shares, in a global context of lowering technology costs.

Among other technologies, the European Commission's 'Clean Energy for All Europeans' package (November 2016) addresses wind energy in its key aim "Achieving global leadership in renewable energies" [2]. Moreover, innovations in the area of wind energy address two of the five dimensions of the Energy Union strategy, namely 'decarbonising the economy' and 'research, innovation and competitiveness', ensuring breakthroughs in low carbon technologies and driving the transition of the energy system [3].

One of the basic physical laws governing wind energy conversion systems states that the power from a wind turbine is proportional to the square of the rotor radius and to the cube of the wind velocity. Therefore, two of the most critical strategic areas in the wind industry are manufacturing and development of larger rotors as well as enhanced and innovative offshore support structures. As a result, the R&D activity on these issues has intensified over the years.

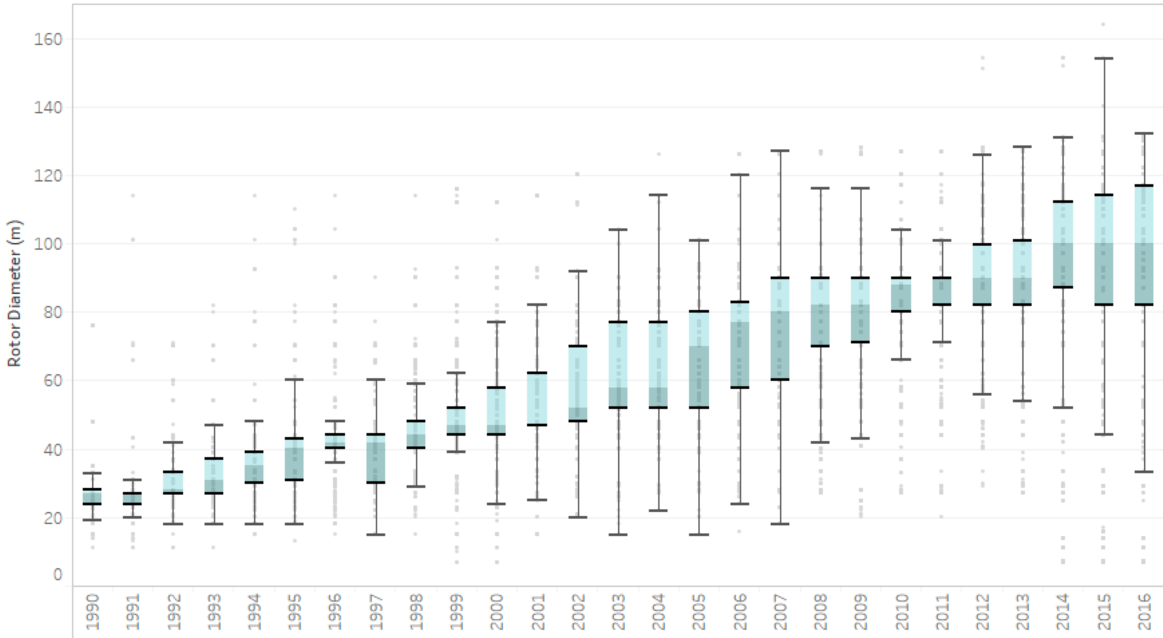


Figure 1. Evolution of the rotor diameter of onshore wind turbines installed in Europe
Note: Whiskers extend to data within 1.5 the IQR[6].
Source: JRC Wind Energy Database.

As shown in Figure 1, the rotor blades of the wind turbines installed evolve towards larger designs with the aim of maximizing the annual electricity production and extending the wind energy development to medium and low wind speed areas. In order to get longer and stiffer blades, the wind turbine manufacturers are focusing on improving some technological aspects including the increase of their aerodynamic efficiency, the reduction of their weight and the improvement of their reliability getting high resistance to failures.

[6] IQR stands for Interquartile range. It is equal to the difference between 75th and 25 percentiles.

This becomes even more relevant for offshore wind where the trend goes towards even longer blades to power the next generation wind turbines in the 13-15 MW range [4],[5].

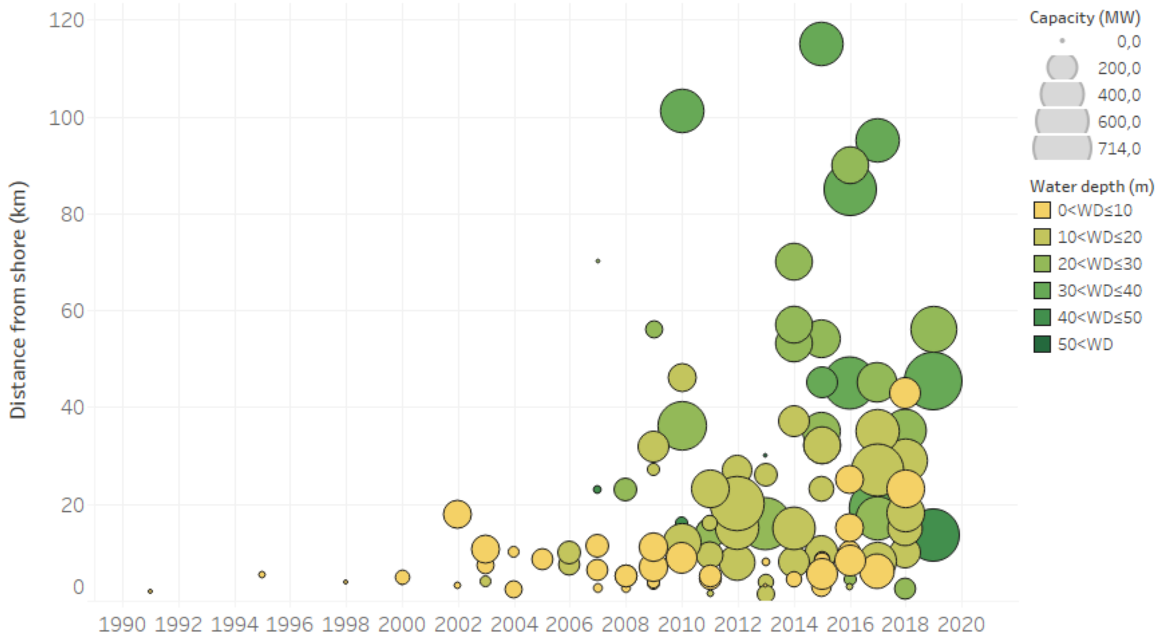


Figure 2. Evolution of global offshore wind projects according to their project size, distance to shore and water depth

Note: Fully commissioned, partial generation and under construction projects are represented in the figure.

Source: JRC Wind Energy Database.

In order to harness higher wind speeds, offshore wind projects are evolving towards bigger distances from shore, deeper waters and larger project sizes as displayed in Figure 2. In a context of deeper waters and harsh marine environments, developers aim to find new types of support structures and to optimize installation and operation activities.

1.2 Aim and scope of this study

This study aims at mapping and discussing general R&D trends on blades and offshore support structures for wind energy. It uses the Tools for Innovation Monitoring (TIM)[7] software developed by the JRC to do a quantitative horizon scan exercise based on scientific publications in journals and conference proceedings.

As detailed in Annex 1, this mapping starts by designing search strings for two intensive wind energy research areas: blades (more established, in the expansion phase) and support structures (more emerging, at the formation stage). Specialised wind-energy technology analysts use the TIM tool to create and process datasets, which they subsequently analyse and refine.

The results, described in Chapter 3, focus on the main organisations, research areas and countries active in research on blades and offshore support structures. They also include an overview of the evolution in time of scientific collaboration in these domains.

[7] http://timanalytics.eu/

2 Approach and terminology

This work uses the Tools for Innovation Monitoring (TIM) software developed by the JRC to retrieve bibliometric data on wind energy components (blades, offshore wind support structures). TIM counts activity levels and uses network analysis to identify and visualise relationships between entities publishing scientific content.

The searches in this report focus on the blade component and offshore wind support structures, which are expected to have a strong influence on future cost reduction and thus attract the attention of present and future R&D efforts.

Based on the results from bibliometric searches with TIM a taxonomy is created to identify the main areas of publication activity of organisations and countries. The recognised collaboration patterns and topics of the leading organisations are complemented with evidence on their activities from the organisations' websites, industry news and funding. Finally funding on wind energy projects from the Horizon 2020 programme is screened and contrasted with the publication activity of the leading organisations in blades and offshore support structures.

2.1 Counting and mapping scientific publication activity

We used TIM to retrieve information from the SCOPUS database about scientific publications and **entities** (organisations authoring or co-authoring publications) related to wind energy. We designed Boolean search strings for the TIM tool to retrieve documents containing specific keywords in the title, abstract or keywords of publications (ti_abs_key) in a limited period in time (emm year), as documented in related publications ([6]–[8]) and detailed in Annex 1.

The analysis draws primarily on network graphs produced by TIM to visually map scientific co-publication patterns among organisations and countries.

The network graphs are a combination of **nodes** (bubbles) and **edges** (lines). The nodes represent the values of a certain field in the document, for example name of the entity or country. The size of the node is based on the **publication count** (number of documents of the specific item). An edge between two nodes (for example, between countries, organisations, keywords…) means **co-occurrence** of documents between these nodes; in other words, those nodes have **documents in common** (co-filed patent, **co-publication**).

The properties of the **network graphs** are used to identify and map patterns of scientific collaboration based on yearly counts of edges and nodes. In this report, we designate our network graphs as '**bibliometric maps**' or '**network maps**', and more specifically as 'keyword maps' or 'sociograms' when plotting scientific co-publication structures and patterns across topics or organisations.

In network graphs, some nodes may be assigned to **communities** (groups of nodes sharing similar attributes, e.g. co-publication on a given topic or by groups of countries). The **colour** of these **nodes** and corresponding **edges** indicates the main community to which the nodes are attributed to. The quality and relevance of the communities can be measured by 'modularity', a network property often used to quantify the density of links within communities as compared to links between communities. TIM computes modularity using the Louvain Modularity algorithm. This algorithm is a commonly accepted clustering method of nodes in network graphs [9].

2.2 Taxonomies

This report not only addresses publication counts, but also uses results from bibliometric analyses to gain further insight into leading organisations, countries and collaboration patterns (items 3.2 and 3.3), at the more disaggregated subtopic-level.

For the classification of the subtopics of our searches we developed the taxonomy outlined in Table 1 and Table 2. This draws on and complements already existing taxonomies on wind energy [10] and the currently developed taxonomy of topics in the wind energy research area and standard metadata by DTU Wind Energy, ECN, FORWIND, CENER and SINTEF [11],[12],[13].

Publications retrieved for blades are classified according to one or more of the following categories outlined in Table 1: articles addressing aerodynamic effects, research on the operation and maintenance of the blade, material research, add-on devices attached to the blade and research addressing the impact of loads on the blade.

The taxonomy used for offshore wind support structures (Table 2) covers topics related to grounded support structures, floating support structures, the installation & lifting of offshore wind support structures and innovative & hybrid concepts.

The creation of the taxonomy followed a text analysis approach (Bottom-up) in which keyword entries and abstracts of the retrieved articles were analysed.

Table 1. Taxonomy used for blade related publications

Categories	**Description**	**Subtopics**
Aerodynamics	Articles addressing specific aerodynamic effects and the development of aerodynamic simulation models	• Wake effect • Vortices • Tip loss • Airfoil design • Flutter phenomenon • Modelling, simulation and optimization
O&M[8]	Articles describing events affecting the operation and maintenance of a wind turbine blade	• Noise • Icing • Lightning • Damage issues (Delamination, throw distance, fracture)
Materials	Articles addressing blade material alternatives, material life cycle and material recycling	• End of Life treatment • Coatings • New materials (e.g. carbon fiber) • Adhesive joints
Add-on devices	Articles related with additional devices attached to the blade to improve aerodynamic performance or to reduce noise emissions	• Vortex generators • Trailing edge flaps • Serrations • Surface plasma actuators • Wavy blade sections
Loads	Articles addressing the impact of forces/loads on the blade and their mitigation	• Fatigue loads • Vibrations • Turbulence • Load reduction techniques (control systems)

[8] O&M stands for Operation and Maintenance

Table 2. Taxonomy used for offshore wind support structures related publications

Categories	Description	Subtopics
Grounded support structures	Articles addressing specific topics related to ground-based offshore wind support structures such as monopiles, jackets structures, tripods, multi-piles, gravity based foundations, suction buckets or suction bucket jackets	• Soil-Pile interaction • Effects arising from soil properties • Fatigue loads • Transition pieces • Structural optimisation • Dynamic response analysis • Scour protection • Loads (Wave slamming forces, lateral loads, seismic loads) • Ice (drifting level ice)
Floating support structures	Articles addressing concepts of and effects on floating support structure devices with a strong emphasis on spar-buoy, semi-submersible and tension leg platforms typologies	• Coupled analysis (Aero-hydro-servo-elastic simulations • Dynamic response analysis • Aerodynamic damping • Floating Vertical axis wind turbines (VAWT) • Mooring system design • Wave tank tests
Installation & Lifting operations	Articles related with the installation and lifting of offshore wind support structures	• Lifting techniques • Installation vessels • Pile driving, hammering, underwater noise • Effects related with the lifting vessel • Risk minimising techniques
Innovative and hybrid concepts	Articles related with novel support structure concepts or hybrid systems applied on an offshore wind support structure or models describing extreme load cases	• Downwind prototype on monopile support structure • Combined wind-wave energy converters • Multi-unit floating offshore wind turbines • Survivability of combined concepts • Modelling of hurricane load cases

3 Results

3.1 Publication and collaboration activity

The searches on blades and offshore wind support structures retrieved 9109 and 1876 published documents in the period 1996 - 2016, respectively (using search strings Nr 7 and 10 in Annex 1 (see Table 3)). For both searches the majority of retrieved documents are published in scientific articles and conference proceedings. Similarly to the entire wind energy sector (search string Nr 4), publication activity on blades and offshore wind support structures increased significantly in the last ten years. Moreover the share of publication counts for both components within the wind energy topic slightly increased over this period of intensified publication activity (Figure 3).

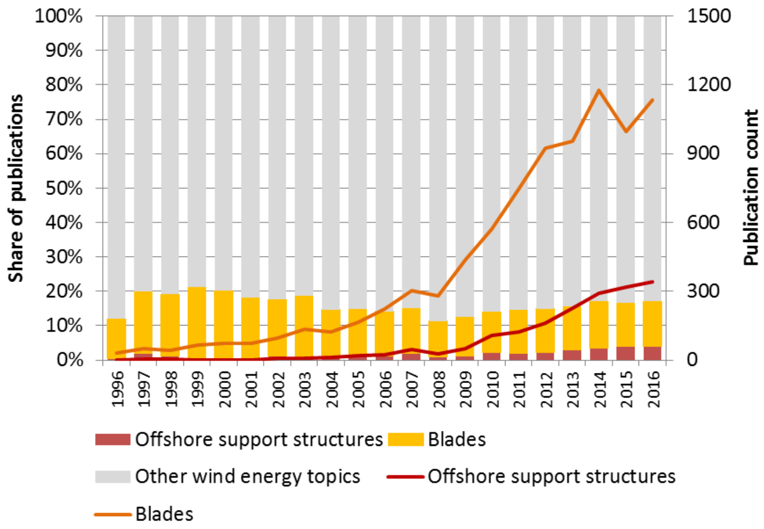


Figure 3. Publication activity in blades and support structures (1996-2016)
Source: JRC based on TIM with data from Scopus

In addition, the retrieved publications suggest a stronger collaboration among institutions for both blades and offshore wind support structures research areas (Figure 4). The average counts of collaborations (different affiliations of the co-authors) per publication increased from around one to 1.5 institutions before 2000 to around 1.7 currently.

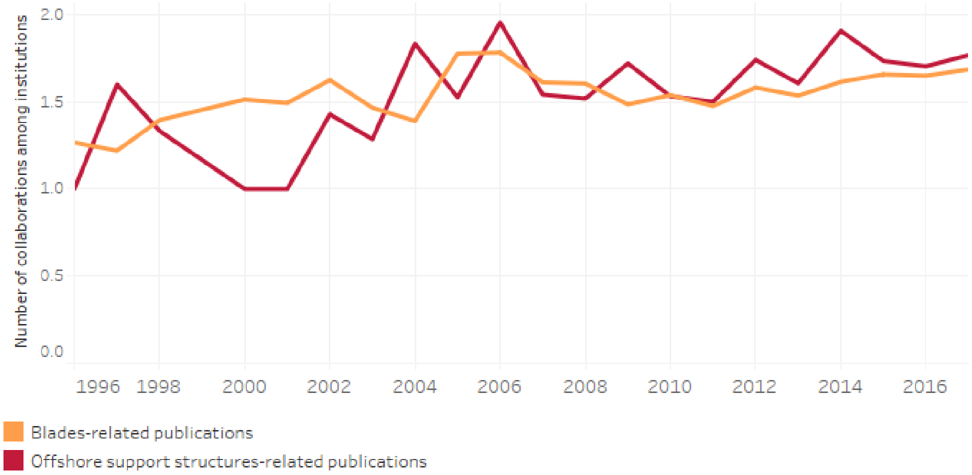


Figure 4. Evolution of the average number of collaborations per publication
Source: JRC based on TIM with data from Scopus

3.2 Leading organisations

3.2.1 Top 5 organisations in publication activity on blades

From our bibliometric searches (Annex 1) for 1996 to 2016, it appears that research activity in the area of wind blades showed a rather low concentration in terms of publication counts per organisation. Only 8 % of the publication counts originate from the Top 5 organisations (see Figure 5).

Within the Top 5 organisations Technical University of Denmark (DTU) accounted for 35 % of the publication counts between 1996 and 2016. Whereas National Renewable Energy Laboratory (NREL), Sandia National Laboratories (Sandia), Delft University of Technology (TU Delft) and Aalborg University (Aalborg) show comparable figures, each around 14 % to 19 %.

With 316 publication counts DTU leads the Top 5, followed by NREL with 178. In this period Aalborg, Delft University of Technology and Sandia National Laboratories go head to head accounting for approximately 130 to 140 contributions to scientific articles each.

Figure 5. Total counts of publications on blades by the Top 5 organisations (1996-2016)
Note: A count of publication means that an organisation is either a single author or is co-authoring with multiple other organisations (e.g. a publication with three organisations is considered as one publication count for each organisation)
Source: JRC based on TIM with data from Scopus

Among these Top 5 players publication activity remained almost constant below 10 publications per year until 2006, followed by a moderate increase between 2007 and 2012. From 2013 onwards an increased publication activity could be observed, particularly for DTU and Delft University of Technology (see Figure 6).

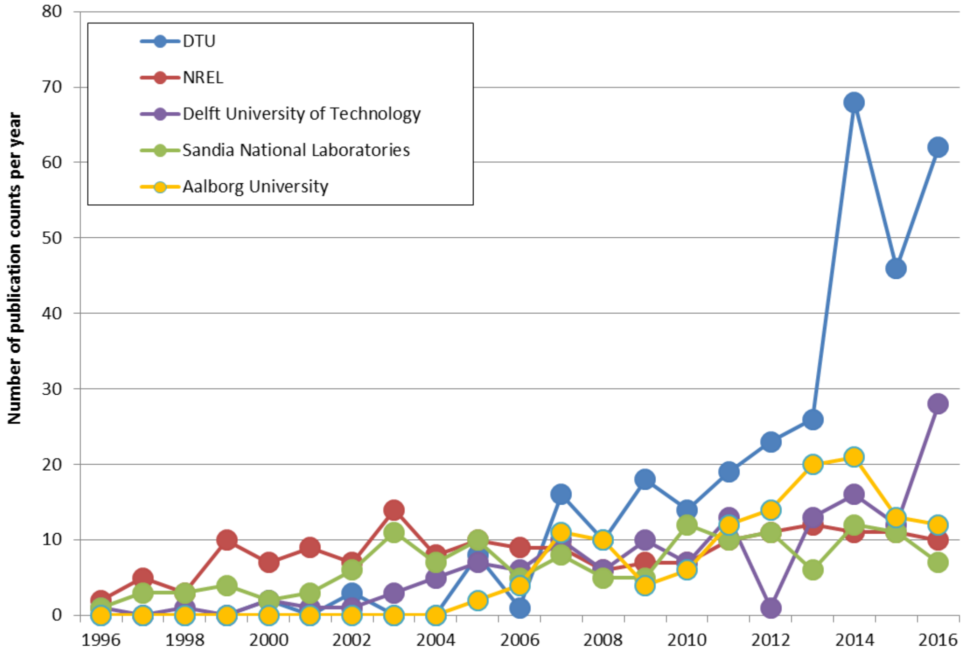


Figure 6. Evolution of publication activity on blades by the Top 5 organisations (1996 – 2016). Note: A count of publication means that an organisation is either a single author or is co-authoring with multiple other organisations
Source: JRC based on TIM with data from Scopus

To obtain the full picture of the collaboration patterns of these organisations in a bibliometric map, exports from TIM are screened and institutions that belong to the same entity are merged. A full list of all merged institution of the Top 5 organisations can be found in the Annex 1.

Figure 7 shows the full bibliometric map of the Top 5 organisations publishing in the area of blades in the period 1996-2016, as retrieved by our bibliometric searches. The Top 5 organisations form the strongest collaboration clusters in terms of publication activity (size of nodes plotted as bubbles, as defined in item 2.1) and co-publications (size of edges plotted as lines, as defined in item 2.1).

Among the identified Top 5 organisations, the TIM searches (see Annex 1) found only DTU and TU Delft in the same co-publication network (orange group), suggesting more established collaboration ties between them. One example of the collaboration between these two major players can be seen in 'Materials and Structures' domain of the European Academy of Wind Energy (EAWE) focussing on the use of advanced materials [14].

A more detailed look at the DTU/TU Delft cluster unveils that also Cranfield University (UK), Chongqing University (CN) and the Norwegian University of Science and Technology (NO) are co-publishing with DTU on blades (detailed in Figure 8).

Both US research organisations in the Top 5 (NREL and Sandia) show in their surrounding co-publication pattern exclusively collaborations with US organisations, suggesting closer relationships among them than to organisations outside the US (detailed in Figure 8). An example for this preferred domestic collaboration can also be seen in a more recent research collaboration of Sandia together with other US organisations and the blade manufacturer TPI Composites, using the technique of additive manufacturing (also known as 3D printing) to produce a mould for turbine blades aiming for cost reduction in the production process [15].

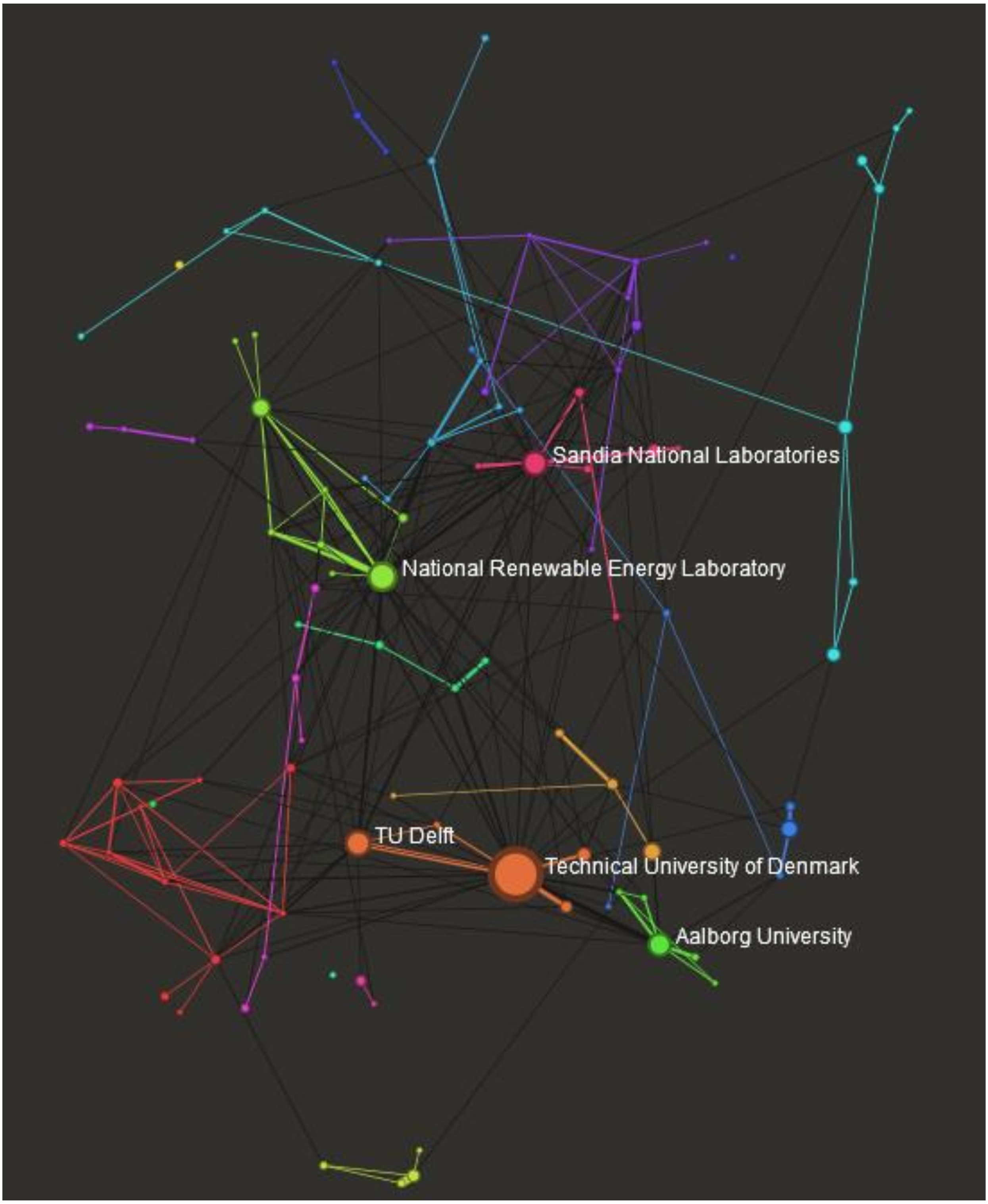
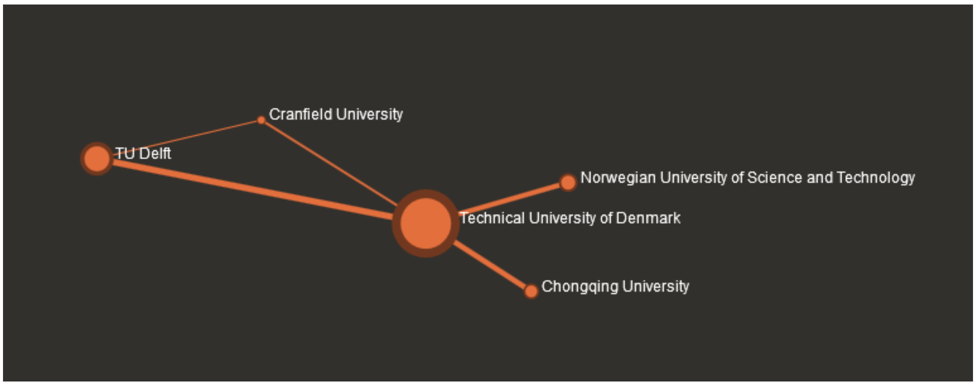
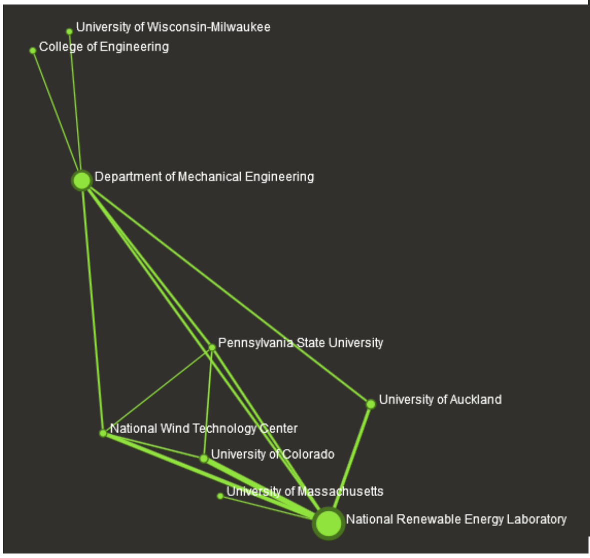


Figure 7. Bibliometric map of the Top 5 organisations publishing on blades (1996-2016)
Source: JRC based on TIM with data from Scopus

Co-publication network retrieved for DTU,and TU Delft



Co-publication network retrieved for NREL



Co-publication network retrieved for SANDIA

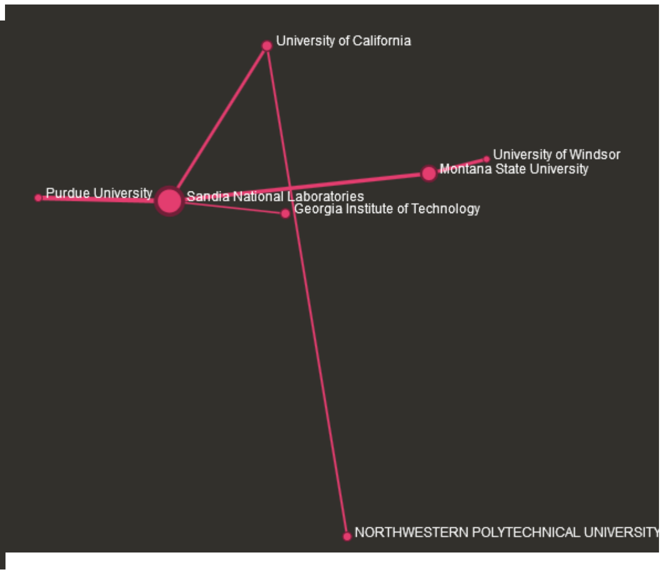


Figure 8. Detailed views of Figure 7
Source: JRC based on TIM with data from Scopus

3.2.2 Main areas of publication activity on blades

Based on the taxonomy outlined in section 2.2 we analysed for the Top 5 organisations the latest trends in blades-related publications, and contrasted these trends with ongoing research activity (e.g. research programmes, joint projects etc.) by these research organisations. We only analysed the period 2013-2016, because the publication activity of the Top 5 organisations increased significantly during those years (Figure 6). The Top 5 organisations focus their publications on aerodynamic effects followed by new solutions in O&M and load impacts on blades.

DTU's strength from 2013 onwards lies in publications addressing aerodynamic effects such as the modelling of wake effects or vortices, (45 % of retrieved articles) followed by publications on O&M related topics (19 %) and material research (13 %, Figure 9). These bibliometric results reflect well DTU's expertise. For example, DTU's aerodynamics know how triggered industrial research cooperation such as the recently announced collaboration with Vattenfall in the joint project 'OffshoreWake' to investigate the shadow effect offshore wind projects have on each other [16]. DTU's research on both add-on devices and impacts of loads on the blade accounted for 11 % of the publication activity retrieved for the period 2013-2016. This broad scope goes in line with DTU's prominent role in different joint research associations like the European Academy of Wind Energy (EAWE) or the organisation of the EERA Joint Programme on Wind Energy (IRP

Wind)[17][18]. Moreover significant investments with respect to blade research have been undertaken such as the recently completed DTU wind tunnel (Poul La Cour Wind Tunnel) at DTU Risø Campus at a total cost of EUR 11.5 million (DTU's direct contribution: EUR 5.5 million) [19]. DTU's capabilities in blade research are also visible in its current research focus. National funded projects focus on composite structures and materials for wind turbine blades (DCCSM project), fast and efficient fatigue test of large wind turbine blades (BLATIGUE project), wind turbine erosion (EROSION project) or the industrial adaptation of a prototype flap system together with industrial players like Siemens (INDUFLAP2 project) [20]. Furthermore the EU FP7-funded project InnWind.eu elaborated the innovations needed at blade level towards the next generation offshore wind turbine [21].

An even stronger focus on topics in the area of aerodynamics can be witnessed for NREL accounting for 70 % of all blade-related publications. Particularly, simulation and modelling approaches contribute to NREL's publication activity in the field of aerodynamics. Similarly to DTU, NREL focus in aerodynamics is built on its strong capability in blade testing in three facilities of their National Wind Technology Center (NWTC) used to validate blades and components from smaller than 1 m to more than 50 m in length. Moreover NREL uses the NASA Ames wind tunnel to investigate aerodynamics, force predictions, and turbine designs [22] [23].

Similarly to DTU and NREL, research priorities of TU Delft are in the area of aerodynamics (45 %) showing an upward trend in the last years. Additionally, research at TU Delft concentrates on load issues (34 %) such as reduction of fatigue loads or individual pitch control for load reduction. It should be noted that TU Delft profited from its participation in the Dutch 'Far and Large Offshore Wind' (FLOW) and 'Growth through Research, development & demonstration in Offshore Wind' (GROW) joint research programmes [24][25]. FLOW was set up as a public private partnership working on innovations to reduce the cost of offshore wind energy. Among others FLOW focussed on improvements in blade design and included multiple industrial players. FLOW ended 2016, however in its successor programme GROW, blade research throughout the entire value chain plays a prominent role.

Research activity of Sandia and Aalborg University is more established around the O&M topic with both focussing on damage and degradation issues and Aalborg on icing effects on the blade. As an example, Aalborg University's scope in O&M can also be seen in its involvement in the development of a type of blade sensor technology that can deliver measurements of blade geometry changes on wind turbines while they are in operation. To do so, Aalborg seeks collaborations with EU companies such as PolyTech, KK Wind Solutions and LM Wind Power on sensor technologies for blades [26].Nevertheless, Sandia and Aalborg University also have a high share of publications focused on the research areas of aerodynamics and loads respectively.

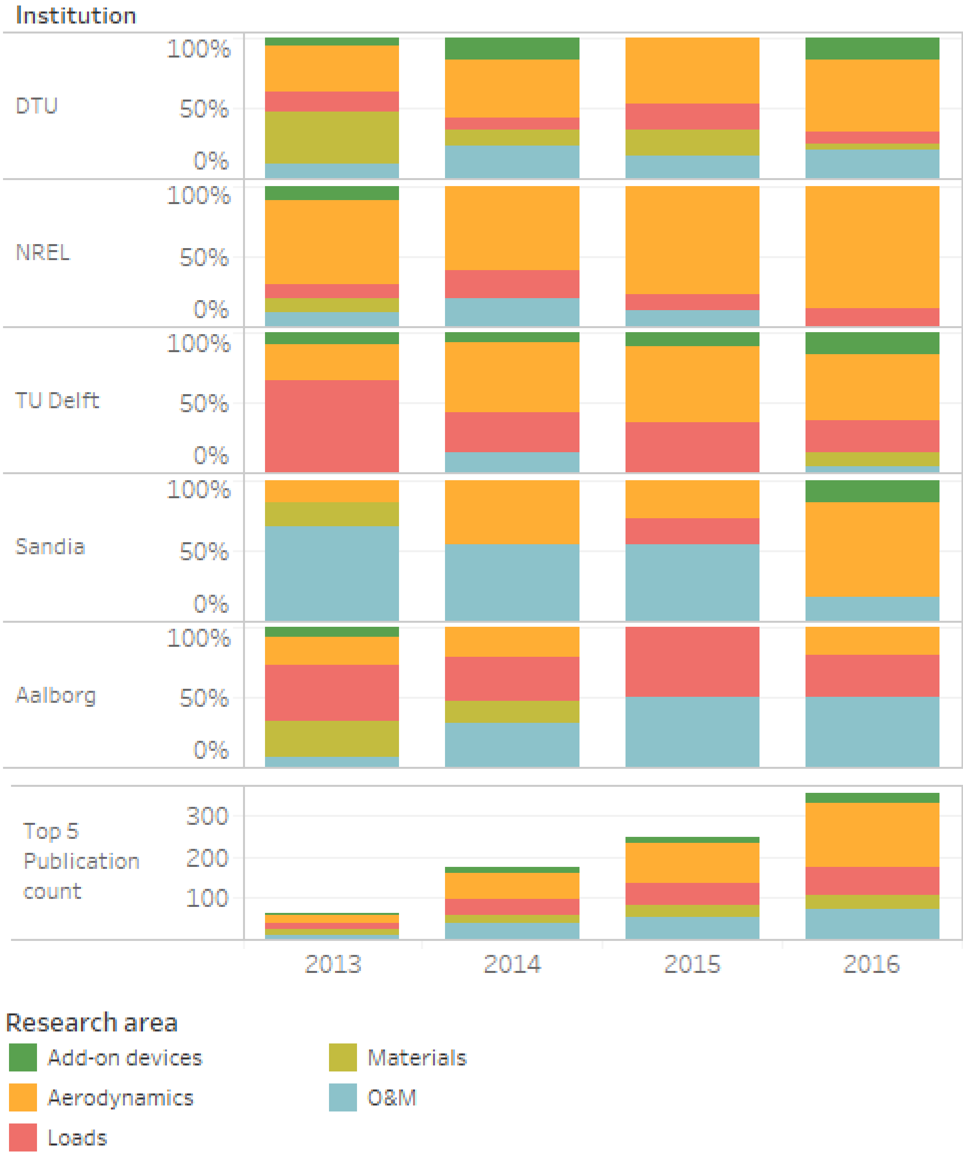


Figure 9. Main research areas addressed by blades-related publications of the Top 5 organisations
Source: JRC based on TIM with data from Scopus

When analysing only the most recent publication activity on blades retrieved for 2015 and 2016, DTU appears as keeping the leading position (see Figure 10). Other organisations are also identified as entering into the Top 5, particularly originating from China. In 2015 the North China Electric Power University (CN) was ranked second with publications mainly about vortex modelling in the area of aerodynamics. In the same year the University of Strathclyde (UK) ranked fifth, publishing articles in the area of aerodynamics and loads, but with a stronger emphasis on offshore wind, mostly based on national funding by EPSRC (Engineering and Physical Science Research Council). In 2016 two Chinese and one Norwegian organisation apart from DTU and TU Delft appeared among the Top 5. In general the University of Shanghai for Science and Technology (CN) published in the area of aerodynamics but additionally a focus on O&M issues such as de-icing techniques and the characteristics of vibrations on the blade is set. Nanjing University of Aeronautics and Astronautics (CN) concentrated its research on the vortices and add-on devices such as vortex generators, as from the publications retrieved by our bibliometric searches.

For the Norwegian University of Science and Technology (NO), we retrieved publications issued in 2016 on O&M, addressing the impact of pitch faults and icing issues of the blade. Scientific articles were also retrieved on aerodynamic effects on the blades of floating offshore wind farms.

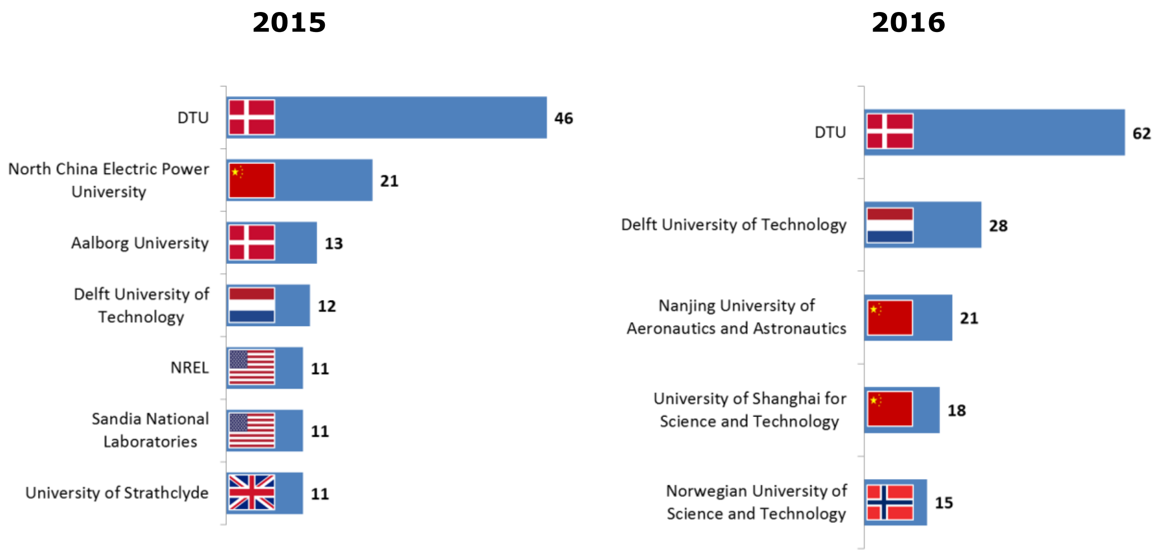


Figure 10. Publication counts within the Top 5 organisations publishing in the area of blades in 2015 (left) and 2016 (right)
Source: JRC based on TIM with data from Scopus

3.2.3 Top 5 organisations in publication activity on offshore wind support structures

From our bibliometric searches (Annex 1) for 1996 to 2016, it appears that scientific publication activity on offshore wind support structures showed a rather low concentration in terms of the publication counts per organisation. Only 12 % of the publication counts originate from the Top 5 organisations (see Figure 11). Within the Top 5 organisations Norwegian University of Science and Technology (NTNU) accounted for 37 % of the publication counts between 1996 and 2016, with Technical University of Denmark (DTU), Aalborg University (Aalborg), National Renewable Energy Laboratory (NREL) and Delft University of Technology (TU Delft) showing comparable figures from around 13 % to 17 %.

With 116 publication counts retrieved, NTNU leads the Top 5. DTU, Aalborg, NREL and TU Delft account for about 40 to 55 contributions to scientific articles each.

Figure 11. Total counts of publications on offshore support structures by the Top 5 organisations (1996-2016)
Note: A count of publication means that an organisation is either a single author or is co-authoring with multiple other organisations
Source: JRC based on TIM with data from Scopus

Among these players the publication activity retrieved began from 2006 onwards, with the exception of TU Delft which already published earlier but still on a rather low level (below 5 publication counts retrieved per year). From 2013 onwards an increased publication activity could be observed, particularly for NTNU (see Figure 12).

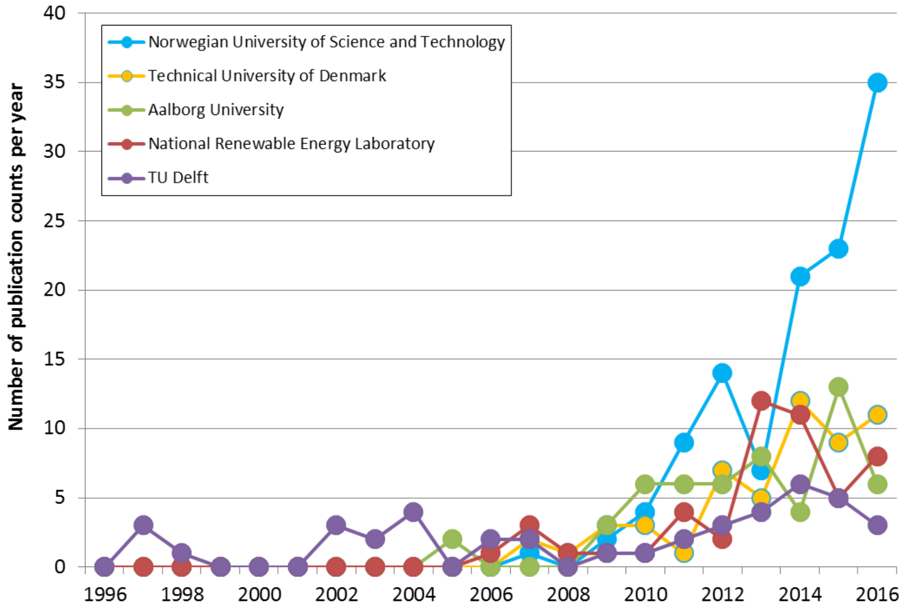


Figure 12. Evolution of publication activity on blades by the Top 5 organisations (1996 – 2016)

Note: A count of publication means that an organisation is either a single author or is co-authoring with multiple other organisations

Source: JRC based on TIM with data from Scopus

To obtain the full picture of the collaboration patterns of these organisations in a bibliometric map, exports from TIM are screened and institutions that belong to the same entity are merged. A full list of all merged institutions of the Top 5 organisations can be found in the Annex 1.

Figure 13 shows the full bibliometric map of the Top 5 organisations publishing on offshore wind support structures in the period 1996-2016. It can be observed that the Top 5 organisations form the strongest collaboration clusters in terms of publication activity retrieved (size of nodes plotted as bubbles, defined in item 2.1) and co-publications (size of edges plotted as lines, as defined in item 2.1).

Among the identified Top 5 organisations only NTNU and DTU are part of the same research co-publication network (orange group in Figure 13) indicating an advanced collaboration between them.

The NTNU/DTU co-publication map shows a denser network of 10 collaborators with the strongest ties on support structure research between NTNU, DTU, Cranfield University and the Norwegian Marine Technology Research Institute (detailed in Figure 14).

Like blade-related research, the co-publication network of NREL is exclusively made up by US organisations, indicating these may have closer relationships among themselves than to organisations outside the US. On the contrary, the cluster around Aalborg University is made up by many international players from the United Kingdom, South Korea, Australia and the United States. Moreover the energy utility Ørsted (previously DONG) is part of this co-publication network (detailed in Figure 14). The objective of industrial players like Ørsted within these collaborations is to achieve significant progress in the reduction of costs of monopile foundations. Long lasting research collaborations exist between Ørsted and the University of Oxford through the Pile Soil Analysis (PISA) project, in which also other major industry players such as RWE, Equinor , SSE or Scottish Power were involved on a recent project aiming for the reduction of cyclic loading from wind and waves to optimise wind turbine foundations [27][28].

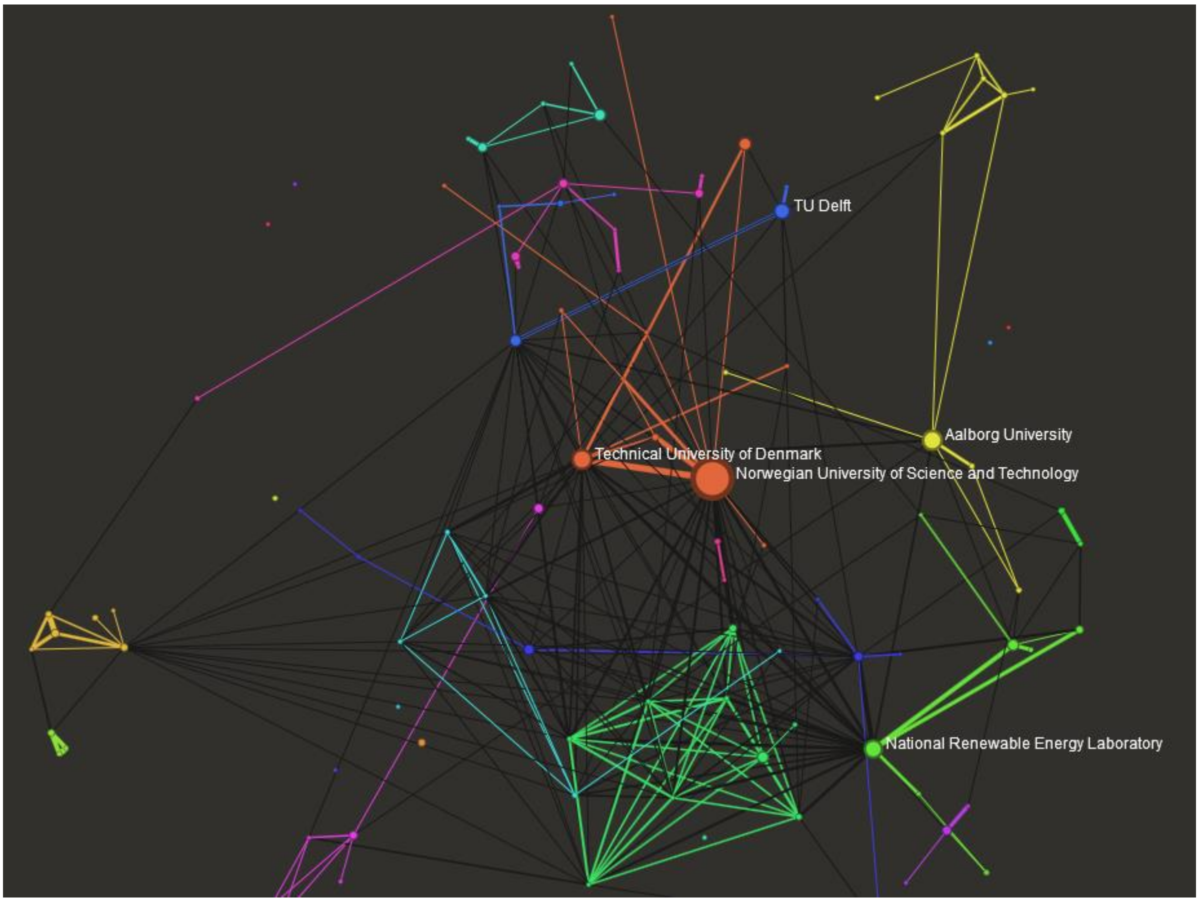
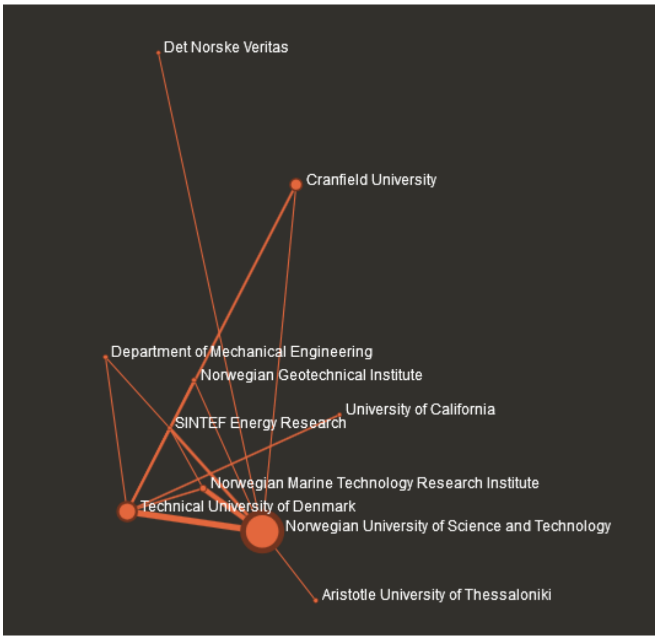


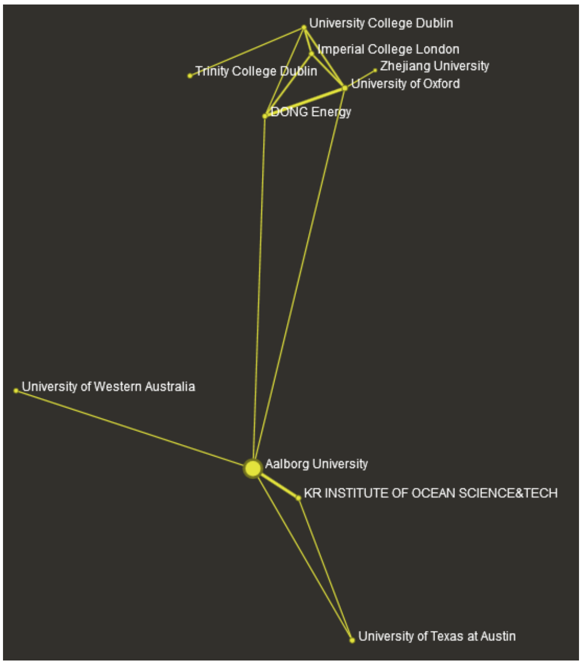
Figure 13. Bibliometric map of the Top 5 organisations publishing on offshore support structures, 1996-2016

Source: JRC based on TIM with data from Scopus

Co-publication network of NTNU and DTU



Co-publication network of Aalborg



Co-publication network of NREL

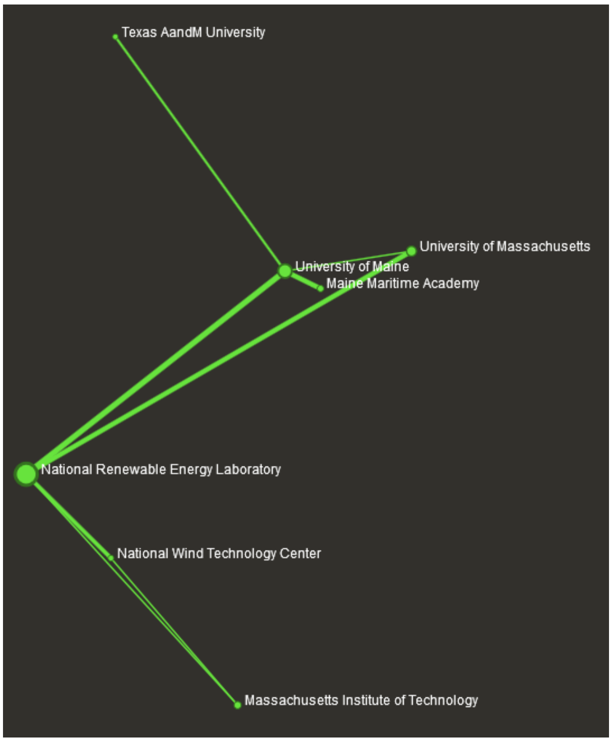


Figure 14. Co-publication networks for selected organisations publishing on offshore support structures, 1996-2016 (details of Figure 13)
Source: JRC based on TIM with data from Scopus

3.2.4 Main areas of publication activity on offshore wind support structures

Based on the outlined taxonomy in section 2.2 we analysed the latest trends in the research areas addressed in publications on offshore wind supports structures retrieved by our TIM searches (Annex 1), and put them in context with their ongoing research activity. Our analysis focuses on the Top 5 organisations in the period 2012-2016, when their publication increased significantly (Figure 12).

Our searches show NTNU as the most active author in this research field, publishing predominantly on grounded (52 %) and floating (34 %) offshore support structures in 2012-2016. The focus in the publications on ground-based support structures lies on design optimisation and fatigue load analysis. Articles retrieved on floating concentrate on dynamic response analysis of spar-type and semi-submersible floaters. On a lower but constant level NTNU publishes articles related with installation & lifting operations (8 %) and innovative and hybrid concepts (6 %). Publications on installation & lifting operations elaborate on the lifting techniques for monopiles and on vessel shielding effects. Hybrid concepts especially focus on combined wind and wave energy converters. For the investigated period (2012 – 2016) a trend towards publications on ground-based support structures can be observed. NTNU also benefits from a strong industrial research environment in Norway such as by the energy company Equinor (formerly Statoil) and its activities in floating offshore which led to the completion of the 30 MW Hywind Scotland Pilot Park at the end of 2017 [29][30].

Similarly publications on support structures at DTU focus on grounded (56 %) and floating (40 %) platforms over the period 2012 – 2016. Retrieved publications on grounded support structures almost exclusively focus on monopiles and associated topics such as load effects. Publications on floating support structures at DTU show a special emphasis on dynamic response analyses of all three main typologies. Moreover DTU shows an increased publication activity on vertical axes wind turbines (VAWT) mounted on floating devices. DTU's current projects in this area focus on the optimal design of bottom fixed support structures for all relevant water depths including deep waters in excess of 50m (e.g. ABYSS project) [31] and the development of new design methods for bottom fixed support structures which offer a reduced risk and uncertainty against extreme wave loads (DeRisk project). Both projects are funded by the Innovation Fund Denmark and include research institutions as well as renowned industrial players (DHI, Ørsted, University of Oxford, University of Stavanger, Statkraft and Equinor) [32]. The EU FP7-funded project InnWind.eu elaborated the innovations needed in both grounded support structures and floating support structures carrying the next generation of offshore wind turbines [21].

Most publications retrieved for Aalborg University were on ground-based support structures (81 %) and more specifically on soil-pile interaction, soil properties and soil dynamics. The remaining articles retrieved (19 %) on floating address models on mooring techniques and ultimate limit state designs for extreme sea states. Moreover, recently announced research projects in Aalborg's research programme seem to focus on the modelling and control of floating wind energy systems [33].

Even though the potential for floating offshore wind in the US is lower than in Europe (2450 GW versus 4000 GW) [34], research institutions in the US are focusing on the demonstration of floating offshore wind solutions. In contrast to the other Top 5 organisations, for NREL our searches retrieved more scientific articles on floating support structures (63 %) than on grounded support structures (34 %). Based on our searches, the main scientific activities in both substructure categories are found to be on aero-hydro-servo-elastic models. Moreover, the effect of drifting surface ice in cold regions on grounded support structures is investigated. NREL's capabilities in floating offshore wind were also used during a research partnership with the Norway-based energy company Equinor in order to develop software tools for the Hywind floating concept [35].

For TU Delft, the publications retrieved show strong research capabilities on grounded support structures (74 %), primarily in dynamic response analysis techniques such as dynamic sub-structuring. For floating support structures (16 %) and installation & lifting operations (11 %), results from our search (see Annex 1) indicate more moderate publication levels. This emphasis on grounded support structures and the installation process is also apparent in the Dutch GROW programme, where TU Delft is leading a project on the 'Gentle Driving of Piles (GDP)'[36]. This project aims to make the pile installation process as efficient as possible by means of testing a novel pile installation method based on simultaneous application of low-frequency and high-frequency vibrators. Project partners include other research institutes (TNO, Deltares, ECN), marine contractors (Van Oord offshore wind projetcs, Boskalis, IHC, Deaway Heayy Lifting), project developers (Eneco, Shell) and wind companies (SIF, DOT) [37].

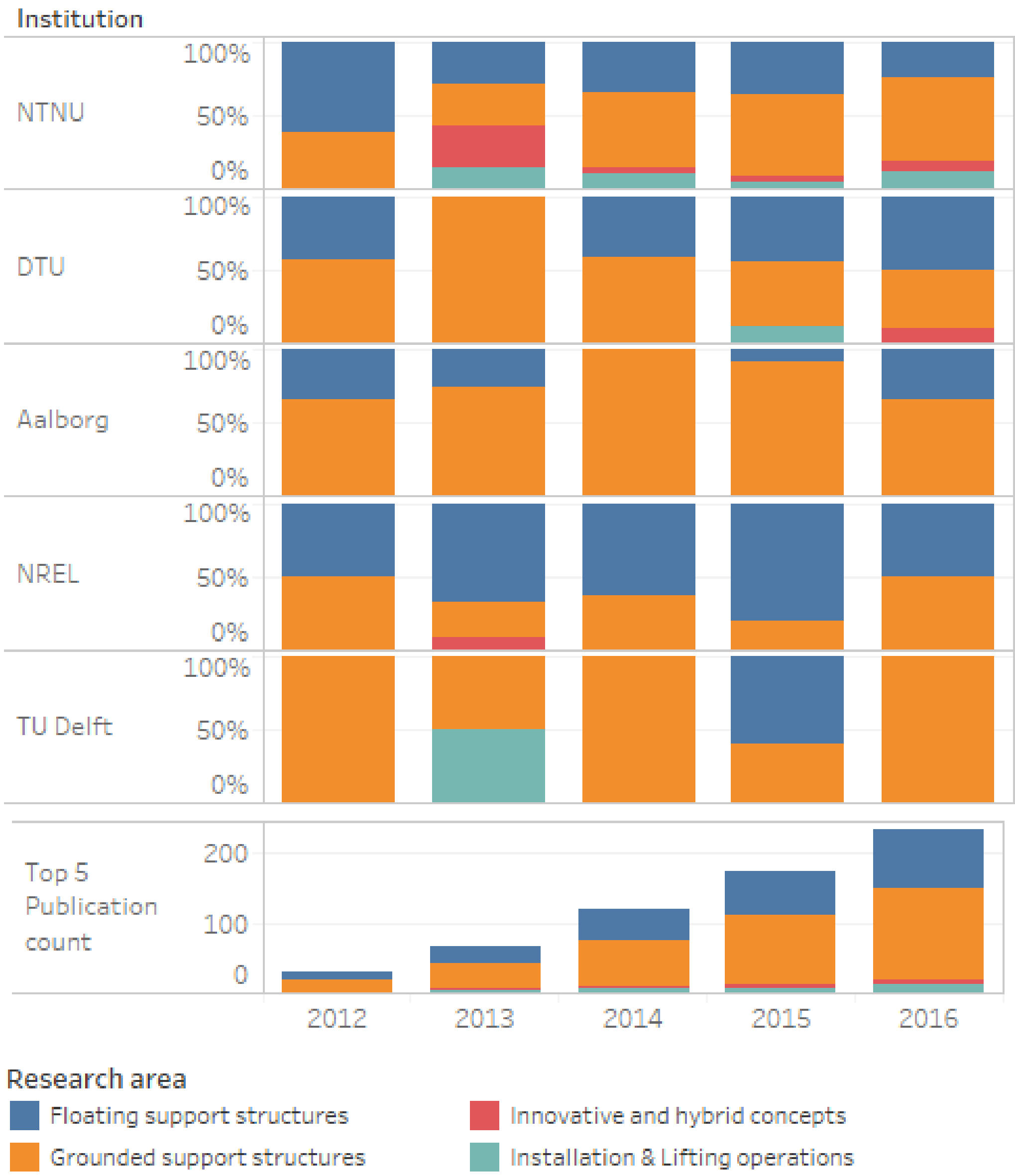


Figure 15. Main research areas addressed by offshore wind support structure-related publications of the Top 5 organizations
Source: JRC based on TIM with data from Scopus

The recent trends observed from publications retrieved for 2015 and 2016 on offshore wind support structures show that apart from NTNU's leading position, more and more organisations and even industrial players are entering the Top 5 (see Figure 16). In both years Universidade de Lisboa ranks among the Top 5, with contributions on floating semi-submersible devices and to a lesser extent on fatigue analysis of grounded support systems. Portugal holds excellent wind resources offshore but its steep coastline does not allow significant deployment of ground-based offshore wind. As such the development of floating concepts is crucial to develop a domestic offshore wind market. The focus on floating goes in line with Universidade de Lisboa's strength in research about marine structures and marine dynamics at the Centre for Marine Technology and Engineering (CENTEC). Moreover, Portugal hosts the Windfloat project, a 25 MW pre-commercial floating wind farm located 20 km off the coast using a semi-submersible platform. The project was awarded by NER 300, one of the world's largest funding programmes for innovative low-carbon energy demonstration projects [38].

In 2015 Cranfield University, Norwegian Marine Technology Research Institute/ MARINTEK and the Energy utility Ørsted (previously DONG Energy) hold the split fifth place. In that year research of Cranfield University focused on the response analysis of floating devices and on corrosion fatigue of monopiles. Cranfield's entering into the Top 5 followed substantial investments in 2014 (EPSRC funded) in the new Centre of Renewable Energy Marine Structures (REMS) (EUR 9.4 million) a collaborative partnership between Cranfield University and the University of Oxford [39] [40].

For the Norwegian Marine Technology Research Institute/MARINTEK, our searches in TIM retrieved almost exclusively publications on floating support structures such as different concepts on v-shaped semi-submersible devices or spar platforms. For the energy utility Ørsted (previously DONG Energy), our search retrieved articles mainly on the design optimisation and soil-pile interaction of monopiles.

In 2016 the Shanghai Jiao Tong University appeared in the second rank of the Top 5 with publications mostly in the area of floating support structures. Within this topic a focus was on hydrodynamic and coupled dynamic response analysis. Building on their knowledge in these topics Shanghai Jiao Tong University collaborates with Oxford University on structural designs that will increase the resilience of wind turbines in typhoon conditions [41]. This collaboration is funded by EPSRC under the Joint UK-China Offshore Renewables Energy (ORE) programme [42].

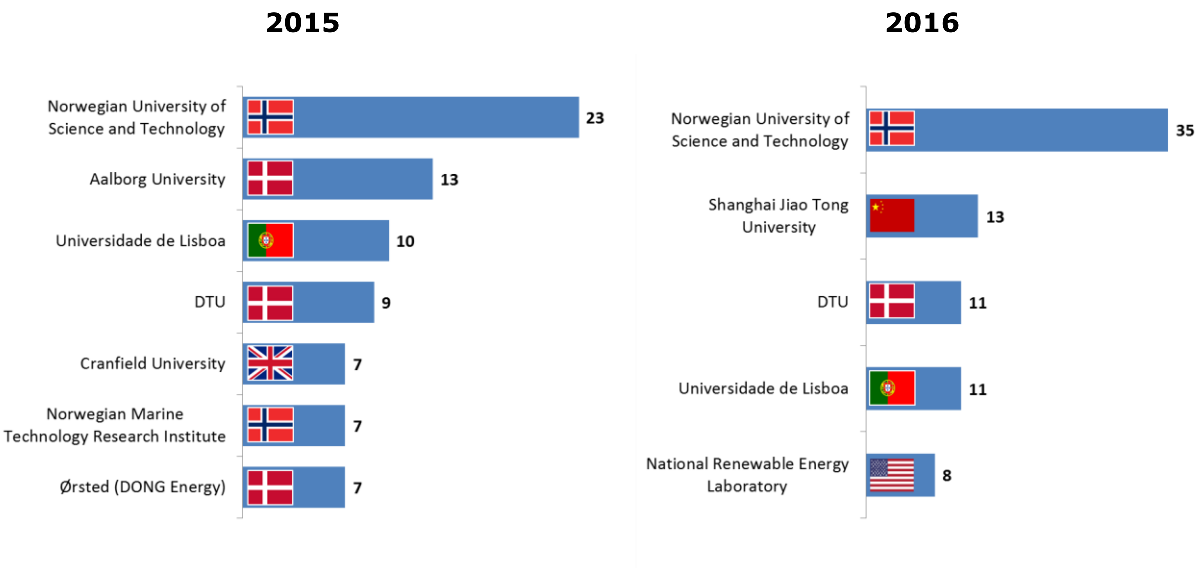


Figure 16. Publication counts within the Top 5 organisations publishing in the area of offshore wind support structures in 2015 (left) and 2016 (right)
Source: JRC based on TIM with data from Scopus

3.2.5 EU research funding in the area of blades and offshore wind support structures

Horizon 2020 is the biggest EU Research and Innovation programme (2014-2020). The total budget allocated to projects on wind energy is estimated to be more than EUR 150 million with around 35 % allocated to projects addressing different research areas in blades and offshore support structures (Figure 17).

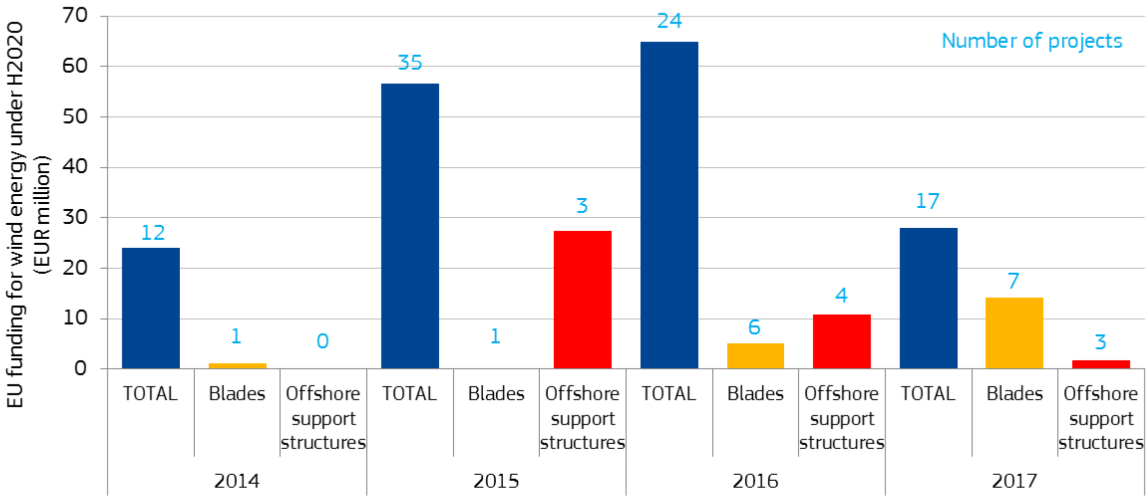


Figure 17. EU funding for wind energy under the Horizon 2020 programme. Focus on blades- and offshore support structure-related research projects
Source: CORDIS (data retrieved on 20/5/2018)

Overall, the research areas funded under Horizon 2020 programme share similarities with those addressed in the retrieved publications.

As previously shown in section 3.2.2, among the Top 5 organisations in terms of retrieved publication counts, most blades-related publications are on aerodynamic effects followed by new solutions in O&M and load impacts on blades.

Horizon 2020 currently finances wind energy projects related with aerodynamic effects and aimed to demonstrate new rotor blade concepts for longer blades. These projects are

TRIBLADE (demonstration of a "3-in-1" modular blade) and VORTEX (disruptive concept of a bladeless Vortex wind generator). Like the Top 5 publishing institutions identified by our bibliometric searches, Horizon 2020 also finances projects in the O&M research area. In that area some focus is set on lightning interception and protection solutions during wind turbine operation such as in the LIBI project (Lightning Interception Blade Implant) and the SPARCARB project (Lightning protection of wind turbine blades with carbon fibre composite materials). Other projects aim to develop novel concepts for blade inspection procedures such as the Wind-Drone project (A powerful drone allowing safe, reliable and effective inspections of wind turbines) and the SheaRIOS project (Wind Turbine Shearography Robotic Inspection On-blade System).

Unlike our bibliometric search results of the Top 5 publishing institutions, Horizon 2020 currently allocates funding to a significant number of research projects on materials. Some of these projects aim to develop advanced materials for longer blades. Some relevant examples are DACOMAT (development of more damage tolerant and predictable low cost composite materials) and POWDERBLADE (advanced composite material consisting of carbon-glass hybrid). Other projects aim to develop environmental and economic solutions for the end-of-service life of blade materials such as in the EcoBlade project (Eco-efficient decommissioning of wind turbine blades through on-site material shredding and separation). Among the identified Top 5 publishing institutions in blades-related publications only DTU participates in the Horizon 2020 funded-project DACOMAT.

With regards to offshore support structures, we defined rather specific search strings in order to obtain more precise results – e.g. to exclude structures for bridges, oil platforms etc (see Annex 1, search strings 7 and 8). The results indicate that the Top 5 publishing organisations issue most of their publications on grounded foundations followed by floating platforms (as previously shown section 3.2.4). Research on both innovative and hybrid concepts, as well as on installation and lifting operations show low publication activity. The portfolio of projects funded by Horizon 2020 is very diverse, addressing not only grounded and floating support structures but also other research areas. Expanding the search string to include these topics, and/or doing more detailed text-mining on wider results for wind energy in general (search strings 4 or 6) might retrieve further publications.

Grounded and floating support structures are hot research areas among the offshore wind energy projects funded by the Horizon 2020 programme. Horizon 2020 also allocates funding to a significant number of projects aimed at demonstrating new floating offshore wind solutions. The most funding (EUR 7.3 million) is allocated to the project LIFES 50plus (Qualification of innovative floating substructures for 10 MW wind turbines and water depths greater than 50 m) followed by different projects aimed to demonstrate new floating concepts including FLOWSPA (a floating platform that combines spar and semisubmersible technologies), WTSS, SATH (a new twin floating platform) and FLOW. On the other hand, currently DEMOGRAVI3 (demonstration of the innovative gravity foundation GRAVI3) is the only project on grounded support structures under Horizon 2020 although it is funded with more than EUR 19 million, which exceeds the total funding allocated to all current projects on floating platforms (EUR 7.3 million).

As shown in section 3.2.4, the research areas of both innovative and hybrid concepts and installation and lifting operations are marginal in terms of publication activity retrieved by our bibliometric searches among the Top 5 institutions. On the contrary, Horizon 2020 currently supports different projects in these research areas including POSEIDON (Hybrid floating and wave device), OptiLift (framework to improve offshore lifting and logistics) and GroutTube (innovative equipment/concept for offshore grouting of multi-pile foundations).

Some of the identified Top 5 institutions currently participate in Horizon 2020 funded-projects on offshore wind support structures. As an example, DTU participates in the LIFE50 plus project together with other universities, research institutions and industrial players from the United Kingdom, Italy, Spain, Germany and France. NTNU and Aalborg, who are not part of the same co-publication network identified in our work, collaborate in the Horizon 2020 funded-project MARINET2 (Marine Renewable Infrastructure Network for Enhancing Technologies 2). This project aims at a continued integration and enhancement of all leading European research infrastructure and facilities specialising in research, development and testing of offshore renewable energy systems.

3.3 Leading countries and collaboration patterns

3.3.1 Leading countries in publication activity on blades

At country level our bibliometric searches (Annex 1) identified the United States and China leading in publishing activity in the area of blades, followed by the UK, Denmark and Germany. However the entire EU28 top up the United States and China in terms of publication counts in the period 1996-2016 by more than 40 % (see Figure 18).

From 1997 onwards, the United States showed the strongest publication activity among countries in the research area of blades. Between 2002 and 2006 more and more countries authored publications in this topic with Denmark, Japan, the United Kingdom and especially China being increasingly active. The following periods show China closing up to the United States and an increased total number of countries publishing scientific articles on blades. Notably this increase in Chinese publication activity follows several policies (e.g. the Medium and Long Term Development Plan for Renewable Energy in 2007 [43] or the 12th Five Year Plan for National Strategic Emerging Industries in 2012 [44], [45]) by the Chinese government since 2007 as climate change mitigation has become a national priority in China's long-term central planning. Among other targets on wind energy the 12th Five Year Plan focuses on technology innovation in the sector of onshore and offshore wind. Similarly publication counts from the EU 28 seem to increase in line with the EU's measures on spurring the renewable energy production in 2001 (Directive on the promotion of electricity from renewable sources in the internal electricity market) and 2009 (Directive on the promotion of the use of energy from renewable sources) [46], [47].

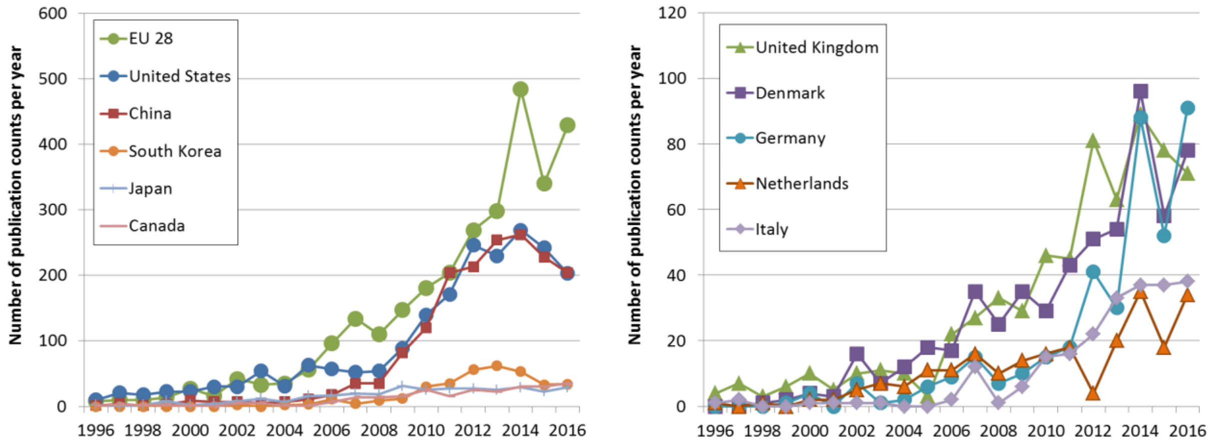


Figure 18. EU28 and others (left hand side) and top EU countries (right hand side) publishing on wind blades, 1996-2016

Note: A count of publication means that the country is represented by one or more organisations on the publication (e.g. three organisations from the same country on a publication are counted as one publication from that country)

Source: JRC based on TIM with data from Scopus

Figure 19 shows the bibliometric map on country collaborations in the area of blades between 1996 and 2016. The size of the node (bubble) indicates the publication count (number of documents retrieved) for a country; the edge (line) thickness is relative to the count of publications co-authored by organisations based in each of the two countries (nodes) linked by that common edge. Co-publication networks at country level that tend to appear more together than with others form clusters with the same colour.

In the period 1996 to 2016, the most distinct collaboration cluster (co-publications) can be found between the United States, China, South Korea and Japan (orange group). Denmark, the United Kingdom and Norway form the second strongest collaboration pattern in blades. The strongest collaboration between two countries was found for China and the United States sharing 106 co-published documents. China and the US collaborate in the area of aerodynamics research or material research on the improvement of the blade's mechanical properties. Collaborations within this cluster is complemented by Japan and South Korea, which are both active in the area of blade related O&M topics such as structural health monitoring techniques for blades, icing or blade erosion.

An example for intensified efforts in future European blade technology research collaboration can also be seen in the Offshore Demonstration Blade (ODB) project focussing on aerodynamic and structural enhancements, blade monitoring systems and protection against blade erosion. The products will be developed and retrofitted to the Offshore Renewable Energy (ORE) Catapult's 7 MW Levenmouth Demonstration Turbine in Scotland for demonstration purposes. The two-year Demowind-funded project (Horizon 2020 Framework Programme) will be coordinated by the UK's ORE Catapult Development Services Ltd (ODSL), and involve leading organisations in wind turbine innovation including CENER, Bladena, TNO, Aerox, Siemens Gamesa Renewable Energy, Total Wind, Dansk IngeniørService A/S (DIS), the Technical University of Denmark (DTU) and the Cardenal Herrera University (CEU) in Spain [48][49]. Moreover ORE Catapult has signed a £ 2.3 million research partnership (Wind Blade Research Hub) with the University of Bristol to look at building blades for the 13-15 MW turbine generation [50].

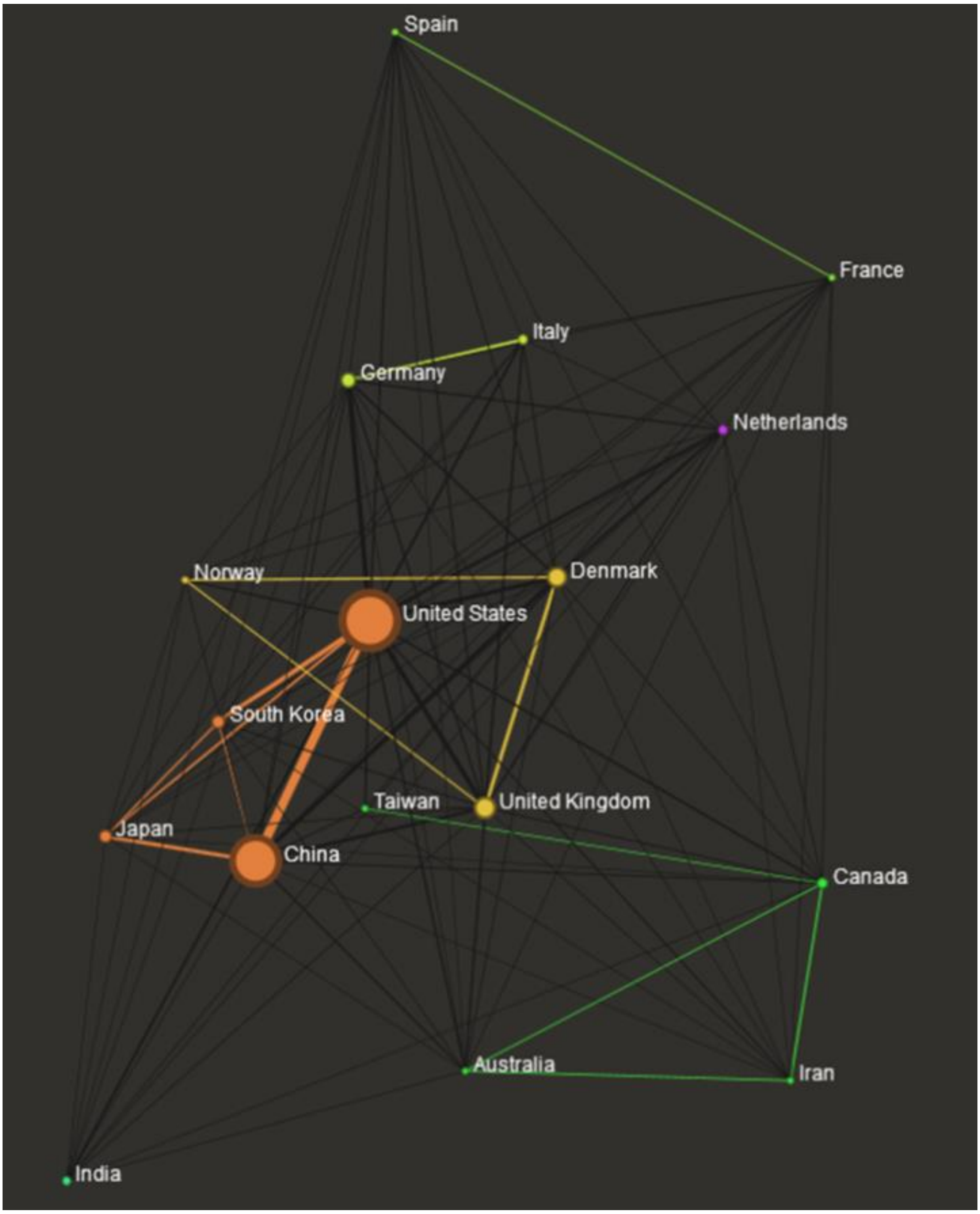


Figure 19. Network maps for country-level co-publication on blades (1996 – 2016).
Source: JRC based on TIM with data from Scopus

In 2015 our bibliometric search identified the United States leading in terms of publishing in the area of blades followed by China. At a more moderate level the United Kingdom, Denmark and Germany followed. 2016 saw a slight decrease in the retrieved top publishing countries with China overtaking the United States. Compared to 2015, Germany and the United Kingdom changed places. In both years the strongest contributors in the RoW[9] are India, South Korea and Canada (see Figure 20).

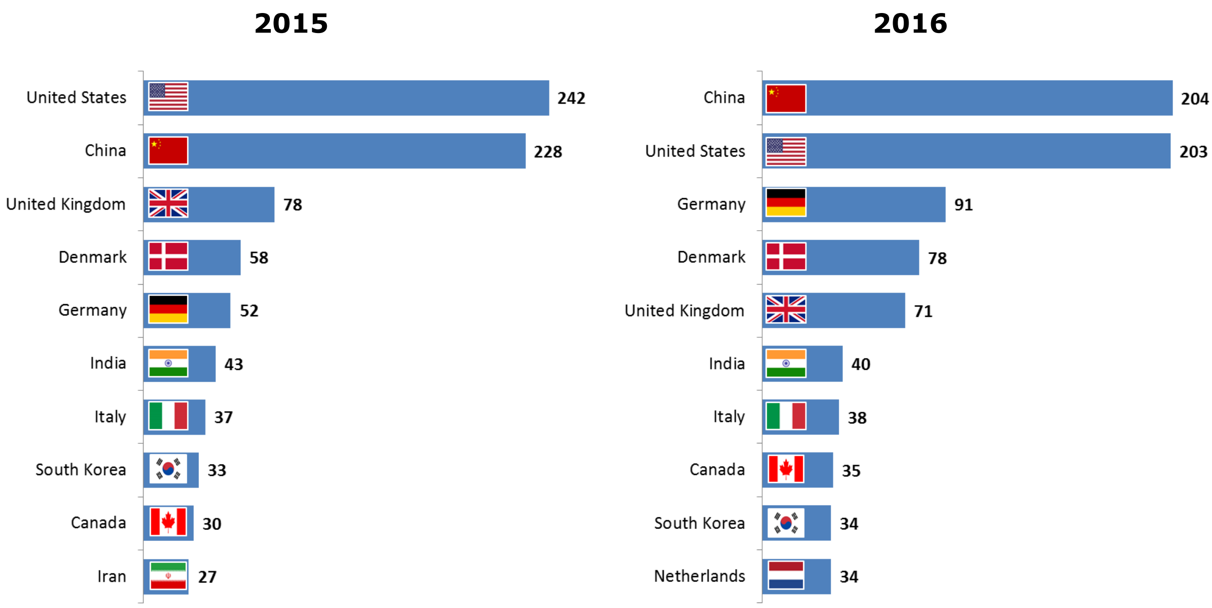


Figure 20. Top 10 countries publishing (publication counts) on wind blades in 2015 (left) and 2016 (right)
Source: JRC based on TIM with data from Scopus

[9] RoW stands for rest of the world.

3.3.2 Leading countries in publication activity on offshore wind support structures

Like blades-related research, our bibliometric searches (Annex 1) on support structures identified the United States and China leading publishing activity, followed by Germany, the UK, Norway and Denmark. However, the entire EU28 top up the United States in terms of publication counts in the period 1996-2016 by more than 130 % (see Figure 21).

Within the investigated period, increased publication activity in offshore wind support structures started in Germany, the United States, the United Kingdom and Japan from 2002 onwards. From 2006 to 2011 the United States and Germany could maintain their leading position in a growing research topic and in spite of new entrants from Denmark, Norway and China. Again it seems that China's uptake in publication activity on offshore wind support structures follows governmental policies put in place in 2009 and 2014 (e.g. the Offshore Wind Development Plan [51] and the China Offshore Wind Power Development Plan (2014-2016) [52]).

From 2010 onwards it can be observed that both the number of European countries and their publication counts increase. Notably most of these countries showed a substantial increase in offshore wind deployment (e.g. Germany, United Kingdom, Denmark) or are home of companies or projects with innovative offshore wind projects (e.g. Hywind Scotland Pilot Park by Norwegian energy utility Equinor (formerly Statoil) or the Windfloat project in Portugal) [30], [38].

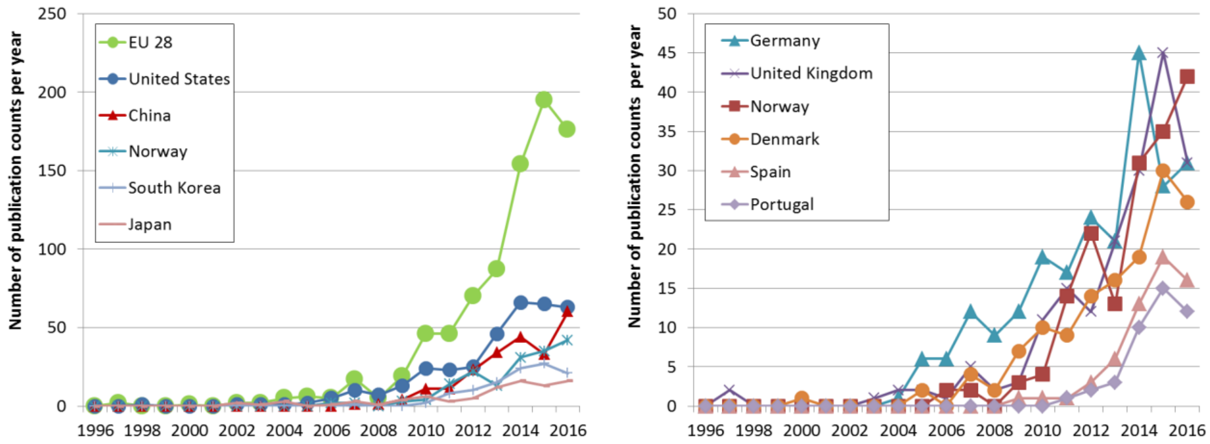


Figure 21. EU28 and others (left hand side) and top EU countries (right hand side) publishing on offshore wind support structures, 1996 -2016
Source: JRC based on TIM with data from Scopus

Figure 22 shows the bibliometric map on country collaboration in the area of support structures between 1996 and 2016.

In the period 1996 to 2016, the most distinct collaboration cluster can be found between the United States and South Korea (light green group). Three other clusters are formed with multiple countries yet showing lower collaboration intensity:

- Denmark, the United Kingdom, Norway, Finland and France (yellow group)
- Germany, the Netherlands, Spain, Taiwan and the Russian Federation (orange group)
- China, Japan, Singapore and Australia (green group)

The strongest collaboration (co-publications) between two countries was found between South Korea and the United States as well as between the United States and Germany (although not being part of the same collaboration cluster) sharing 29 co-published documents each.

South Korea and the US especially collaborate in the area of floating support structures with a special emphasis on coupled dynamic analysis of floating devices and concepts of multi-unit floating devices. Moreover it can be observed that the thematic focus of this collaboration is also shared in the relevant IEA offshore wind working groups (such as IEA Task 23 on Offshore Wind Technology and Development and IEA Task 30 on Offshore Code Comparison Collaboration and Offshore Code Comparison Collaboration). The strongest European collaboration cluster (yellow group) shows a more diverse research pattern. Although most co-published articles focus on floating devices a significant number of articles also elaborate on ground-based support structures and installation & lifting operations.

Upcoming country collaboration on offshore support structures is envisaged in the Joint UK-China Offshore Renewable Energy program. Under this EPSRC funded initiative 3 out of 5 research projects focus on offshore support structure related topics. Oxford University and Shanghai Jiao Tong University will investigate structural designs and their resilience of wind turbines in typhoon conditions. The University of Exeter and Dalian University of Technology will look to increase resiliency in floating offshore wind platforms. Cranfield University and Harbin Engineering University will explore potential synergies in the installation and operation of different offshore energy facilities, with the aim of lowering the overall costs [41].

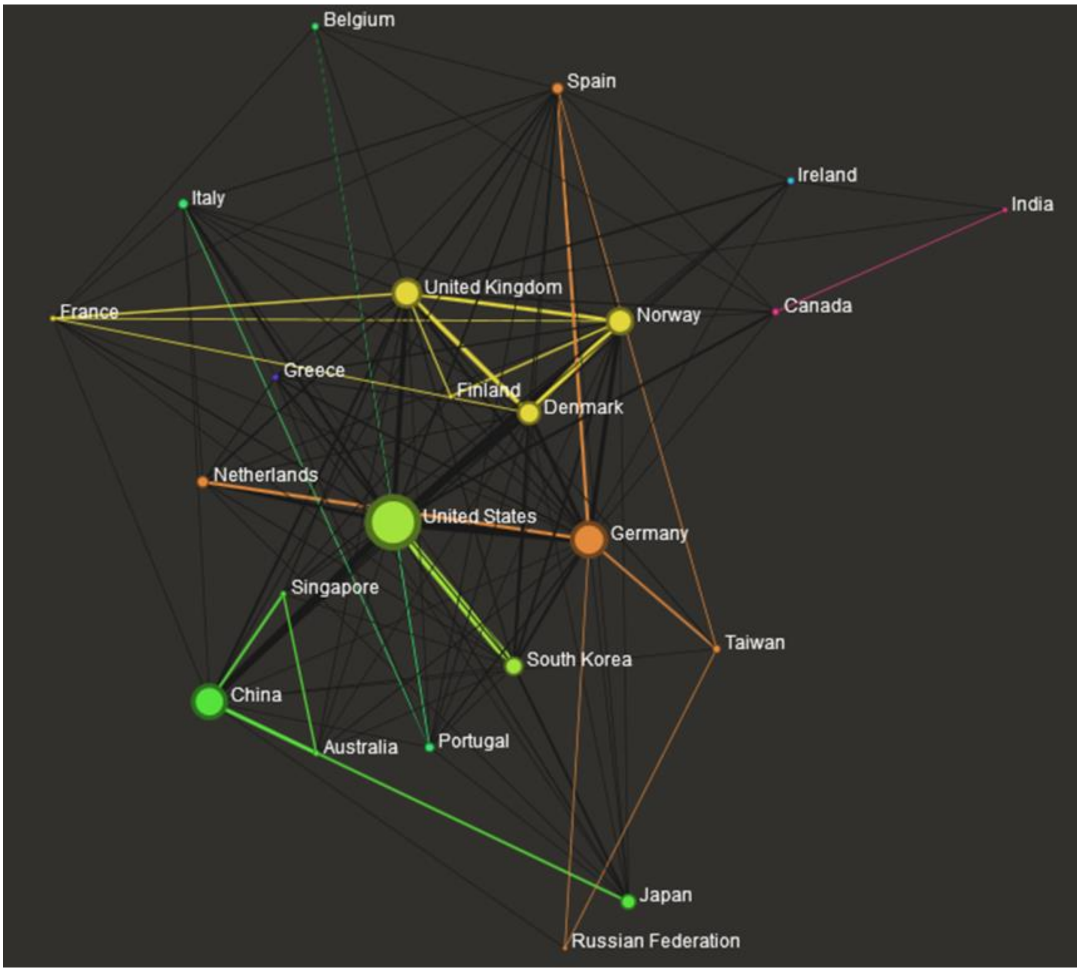


Figure 22. Network maps for country-level co-publications on support structures (1996 – 2016).
Source: JRC based on TIM with data from Scopus

In 2015 our bibliometric search identified the United States leading in terms of publishing in the area of supports structures followed by the United Kingdom. At a more moderate level Norway, China, Denmark, Germany and South Korea followed. In 2016 China claimed the second spot overtaking Norway and the United Kingdom. Compared to 2015, Germany and the United Kingdom changed places. In both years the strongest contributors in the RoW were South Korea and Japan (see Figure 23), both recently undertaking significant efforts towards offshore wind deployment [53], [54].

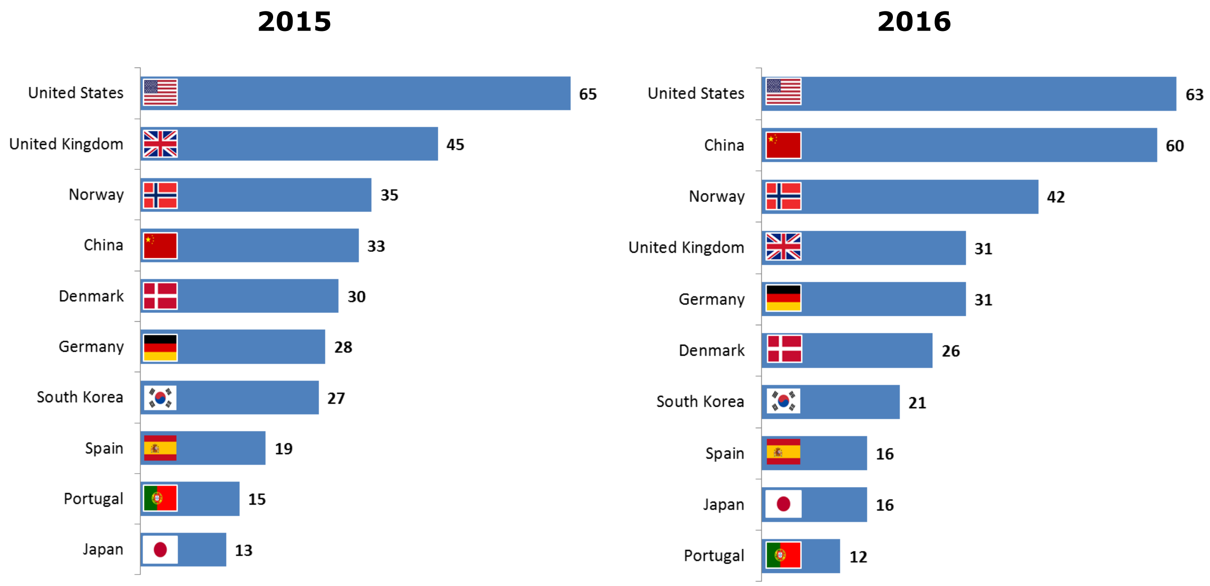


Figure 23. Top 10 countries publishing (publication counts) on offshore wind support structures in 2015 (left hand side) and 2016 (right hand side)
Source: JRC based on TIM with data from Scopus

3.4 Structure and evolution of co-publication networks

As discussed earlier (item 2.1), the size of a node indicates the number of documents retrieved (publication counts retrieved for one organisation), whereas the edge thickness is relative to the number of documents in common (counts of co-publications retrieved between two different organisations). Thus these numbers give an indication on the relevance of a single organisation and its collaboration ties. The overall structure of a research field and its evolution is rather dependent on the temporal development of the number of nodes and edges of the entire sociogram (a network graph that maps co-publication activity between different organisations).

We used TIM to show how networks for both blades and offshore support structures grow over time. We plotted the densification of these two co-publication networks using the expression shown in Annex 1 (Equation 2) with the data plotted in Figure 24,

- Number of nodes: yearly counts of **new entrants** (organisations[10] for which TIM retrieves publications in a given domain for the first time). This can be seen as a proxy of the openness and/or attractiveness of a research domain for new entrants to publish on.
- Number of edges: yearly counts of **co-publications** by different organisations, including both new entrants and incumbents. This can be seen as a proxy of the collaboration intensity in a research domain.

[10] Data in the following figures refer to unmerged organisation names (raw data retrieved by TIM from the Scopus database). Annex 2 lists full list of the unmerged organisations (e.g. 20 entities for DTU, 2 entities for NREL and Sandia each, etc.)

Figure 24 shows the evolution of new entrants publishing in blades and offshore wind support structures over time. For blades the counts of new entrants remained on a modest level between 1996 and 2004, followed by a steep increase until 2014. A similar development though on a much lower absolute scale can be seen for offshore wind support structures. At the same time collaboration intensity grew over the investigated period forming stable collaborations.

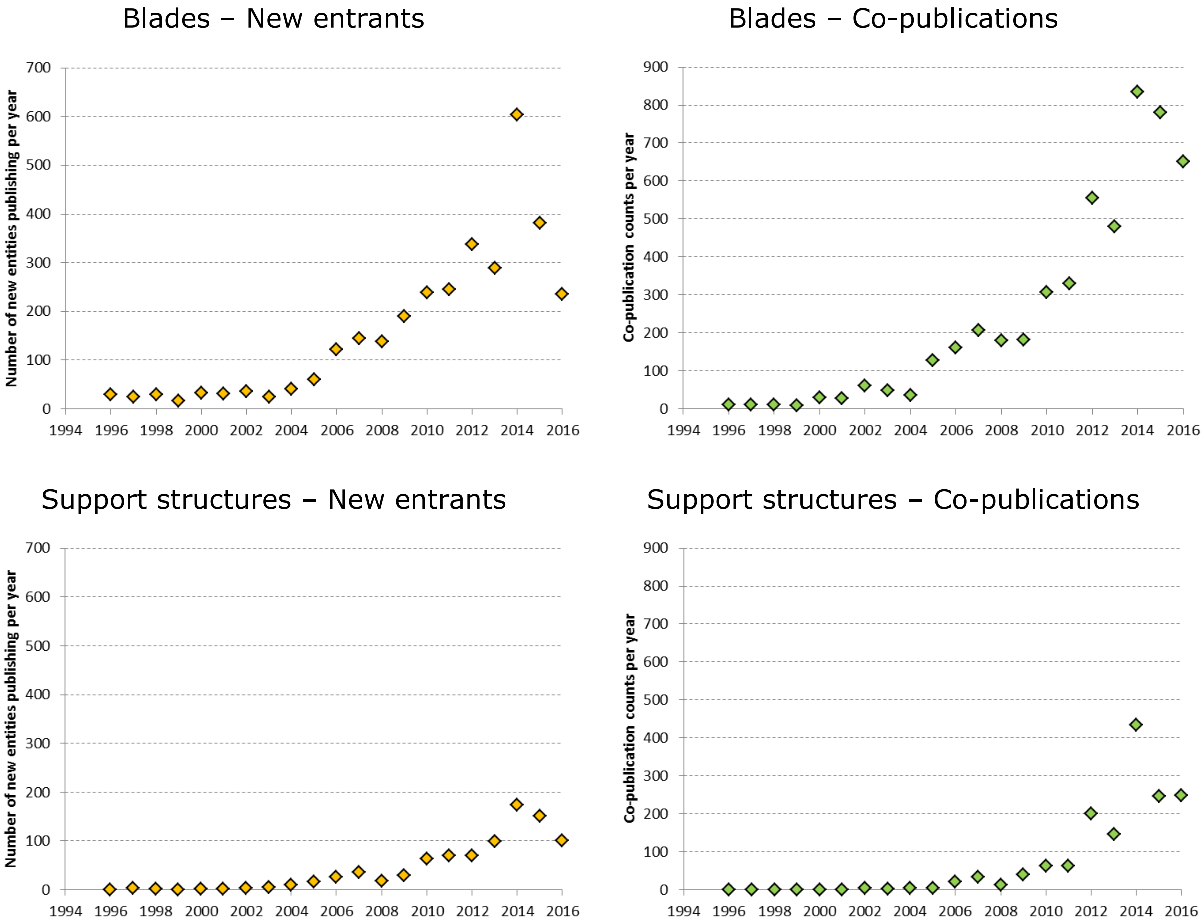


Figure 24. Counts of new organisations (new entrants) publishing per year and collaboration intensity (co-publications) for blades and offshore wind support structures, 1996-2016
Source: JRC based on TIM with data from Scopus

Network graphs of emerging fields grow and become denser, meaning that the number of edges per node increases. As shown in section 2.6 and detailed in Annex 1, this can be described by a power law scaling relation [55], [56]. To visualise the densification of the two investigated technologies and to calculate the densification exponent α, describing the densification of a scientific field, we plotted the cumulated yearly counts of co-publications (collaboration intensity) against the cumulated counts of new organisations publishing (new entrants) in one graph (see Figure 25). For both densification graphs we defined the starting year with the first year of the dataset when both edges and nodes are > 1. Although the research on blades is more advanced in terms of total counts compared to the research activity in offshore wind support structures both fields grow/densify at a similar scale. For the co-publication networks on blades and on support structures α is found to be 1.354 and 1.346, respectively. Densification exponents at this scale indicate growing research fields with shared fields of collaboration and increased exchange among partners.

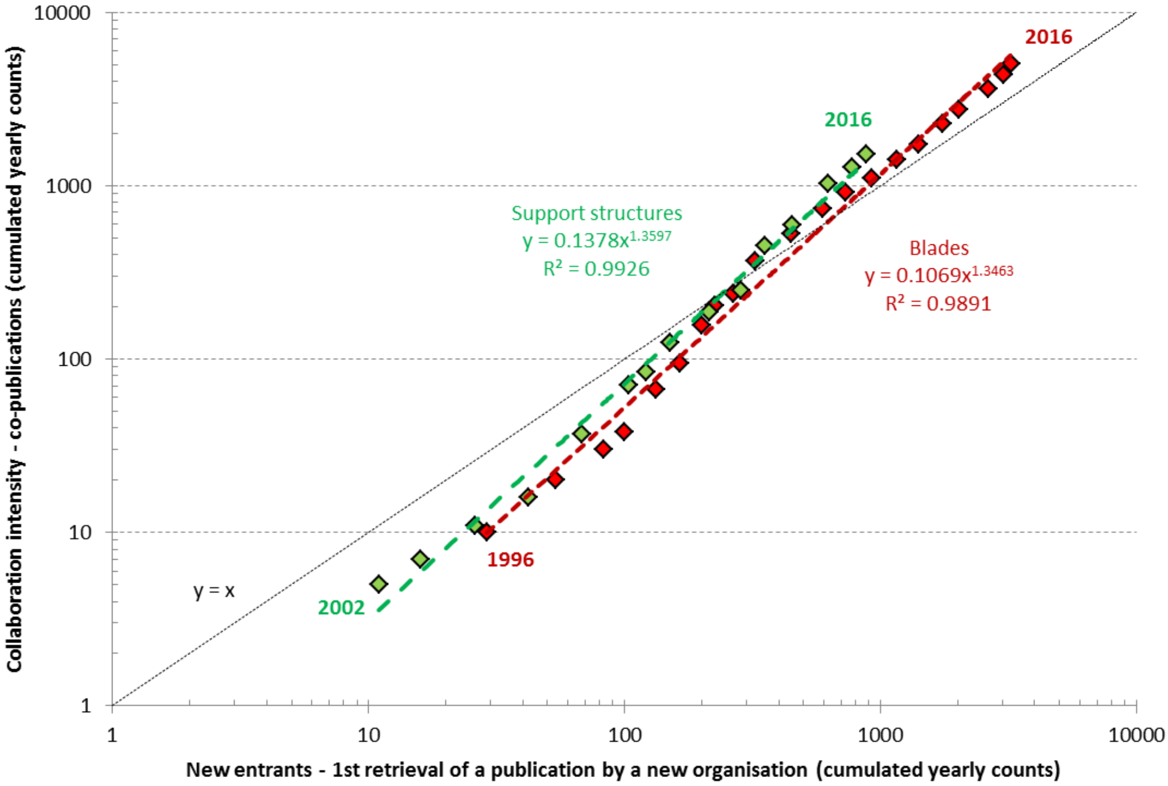


Figure 25. Densification of co-publication networks for blades and offshore wind support structures, 1996-2016
Source: JRC based on TIM with data from Scopus

In line with prior visual observation that the 'sociograms' tend to densify over time, the log-log plot in Figure 25 shows a clear power-law correlation between yearly counts of new entities starting to publish in the field (nodes in the horizontal axis) and the intensity of collaboration measured by yearly co-publications counts (edges in the vertical axis).

The black dotted 'reference line' shows one-to-one growth for 'new entrants' versus co-publications. Steeper plots compared to this 'reference line' indicate that a field is evolving, while more moderate slopes tend to correspond to more established fields.

Here, the slopes are similar for wind blades and support structures, suggesting densification at similar rates. The rightward shift for wind blades (red plot) indicate that the blades sector is more 'populated', with more organisations publishing in the field.

Intensified research on blades started much earlier (1996), as seen from the plots, and a general search string retrieved sufficient records for bibliometric analysis. Offshore wind support structures, on the other hand, are a newer field and there was need for more specific search terms to define a query with reasonable bibliometric precision. Being so specific could entail missing out on novel concepts we may be unaware of.

4 Conclusions

This report presents a bibliometric analysis of scientific articles issued on blades and on offshore wind support structures. It uses the JRC-developed TIM software for data analysis and visualisation, drawing on text mining and network analysis to count publication activity levels and identify collaboration patterns between entities.

Our bibliometric searches detected increasing densification in the co-publication networks mapped by TIM for blades and on offshore support structures. This indicated that scientific publication activity could be intensifying, and this was confirmed by experts and by literature on wind energy. Both provided evidence of growth in these two research fields, and of intensified collaboration among partners – following the wind-energy industry orientation towards larger blade designs and innovative offshore support structures.

On country level the United States and China are leading in terms of publishing activity, still the entire EU28 outperforms them. The increasing publishing activity, for both blades and offshore support structures, seems to follow the countries' clean energy policies focussing on technology innovation in the onshore and offshore wind sector (e.g. China's 12th Five Year Plan or EC's clean energy directives). Furthermore publication activity in offshore support structures seems to be triggered by a strong deployment of offshore wind in the main European markets.

With respect to country collaboration, the United States shows the highest density of co-publication linkages to other countries. The most distinct collaboration cluster detected from co-publications on blades was found between the United States, China, South Korea and Japan. For offshore support structures, the United States and South Korea form the strongest collaboration cluster, again from their co-publication network mapped by TIM from our bibliometric searches.

TIM also used these searches to map co-publication networks between organisations. A closer look at the leading organisations in blade-research publications unveils that European institutes have been at the forefront over the entire period 1996-2016, with DTU, TU Delft and Aalborg University among the Top 5. The National Laboratories NREL and Sandia complete the Top 5 positions. These leading organisations mainly publish scientific documents on blade aerodynamic effects, followed by new solutions in O&M and load impacts on blades. Especially DTU and NREL show significant strength in the area of aerodynamics. They build on their long-lasting experience in this field, incentivised through industrial research cooperation, national and EU research funding. Moreover, both institutions made significant investments in test facilities or seek cooperation with other research facilities to test blades.

For the leading European organisations on blade research, our TIM searches detected co-publication networks with institutes across the world. For the leading US organisations (NREL and Sandia), on the other hand, the co-publication networks suggest a tendency to form collaboration clusters with partners inside the United States rather than with organisations outside the US.

DTU is seen to maintain its leadership position in the most recent publication activity on blades. However, the increasing research-publication activity in China has resulted in some Chinese research institutions ranking among the top organisations.

Regarding publication activity in offshore wind support structures (1996-2016), European organisations were even stronger represented than in blade-related research (NTNU, DTU, Aalborg University and TU Delft), with NREL being the only US organisation within the Top 5. For European institutions, TIM detected strong publication activity on grounded support structures and floating devices, whereas for NREL most publications were found on floating support structures. All of these leading organisations share a strong industrial research environment. As an example, the Norwegian energy utility Equinor (formerly Statoil) encourages research by European research institutes, and also builds on NREL's capabilities in floating offshore in order to develop software tools for Equinor's 30 MW Hywind floating concept.

Like in the case of blades, European organisations form dense co-publication networks with national and international partners. Moreover these networks include industrial players such as Ørsted aiming to achieve significant progress in further cost reductions in foundations.

NTNU has been keeping its leading position. More recently, however, new players such as Universidade de Lisboa and the Chinese Shanghai Jiao Tong University have become increasingly active – especially in floating solutions. In countries such as Portugal, the development of floating concepts (such as the 25 MW Windfloat project) is crucial to develop a domestic offshore wind market given its steep coastline.

The research areas in blades and offshore support structures addressed by the current EU research funding are generally well represented in the results from our bibliometric searches on the leading organisations in publication activity. Still current EU research funding covers a wider range of thematic areas. For example, the Horizon 2020 funding programme addresses also on advanced materials for blades as well as innovative and hybrid concepts and installation and lifting operations for offshore wind support structures.

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List of figures

List of tables

Annexes

Annex 1. Bibliometric mapping using TIM

Search strings

The search string design follows the approach documented in previous work ([6]–[8]).

Table 3 below lists the three categories of search strings defined in this report for: scope delineation of wind energy technologies (Search Strings Nr 1 to Nr 4); definition of a relevance-proxy (Strings Nr 5 and Nr 6) and; trend analysis of specific wind energy technologies (Strings from Nr 7 onwards).

Table 3. Search strings used in this report, with publication counts as of November 2017.

Nr	Search string texts	**Counts:** articles & proceedings
1.	ti_abs_key:(("wind power" OR "wind energy")) NOT class: patent NOT class: euproject AND emm_year:[1996 TO 2016]	40136
2.	ti_abs_key:(("wind power" OR "wind energy" OR "wind turbine")) NOT class: patent NOT class: euproject AND emm_year:[1996 TO 2016]	63951
3.	ti_abs_key:(("wind power" OR "wind energy" OR "wind turbine" OR "wind energy converter" OR "wind farm" OR "wind park")) NOT class: patent NOT class: euproject AND emm_year:[1996 TO 2016]	68073
4.	ti_abs_key:("wind power" OR "wind energy" OR "wind turbine" OR "wind energy converter" OR "wind farm" OR "wind park") **NOT** ti_abs_key:("wind-powered sporting" OR "natural ventilation" OR "ionospheric effect" OR "ionospheric flow" OR "ocean circulation" OR "lake circulation" OR "wind forcing in the ocean boundary layer" OR "breaking surface waves" OR "stratified lake" OR "stratified water" OR "ocean mixed layer" OR "sediment transport" OR "soil erosion" OR "wind erosion" OR "sand mass flux" OR "space weather" OR "planetary atmospheric waves" OR supernova OR "molecular cloud" OR "magnetosphere" OR magnetopause OR "solar wind" OR "star formation" OR planetary OR galaxy OR interstellar OR mars OR "cable-supported bridge" OR "canopy conductance" OR "cod recruitment" OR "nest ventilation" OR phytoplankton OR "artificial aeration" OR eutrophic OR "infiltration and ventilation") NOT class: patent NOT class: euproject AND emm_year:[1996 TO 2016]	66791
5.	ti_abs_key:(("wind power" OR "wind-energy")) AND class:article AND emm_year:[1996 TO 2017]	20882 (articles only)
6.	ti_abs_key:("wind power" OR "wind energy") **AND** ti_abs_key:("wind-powered sporting" OR "natural ventilation" OR "ionospheric effect" OR "ionospheric flow" OR "ocean circulation" OR "lake circulation" OR "wind forcing in the ocean boundary layer" OR "breaking surface waves" OR "stratified lake" OR "stratified water" OR "ocean mixed layer" OR "sediment transport" OR "soil erosion" OR "wind erosion" OR "sand mass flux" OR "space weather" OR "planetary atmospheric waves" OR supernova OR "molecular cloud" OR "magnetosphere" OR magnetopause OR "solar wind" OR "star formation" OR planetary OR galaxy OR interstellar OR mars OR "cable-supported bridge" OR "canopy conductance" OR "cod recruitment" OR "nest ventilation" OR phytoplankton OR "artificial aeration" OR eutrophic OR "infiltration and ventilation") AND class:article AND emm_year:[1996 TO 2017]	630 (articles only)
7.	ti_abs_key: (("support structure" OR "floating" OR "monopile" OR "suction bucket" OR "mono bucket" OR "jacket structure" OR "tripod" OR "spar buoy" OR "semi-submersible" OR "tension leg platform") AND "offshore wind") NOT class: patent NOT class: euproject	1876
8.	ti_abs_key: (("support structure" OR "floating" OR "monopile" OR "suction bucket" OR "mono bucket" OR "jacket structure" OR "tripod" OR "spar buoy" OR "semi-submersible" OR "tension leg platform") AND "offshore wind") NOT class: patent NOT class: euproject *AND emm_year:[1996 TO 2015]*	1436

9.	ti_abs_key: ("blades" AND "wind turbine") NOT class: patent NOT class: euproject *AND emm_year:[1996 TO 2015]*	7472
10.	ti_abs_key: ("blades" AND "wind turbine") NOT class: patent NOT class: euproject	9109

Delineation of 'wind energy technologies'

In view of delineating the field of wind energy technologies, we ran searches using various keyword combinations. The most basic 'wind energy OR wind power' (Search String Nr 1) yielded about 40 000 scientific articles and proceedings over 20 years. By adding 'OR wind turbine' in String Nr 2, we raised this count by more than 50 % to almost 64 000. Further inserting 'OR wind energy converter OR wind farm OR wind park' in String Nr 3 further increased the count by less than 10 %, to about 68 000 articles and proceedings. String Nr 4 somewhat reduces this count by incorporating exclusion criteria as discussed below in the subchapter 'Relevance of the search results'.

In-depth analysis and enhancement of information from TIM

TIM uses text mining and network analysis to count publication activity levels and identify collaboration patterns between entities. Based on the search string design and the overall aim of the search, additional processing steps inside and outside the TIM tool might be needed. Figure 26 shows process steps for the searches performed in this study, highlighting the processes performed inside and outside the TIM tool.

As our work puts an emphasis on the main players and the identification of the subtopics of the respective research fields, two more advanced functionalities of the TIM tool were applied to the bibliometric analysis.

Many authors provide information on their affiliation at a rather granular level (for example departments, institutes, units and so on). At a more aggregate level, this could entail difficulties in attributing bibliometric counts from subsidiaries to their respective parent organisations. TIM provides an advanced user feature to address this:

- Transformation functionality. The first screening of the organisations from a TIM search showed that a grouping of some organisations is needed to sufficiently cover the top players. As an example, the search on blades resulted in 18 different publishing organisations all belonging to the Technical University of Denmark (DTU). The transformation functionality is used to merge them to one single entry in TIM (see Annex 2 for all merged organisations).

Much of the tabular and visual output provided by TIM focuses on a given part of the dataset (for example keywords, countries, organisations). The connection between these different outputs is normally made ex-post at the analysis stage. TIM has another advanced user functionality which allows to directly exporting a more comprehensive overview (for example, which organisations or countries specialise in more detailed subtopics).

- RSS-functionality: The RSS functionality in TIM can be used to generate more comprehensive tabular overviews (for example affiliations with addresses, author keywords, abstracts, etc.). These can help an analyst identify patterns such as which leading organisations, countries or groups of researchers work on similar research topics or subtopics.

Most notably depending on the total size of the dataset resulting from a search, reasonable effort has to be put into post-processing steps performed outside the TIM tool, such as: screening and grouping of organisations, screening and classification of bibliometric information, analysis of publication abstracts to detect emerging patterns.

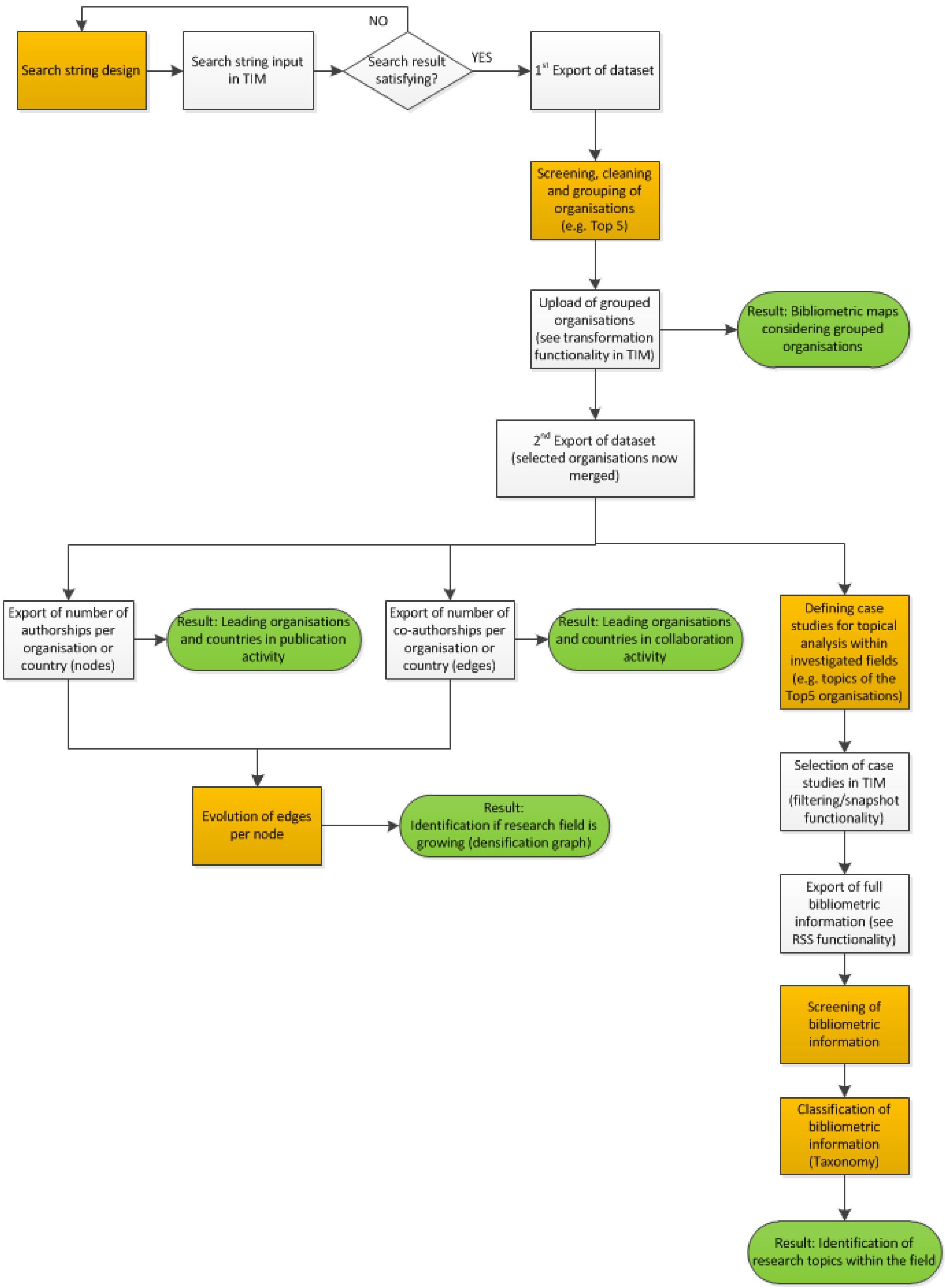

Figure 26. Pre- and post-processing steps from a TIM user perspective.
Note: Process steps performed outside TIM (orange boxes)

Relevance of the search results

Experts have acknowledged that, while "bibliometric analyses generally require specific retrieval", "*the borderline between relevant and not relevant documents is fuzzy* and often determined by users or actors in the domain in question. Sometimes this borderline has to be adjusted according to the actual tasks." [57]

Bibliometricians have developed metrics to measure search performance, such as 'recall' (fraction of the relevant documents in the collection returned by a [search] system, aiming at maximal retrieval of relevant records), 'precision' (fraction of the returned results that are relevant to the information need, aiming at minimal retrieval of irrelevant records) [58], as well as more aggregated bibliometric error measures [59].

For the purposes of this report, we started with very general searches (Strings Nr 1 to 4 in Table 3) to broadly gauge evolution of publication activity in the wind energy sector. Keyword maps and preliminary examination of the underlying datasets indicated that some of the retrieved documents are less relevant to the scope of this work, being related e.g. to planetary science, soil erosion and other topics listed in the right part of String Nr 4 in Table 3. The exclusion criteria in String Nr 4 are not comprehensive, since we did not include every possible exclusion term (in view of bibliometric recall and of keeping the search string within manageable length), and we concentrated the preliminary review on the ca. 400 out of ca. 600 records retrieved for the first three years (1996 to 1998) of a search focusing on scientific articles only (search string Nr 5). We focused on the initial years assuming the share of 'exclusion terms' amid retrieved records would be higher during the earlier stages of wind energy technology development.

For the sake of practicality, we took as a straightforward 'relevance proxy' the ratio

$$RelevanceProxy_{Year\,Y} = \frac{ArticleCounts_{String6,YearY}}{ArticleCounts_{String5,YearY}} \times 100 \qquad (1)$$

The plot in Figure 27 below shows continued increase in yearly article counts (from String Nr 5 in Table 3, shown as yellow diamond marks), with 'relevance proxies' (from Equation 1 above, red square marks) above 97 % in the last ten years 2006-2016, but somewhat lower and less stable in the preceding decade 1996-2005. This can be attributed to the much more modest increase in counts of less relevant articles (captured by the exclusion criteria in search string Nr 6) relative to those more directly relevant to wind energy as a sector of economic and technological activity.

The publication and 'relevance' patterns derived from Search Strings Nr 5 and 6 seem to reflect a more emerging wind energy industry in the first decade, which subsequently grew and matured in the following ten years.

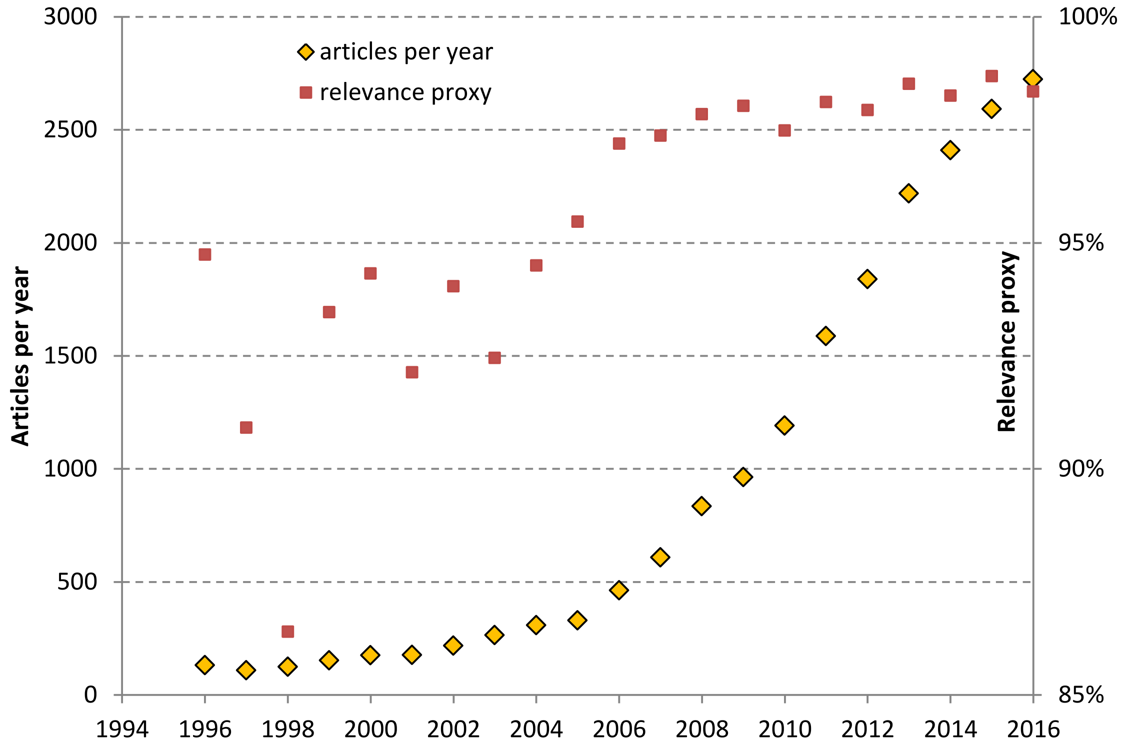

Figure 27. Counts of 'wind energy' or 'wind power' scientific articles (no proceedings), 1996-2016, with 'relevance proxy' plots on the right axis.
Source: JRC based on TIM

Network densification calculation

The combination of the statistical analysis of publications (bibliometrics) [60] and network analysis allows monitoring technological developments [56] and can be used for the identification of emerging topics [6][61][62].

To gain insight into growth patterns of the technologies investigated, we used TIM to plot their network densification patterns, defined by Bettencourt et al. (2009) as a correlation between edges and nodes following a simple power law:

$$y = kx^{\alpha} \qquad (2)$$

where y is the number of edges counted (by TIM) , x the number of nodes counted and k and α are constants. The exponent α describes the densification of a scientific field. Topics that show high densification exponents (α>1) grow and tend to have shared fields of collaboration and exchange, whereas fields without a solid proof of concept show lower values (α~1) [56].

Annex 2. Institutions merged in TIM to their respective parent organisation

DTU includes the following entities, which were grouped after retrieval from TIM:

Department of Mechanical Engineering, Technical University of Denmark
Department of Wind Energy, Technical University of Denmark
DTU Wind Energy
DTU-Technical University of Denmark
Technical University of Denmark
Technical University of Denmark-DTU
Technical University of Denmark, Department of Wind Energy
DTU Wind Energy, Technical University of Denmark
DTU Risø Campus
Risø Campus
Denmark Technical University
DTU Informatics
DTU Compute
Department of Applied Mathematics and Computer Science, Technical University of Denmark
Department of Chemical and Biochemical Engineering, Technical University of Denmark
Risø Natl. Lab., DK-4000
Technical University of Denmark, Department of Mechanical Engineering
Technical University of Denmark, DTU Compute
Department of Wind Energy, Technical University of Denmark, Risø Campus
Risø DTU

NREL includes the following entities, which were grouped after retrieval from TIM:

National Renewable Energy Laboratory
NREL's National Wind Technology Center

Sandia National Laboratories includes the following entities, which were grouped after retrieval from TIM:

Sandia National Laboratories
SANDIA CORP

Delft University of Technology includes the following entities, which were grouped after retrieval from TIM:

Delft Center for Systems and Control, Delft University of Technology
Delft University of Technology
Technical University of Delft
TU Delft
Faculty of Aerospace Engineering, Delft University of Technology
TUDelft
Delft University
Delft University of Technology Delft
Delft Center for Systems and Control
Faculty of Mechanical, Maritime and Materials Engineering, Delft University of Technology
TECHNISCHE UNIVERSITEIT DELFT
Department of Hydraulic Engineering, Delft University of Technology

Aalborg University includes the following entities, which were grouped after retrieval from TIM:

Aalborg University
Department of Civil Engineering, Aalborg University
Department of Mechanical and Manufacturing Engineering, Aalborg University
Department of Energy Technology, Aalborg University
Department of Electronic Systems, Aalborg University
University of Aalborg
AALBORG UNIVERSITET

Norwegian University of Science and Technology includes the following entities, which were grouped after retrieval from TIM:

Centre for Ships and Ocean Structures, Norwegian University of Science and Technology
Department of Civil and Transport Engineering, Norwegian University of Science and Technology
Department of Marine Technology, Norwegian University of Science and Technology
Norwegian Institute for Science and Technology
Norwegian University of Science and Technology
Norwegian University of Science and Technology, Department of Civil and Transport Engineering
Norwegian University of Technology and Science
NTNU-Norwegian University of Science and Technology

Universidade de Lisboa includes the following entities, which were grouped after retrieval from TIM:

Instituto Superior Técnico, Universidade de Lisboa
Universidade de Lisboa

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