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The production of scientific knowledge on renewable energies: Worldwide trends, dynamics and challenges and implications for management

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ABSTRACT

The present study investigates renewable energy analyzing the last twenty years of worldwide scientific production and the dynamics of interest around relevant policies in this direction. Based on a review on the role of knowledge development in technology transitions, we coupled bibliometric and expert debate approaches to provide decision makers with a sound analysis of thematic and regional trends in the field. Results show that the level of activity of researchers in the field of solar energy is somewhat contrasted only by biomass and wind energy. Despite countries being embedded in a global virtual network, geographical differences still arise: while North America and Europe show isomorphism of national communities and a high diversification of vertical foci, emerging research communities (e.g. BRICS countries) reflect market strategies (e.g. China) and the natural environment (e.g. Brazil) with a higher directionality of researches.

Our findings provide an overall picture on world-wide development of competences as a relevant variable which policy makers should ideally consider in detail when setting integrated research, industrial and energy policies and strategies.

1. Introduction

Technological trends in the field of renewable energy sources (RESs) have been object of interest of analysts ever since the early discussions on sustainable development [1]. Among all drivers, scientific production (i.e. manuscripts published in peer reviewed scientific journals) is the most prominent on driving technology transitions. Indeed, scientific production informs those policies that are subject to an increasing integration between R&D and technology transitions at national level and that are determined by the energy, environmental and socio-economic dimensions [2,3]. Knowledge development in the field of RESs is also a key aspect in sustainability transition studies [4], a growing field of research that includes transition management [5–7], strategic niche management [8–10], multi-level perspective on sociotechnical transitions [11–13], and technological innovation systems [14–16]. Researches from all these theoretical perspectives could benefit from comprehensive bibliometric analyses of sectorial scientific outputs.

Although bibliometric maps and expert knowledge present some limitations, bibliometric maps can support experts in improving their knowledge of a certain domain [17,18]. Bibliometrics, the set of methods to quantitatively analyze scientific and technology literature, provide researchers (as well as public and private decision makers) measurements that can help (i) understand complex dynamics including, for example, the needs for balancing demand pull measures and direct public support towards challenging energy targets [19], (ii) forecast the productivity of national investments [20] and (iii) take strategic decisions for strengthening national innovation systems [21]. In that, a worldwide perspective can help capture changes occurring over time in the setting of knowledge generation and knowledge sharing and which influence the selection environments of technological trajectories [22].

Unfortunately, despite their relevance, scientific productions in the field of RESs are hardly ever analyzed longitudinally as a whole [23,24]. Manzano-Agugliaro et al. [25] made a first attempt to tackle the issue through a literature review, thus favouring logical connections over the comprehensiveness of the representation.

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Conversely, Romo-Fernandez et al. [23] made a first co-word thematic analysis based exclusively on papers published in the journal *Renewable Energy*, whereas Celiktas et al. [24] adopted a country-specific approach. Our study aims to contribute to the literature by presenting a more comprehensive approach. Our paper is organized as follows: first, the "Background" section presents a literature review and the rationale and research questions for analyzing the field of RESs by means of bibliometric maps; the "Methodology" section provides details on how the data was obtained and processed; the final sections provide research results, discussion and conclusions, highlighting the contribution of our findings to current literature.

2. Background

Researches in the field of RESs are often perceived as strongly influenced by uncertainties in public R&D portfolios [26]. Research and industrial pressure on these portfolios may cause different expectations and constraints, especially in relation to incumbent technologies [27] that may have a recursive nature [28], i.e. the tendency to evolve through alternate phases of selection and of corroboration by use. As a result, the selection of technology pathways consists in a combination of individual and collective acts that are strongly interconnected with the creation and diffusion of 'new' knowledge and the formation of technology-specific advocacy coalitions. Even though, since the 1990s, such clusters and networks have started coupling research outcomes with the double-digit growth rate in the RESs market [15], it has been found that selection mechanisms which are associated to sustainability challenges are generally aggravated by strong path-dependencies and lock-ins [4,29]. From this perspective, along with the major role of co-evolution of long-lived infrastructures and technological clusters brought by "network-effects" [30], environmental and socio-economic issues have generated new and particularly relevant selection pressures. This fact has led, for example, to novel energy end-use applications that imply step-changes in improved energy efficiency, coupled with further electrification and the progressive use of hydrogen (e.g. in transportation, it has become one of the dominant directions for facing the climate challenge) [26]. In such context, a useful key for interpretation when dealing with relations between scientific progress and technological transitions (whatever model is to be evaluated) can be found in the study of dynamics in the generation of scientific knowledge. Therefore, the first research question targeted in this study is:

RQ1: *according to the evolution of world-wide environmental and socio-economic priorities, which domains of RESs show the highest generation of scientific knowledge?*

In many cases, diffusion of clean technology is governed by endogenous mechanisms (epidemic learning and learning economies) and by exogenous mechanisms [31] that co-evolve with local energy supply and, most of all, with energy demand systems [26]. Indeed, policies and policy jurisdictions can have a critical influence on the trajectory of technological regimes.

On the one hand, the basic thesis on the innovation gains from regional knowledge spill-overs is relatively easy to find in exemplar renewable energy regions where horizontal cross-fertilization opportunities have shown to be relatively costless and easily turned into international knowledge portals [32]. At a local level, a related variety of industries can speed up lateral absorptive capacity between neighbouring sectors and stimulate innovation cross-fertilization via knowledge spill-overs [33,34]. Similarly, shared infrastructures can deepen synergies of compatible technologies [30]. On the other hand, such local "forces" are not immune from generating trade-offs in knowledge development dynamics. In fact, while a knowledge-based economy develops as a dynamic system at the global level – thus transcending national or geographical boundaries – national and regional systems of innovation may tend to retain wealth from knowledge at local level [22]. Furthermore, models of induced innovation often describe technological change as a cumulative process that leads to the phenomenon of path dependency [35] that could be emphasized at local level. As an example, lack of coordination in national trajectories in Europe had recently raised the need for a comprehensive and articulated approach to link inter-national research, innovation and deployment which then led to the adoption of the Strategic Energy Technology Plan (SET-Plan) in 2007 [36]. Here, strategic objectives have been formulated based on technology roadmaps that identify priority actions for the forthcoming decade (2010–2020). These actions are linked to more specific three-year-period implementation plans (i.e. 2010–2012 for the first edition) [19]. From a theoretical perspective, research development and demonstration (RD&D) policies in the energy sector should have a very long-term perspective and a balanced presence of competing R&D pathways [27], be continuous and persistent, stimulating creativity of research [15], and tolerant to failures by having "many eggs in the basket" [26]. However, the stability of policy measures varies in time and space with local attitudes. As an example, learning from the past, RD&D programmes emerged as significant contributors both to improved cost and performance [30] and to late adopters who can profit from important learning externalities [26]. In some cases, the complex set of impact of RD&D funding have characterized national technology scenarios, like in Japan in the field of GHG-mitigating technologies [37]. In other cases, un-alignment has prevailed and fossil energy subsidies have practically only left spill-over opportunities for post-fossil energy supply technologies [38]. The fact that in many countries RD&D in renewables is much more dependent than RD&D in fossil fuels on the levels of private sector involvement [36] and of market penetration [39] further supports its geographical relatedness with natural and socio-economic resources.

Worldwide trends in scientific production can help understand these complex relations. Scientific publications are an important component of field-specific knowledge. Bibliometric studies can thus be very useful in understanding the relationship between the functional and socio-technical spaces of niche, regime and landscape processes of sustainability transitions and other dimensions of space, such as territory, administration and communication (and their particular topologies) [13]. The second research question targeted in this study is therefore:

RQ2: *are there national peculiarities in the field of RESs knowledge generation? Additionally, can a systematic analysis of these peculiarities draw directions of future theoretical and empirical studies in the field?*

Innovations in the field of RESs not only compete towards incumbent technologies in search for an improved energy productivity [40], but also compete between each other. New technological systems are faced with having to overcome a multitude of forces which favour an "incumbent energy system" and have to set in motion a process of cumulative causation which works in favour of the new technology [15]. A systematic analysis on RESs research can shed some light on where new knowledge is pushing technology frontiers and, in a broader sense, how social constructivism applies to sectorial research communities [41]. This, in turn, can be useful in interpreting the impact of a variety of pressures on knowledge development. From this perspective, specific directions are often determined by the capability of demonstration projects and trials to capture and spread learning for the public good, to catalyze and strengthen national industry and develop national markets [42,39]. More generally, under the multi-level perspective of socio-technical transitions, knowledge development is to some extent influenced by the integration between demand-side dynamics and issue-centred policy areas [43]. As an example, the fact that policies inspired by prevailing innovation systems approaches mainly aim at optimizing the institutional environment of firm-based innovation processes and not at transforming whole systems of production and consumption [44] supports the potential presence of directionality failures, i.e. of un-alignments between directional pressures on research and more targeted impulses towards defined corridors of acceptable development paths [45,46]. In that, knowledge development seems to be influenced also by energy service demand changes, which are frequently referred to as a pulling factor for drastic change in energy supply [38], especially in case of ready to "go big" solutions [26]. Consequently, energy end-use technologies are expected to attract more research efforts than energy supply technologies. The shape of scientific production clusters can help understanding these complex relations. Thus, the third research question targeted in this study is:

RQ3: *Are there dominant exogenous pressures on knowledge development? In particular, are there dominant clusters in knowledge generation within each RES domain?*

Besides informing the above mentioned theoretical framework, these RQs can help informing also more specific studies on technological forecasting [47,48] and science and technology roadmapping [49,50].

Being aware that a systematic analysis of the scientific production in the last two decades in the field of RESs is just at its beginning stage, the sections that follow present a first contribution to answer the above RQs through a comprehensive bibliometric analysis approach.

3. Methodology

Given the overwhelming flood of information, understanding the overall structure of research is becoming more and more difficult [51]. Therefore, in order to answer the RQs above, we adopted a computer-aided bibliometric approach that consists of the following two steps:

I. Publication delineation of the field of RESs;
II. Term map construction.

In step I, we identified publications in the field of RESs. Publication data was taken from the Web of Science (WoS) bibliographic database. The period considered for analysis was 1992–2011. Publications were considered only if they were of the Web of Science document type article or review and if they were written in English. Step I consisted of three substeps. In the first substep, we selected all publications in the 14 journals listed in Table 1. The total number of publications in these journals was 19,782. In the second substep, publications were selected based on keywords occurring in their title and abstract. Table 2 lists the keywords we used. Each keyword was given a score as shown in parentheses in the table. Publications were selected only if the cumulative score of all keywords occurring in the title and abstract of the publication was at least 5. The first choice of the keywords and the corresponding scores was made and validated based on expert knowledge (2 researchers from the industry, 4 from university). After testing many different keywords and scores, the keywords and scores listed in Table 2 were found to provide a reasonably accurate delineation of the field of RESs (i.e. direct analyses on samples from the publication delineation served the scope to verify its soundness). As shown in Table 2 a few keywords also had negative scores: the presence of such keywords in the title or abstract of a publication made it more difficult for the publication to be included in the selection. The keyword-based approach in the second substep yielded 18,419 publications in addition to the 19,782 publications identified in the first substep. In the third substep, we searched for additional publications in the Web of Science database that had not been selected in the first two substeps, but that do have strong citation links (i.e. number of direct citations) with the publications selected in these two substeps. The 9016 most strongly linked publications were added to the selection. In this way, we obtained an overall selection of 19,782 + 18,419 + 9016 = 47,217 publications.

Table 1
List of journals used in the delineation of the field of RESs. Journals are organized per domain within the field of RESs.

Domain	Journals
All RESs	Renewable & sustainable energy reviews
	Iet renewable power generation
	Journal of renewable and sustainable energy
	Renewable energy
Biomass	Global change biology bioenergy
	Biofuels bioproducts & biorefining-biofpr
	Bioenergy research
	Biomass & bioenergy
Geothermal	Geothermics
Solar	Journal of solar energy engineering-transactions of the asme
	Progress in photovoltaics
	Solar energy materials and solar cells
	Solar energy
Wind	Wind energy

During the selection of publications in step I, we distinguished between five domains: biomass, geothermal, hydro, solar, and wind. As can be seen in Tables 1 and 2, most journals and keywords that we used relate specifically to one of these domains. Accordingly, most of the publications selected in step I could be assigned to one or more domains. The number of publications per domain is reported in Table 3. It is noteworthy to point out that some publications were included in our selection because they were published in a general journal in the field of RESs or because they contained general RESs related terms. Such publications did not belong to any of the five domains.

Based on the publications selected in steps I and II, we constructed a number of term maps using the VOSviewer software developed by Van Eck and Waltman [52,53] (freely available at www.vosviewer.com), and in particular the VOS mapping and clustering techniques [54,55] and the automatic term identification technique [53,56] implemented in this software. The idea underlying a term map is to provide a visual representation of a field of science by showing the most important terms occurring in the titles and abstracts of publications. Terms are identified by scanning the titles and abstracts of publications using natural language processing techniques. The most relevant terms are selected for inclusion in a term map by means of a term selection algorithm available in VOSviewer. General terms (e.g. 'conclusion', 'method', and 'result') and terms occurring in only a small number of publications are not included in a term map. Using the VOS mapping technique, terms that often co-occur within the same publications are located close to each other in a term map, while terms that have no or almost no co-occurrences are located further away from each other. In this way, the grouping of terms in a term map provides an indication of the main topics in a field. The larger the number of publications in which a term occurs, the more prominent the term is displayed in a term map. Frequently occurring terms are for instance indicated using a larger font size. For a detailed examination of a term map, it is best to use the VOSviewer software. This software offers extensive support to interactively explore a term map. All term maps presented in this paper can be examined online using the VOSviewer software.

Further details were gathered using so-called overlay visualizations. In an overlay visualization, the terms in a term map are

Table 2
List of keywords used in the delineation of the field of RESs. The score of each keywords is reported within parentheses. Keywords are organized per domain within the field of RESs.

Domain	Keywords (score)
All RESs	"renewable Energ*" (2), "sustainable energ*" (2), "*power conver*" (1), "*power generat*" (1), "*power plant*" (1), "*power system*" (1), "alternative energ*" (1), "electricity generat*" (1), "electricity system*" (1), "energy conver*" (1), "energy generat*" (1), "energy system*" (1), "renewable*" (1), "sustainab*" (1)
Biomass	"bioenergy" (3), "alternative fuel*" (2), "anaerobic digestion" and "energ*" (2), "biodiesel*" (2), "biofuel*" (2), "biogas*" (2), "biomass combustion" (2), "biomass gasification" (2), "biomass power" (2), "biomass production" (2), "biomass pyrolysis" (2), "biomass" and "energ*" (2), "biochar*" (1), "bioethanol" (1), "biomass energ*" (1), "biomass fuel*" (1), "biomass to energy" (1), "energy from biomass" (1), "palm oil" (1), "soybean oil" (1)
Geothermal	"geotherm*" and "energ*" (4), "thermal water" (1)
Hydro	"hydro turbine*" (3), "hydro electric*" or "hydroelectric*" (2), "hydro energ*" (2), "hydro generat*" or "hydrogenerat*" (2), "hydro power" or "hydropower" (2), "tidal energ*" (2), "tidal power" (2), "water power" (2), "hydro electric generat*" or "hydroelectric generat*" (1), "hydro" and "energ*" (1), "tidal stream" (1), "tidal" and "energ*" (1), "wave energ*" (1), "wave power" (1), "fish*" (−4), "hz" or "mhz" or "ghz" (−4), "pulse wave*" (−4), "salmon*" (−4), "sine wave*" (−4)
Solar	"photovoltaic generator*" (2), "photovoltaic module*" (2), "photovoltaic system*" (2), "solar air" (2), "solar cell*" or "photovoltaic cell*" (2), "solar collector*" or "photovoltaic collector*" (2), "solar concentrator*" (2), "solar energ*" (2), "solar panel*" or "photovoltaic panel*" (2), "solar power" (2), "solar thermal" (2), "photovoltaic*" (1), "solar thermal collector*" (1), "solar" and "energ*" (1),
Wind	"wind farm*" (3), "wind park*" (3), "wind turbine*" (3), "wind energ*" (2), "wind generat*" (2), "wind power" (2), "wind turbine generat*" (1), "wind" and "energ*" (1)

coloured to indicate, for instance, the average year in which the publications containing a specific term were published or the proportion of the publications containing a specific term that are from a certain country [53]. Overlay visualizations make it possible to show time trends or to display how the scientific activity of a country is focused on specific topics.

4. Results and discussion

4.1. Production trends of scientific knowledge of RESs

Between 1992 and 2011, the scientific production in the field of RESs showed an exponential growth in both absolute and relative terms (Fig. 1), with the median of the publication distribution between 2008 and 2009 for biomass, 2007 and 2008 for wind and hydro, 2006 and 2007 for solar and 2004 and 2005 for geothermal.

While the larger volume of manuscripts persistently referred to solar energy in a context where each RES was increasing yearly productions (Fig. 2), the relative speed of growth was steadily positive only for biomasses and wind (Fig. 3). This seems to overall suggest an increasing push from the research community towards diminishing society's dependence on fossil fuel energy and, in detail, a sharp rise of scientific investments in parallel with the world economic crisis.

Looking at the sectoral productions, the term map based on all RESs manuscripts between 1992 and 2011 (Fig. 4) helps shedding some light on the different determinants of these trends. In the term map, four different colours can be distinguished. Each colour indicates a cluster of related terms. The clusters were produced using the clustering technique available in the VOSviewer software.

Fig. 4 clearly illustrates the presence of four main clusters with a strong polarization between the solar cluster (red (in web version)) and the ones referring to policy (green (in web version)), wind (blue (in web version)) and biomass (yellow (in web version)). For the solar cluster, links with terms that refer to infrastructure and planning, e.g. "grid", "policy", "demand", "economy", "climate change", "market", etc. were less relevant than the ones that suggest the prevalence of chemical and physical fundamental research, e.g. "acid", "catalyst", "atom", etc. Wind and biomass clusters, on the contrary, show a more balanced presence of keywords that are typical in basic and applied research. In particular, biomass entails a sub-cluster on hydrogen energy and some bridging keywords from the chemical and physical. Because of the high number of connections in each direction of the map, biomass emerges as a largely interdisciplinary field where new streams of researches mainly come from a variety of scientific communities in biology, agronomy, process engineering, chemistry and environmental sciences.

Table 3
Number of publications in each of the five domains within the field of RESs.

Domain	No. pubs
Biomass	11,267
Geothermal	1439
Hydro	3192
Solar	26,045
Wind	5926
Total	47,217

In the overlay map (Fig. 5), each term is coloured based on the average publication year of the publications in which the term occurs. The closer the colour of a term is to blue, the older the publications in which the term occurs. Conversely, the closer the colour of a term is to red, the more recent the publications in which the term occurs. The overlay map highlights some areas of declining interest. Among these, silicon solar cells, geothermal and/or solar heating systems for buildings seem to lose more attractiveness than other fields of RESs. The search for higher performances for the earlier and the relative maturity of these technologies for the later seem to offer an explanation for these trends.

4.2. Geographical distribution of RES researches

First evidence from the analysis of geographical distribution of RES researches clearly concerned -in partial contrast with Manzano-Agugliaro et al. [25] the higher growth rates in Europe and East Asia than in North America and, in absolute terms, the higher volumes of production in Europe (Fig. 6). This could to some extent suggest the so-called "European Paradox" [57] to RESs in East Asian countries. However, in order to properly inform long term energy policy making, it is fundamental to thoroughly understand the trends of RES research described below despite they are sometimes perceived as a low priority dimension for boosting markets in the short term [58].

Solar energy presents an interesting boom of researches in Asia after 2008 (Fig. 7). While the European countries still maintain the higher cumulative number of manuscripts, Asia currently achieved the leadership in terms of annual volumes of scientific production. Also, North America has the same trend of BRICS countries (Brazil, Russia, India, China and South Africa, i.e. a non-geographic aggregation of emerging economies) which perhaps is driven by the need to develop a number of technologies that are already available in the developed countries [21]. Such trends would suggest a tail of investments in new human and intellectual capital in emerging countries, although it is understood that further research is required in order to weight quality and potential impacts (for both

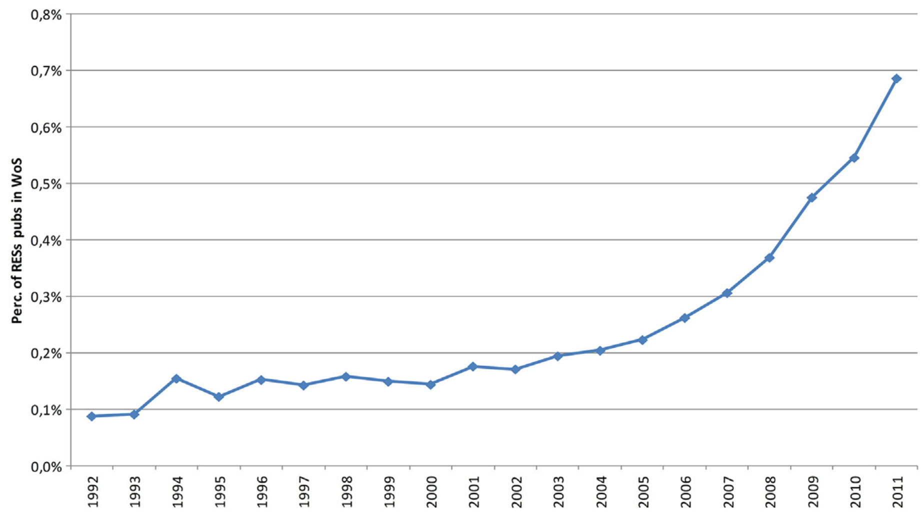

Fig. 1. Percentage of total population of Web of Science manuscripts between 1992 and 2011 that refers to RESs.

industry and academia) from the different scientific contributions. This is even more true if it is considered that our analysis does not include publications in languages other than English, which is in some countries (e.g. in China) not a marginal minority.

Beside China, which has clearly expressed a particularly clear strategic inflection point in 2008 in solar researches, the strategy of overall East Asia (especially, in order, China, South Korea, Taiwan and Japan) to focus on (retail-oriented) solar market is confirmed by the lower ranking in biomass research production (Fig. 8), where the EU-27 countries are largely the major contributors, followed by North America and the BRICS countries, where India and Brazil add a significant number of papers to China's score. Apparently, EU-27 countries have started research investments on biomasses on average two years before the other continents.

The gap between EU-27 countries and other regions is even more increasing in the field of wind energy (Fig. 9), where Asia and North America have started investing more than the than EU-27 did three years later. Here it is possible to notice, given also the lower absolute number of manuscripts, how much national energy policies matter. As an example, the Iranian research community (the major contributor in West Asia) is aligning the need of domestic companies of entering into a market that is in line with US and European efforts to curb Iran's nuclear program.

Similar trends are present also in the field of hydro energy, where the United Kingdom, Spain and Italy are the largest contributors to European leadership (Fig. 10) in a competition where USA and China are the other relevant players and Turkey and India are the new entries. Here, the inflection points are located around 2003 for EU-27, Asia and North America, just after the first economic slowdown in 2001, and show a 2–3 years delay in BRICS, as for the biomass and wind.

Among all the RESs, geothermal energy attracts the minor and less steady volumes of researches (Fig. 11). In this case, beside the leading role of Europe (mainly thanks to Germany, Italy and United Kingdom), USA, Japan and New Zealand have few well-established geothermal research centres, Turkey and Canada are the new entrants.

In sum, EU-27 Countries reflect the European Commission's approach for research and innovation that, beside the non-uniform presence of specific excellences, tends to cover widely and horizontally all the issues that may produce a positive impact for European competitiveness. All the other World regions present

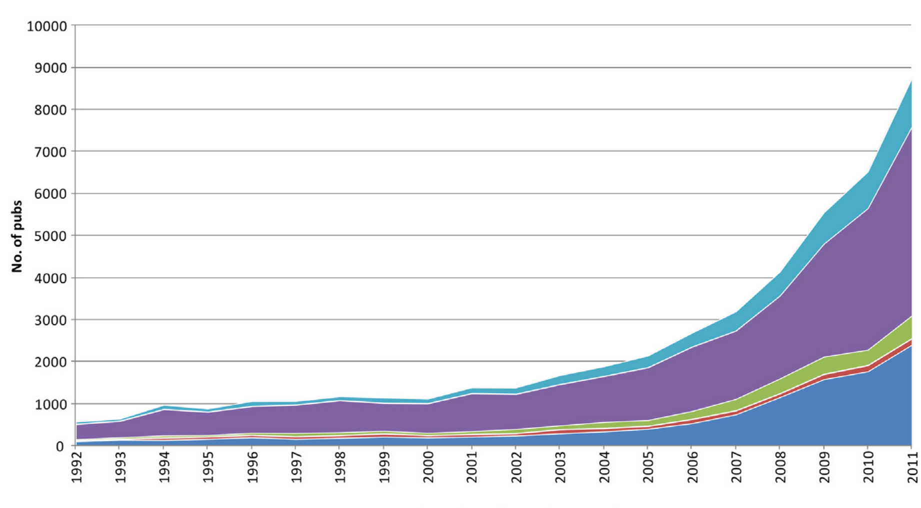

Fig. 2. Number of manuscripts between 1992 and 2011 per RES.

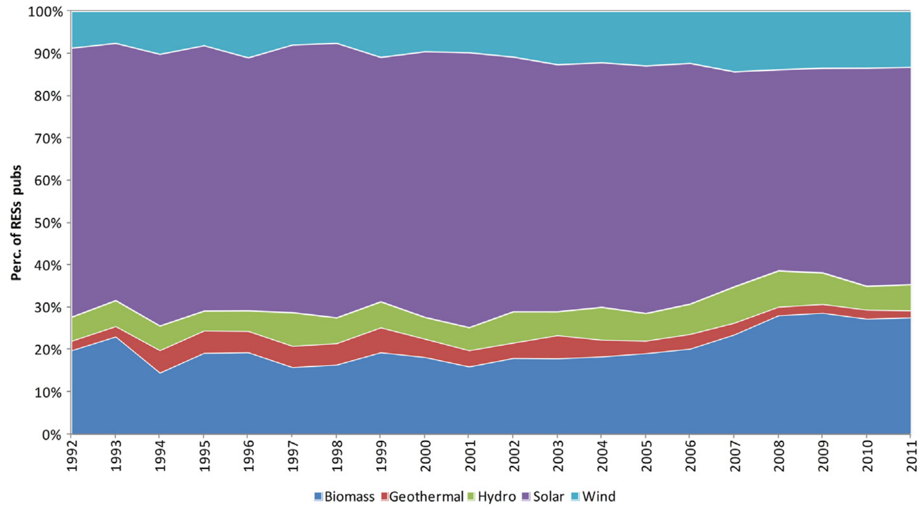

Fig. 3. Percentage of total population of RES manuscripts between 1992 and 2011 that refer to each RES.

strategies oriented to more directional research priorities to address cutting-edge challenges. A straightforward example is given by China's directionality towards solar technologies, that is expected to impact on sectorial structure since solar technologies are marked by complex international consolidation, often in a relatively short time, once breakthrough in markets occurs [39]. In contrast with the increasing gap in scientific production in other RESs domains, such directionality has produced a rapid achievement of USA's annual counts (Fig. 12) that, given the recent news of internationalization processes of domestic companies (e.g. Sunergy Co in Turkey, Hanergy Group in California and Germany, Suntech Power in India, etc.), makes China a potential (and imminent) worldwide leading supplier of both products and competences.

Considering that among the 20 more cited scientific publications on solar topics (14 are from Europe, 5 from USA and 1 from Japan), further research will have to shed light on how research outcomes are capable to move out of the "ivory tower" in both developed and emerging countries [59,60]. What our data demonstrated is that high quality research (i.e. from the perspective of the influence on the scientific community) in developed countries often comes from a limited number of highly specialized centres. Referring to the sample above, 4 manuscripts are authored/co-authored by researchers who work in leading solar companies, 9 (i.e. 4 in Colorado and 5 in Denmark) in leading national laboratories, 4 in a leading university largely funded by the Swedish Energy Agency. Thus, both these and the Chinese experience seem to emphasize that sound and steady dyadic relations between scientific community and industry or national agencies/departments are fundamental for advancing science and transferring knowledge and innovations.

Such dyadic relations seem to co-occur with the persistent presence or the new introduction of national renewable energy research priorities (Table 4) and are often linked to the availability of specific ecosystem and socio-economic services reported in literature; the latter include the funded demonstration projects and field trials that, according to Brown and Hendry [61], helped USA, Japan and Germany in coordinating on-going R&D and in creating competitive solar socio-technical systems. Institutional environment (sometimes combined with international cooperation, like in the case of Iran), intellectual capital and natural resources seem to be the major key drivers of the presence of these dyadic relations.

The experience of the European community provides interesting evidence that these dyadic relations are not necessarily effective only at local or national level, where the selection of leading research centres could take place. In fact, Table 5 clearly shows how the increasing orientation towards bringing together decision-makers from the Member States, industry and research and financial communities at community level –i.e. converging

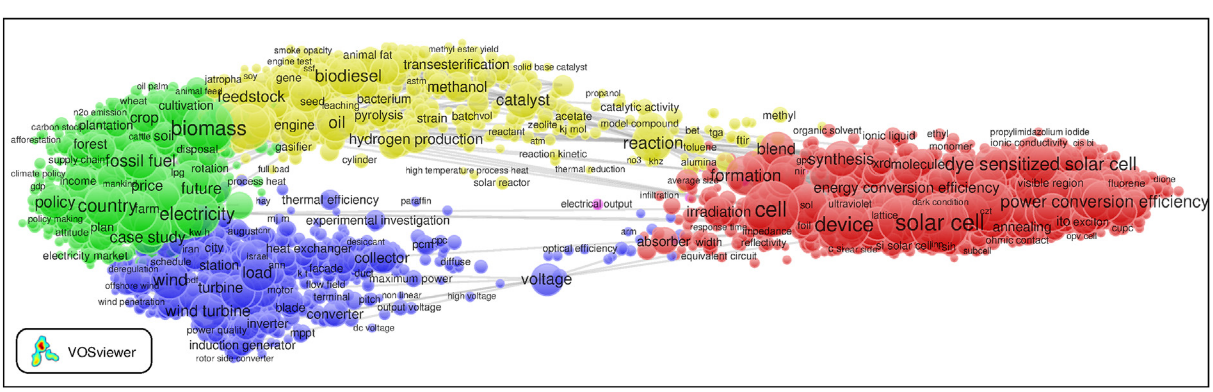

Fig. 4. Term map based on RESs manuscripts from the period 1992–2011. An interactive version of the map is available online at www.neesjanvaneck.nl/renewable_energy/.

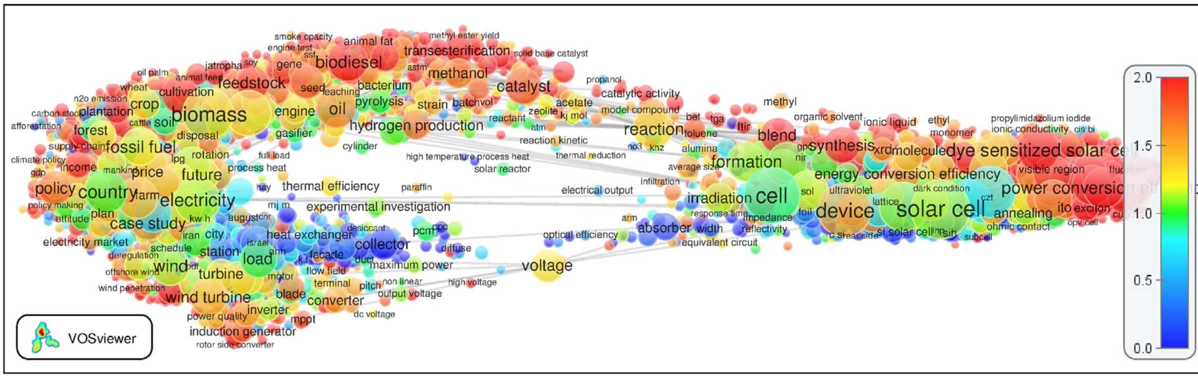

Fig. 5. Overlay map based on RESs manuscripts from the period 1992–2011. The colour of a term indicates the average publication year of the publications in which the term occurs (closer to red is more recent). An interactive version of the map is available online at www.neesjanvaneck.nl/renewable_energy/trend/. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

towards a coordinated and integrated Strategic Energy Technology Plan (SET-Plan) – is capable of reducing difference in national RESs research mix.

With exception of Europe, West Asia (including Turkey, that is the major contributor to the scientific production of West Asia, especially in the field of energy planning and energy potential assessment) and North America, the other world regions present an opposite trend (i.e. focalization on regional-specific energy mix). Only for hydro and geothermal energy the differences in terms of energy mix shares are decreasing in all the regions.

The optimal balance between a useful directionality and a counter-effective isomorphism is a fundamental point in developing a knowledge-based economy and an interesting area for further research.

4.3. New solar trajectories as a playground for fundamental research

Since new scientific knowledge is by definition the result of combining internal (i.e. from a research team) and external (i.e. shared among the research community) contributions, the worldwide evolution of manuscript contents can provide useful information about alternative technology pathways.

Surfing in the term map for solar energy (Fig. 13), it is possible to recognize four highly-polarized clusters that, differently to what happens with the overall scientific production on RESs, do not significantly cover issues like costs, water use, energy efficiency, no environmental problems and social acceptance. In fact, on one side, keywords like “location”, “solar radiation”, “heat”, “battery” suggest the presence of research activities on operation and system integration. These activities have weak links with the three clusters on the other side that are more close to fundamental research. Building on silicon sub-cluster, that is about the oldest and most diffused technology on the market, the green (in web version) area clearly refers to film engineering, with keywords like “band gap”, “heterojunction”, “interface”, “deposition”; the blue (in web version) area refers to photo-electrochemical efficiency of dye-sensitized solar cells, with research streams that vary from a number of sub-clusters on electrolytes and tio2 to more specific sub-clusters on ruthenium, iodide photo-catalytic activity and related different nano-structures for electron transport, in accordance with Kajikawa’s et al. [62] analysis stating that research on electrolytes and modelling is under rapid development. Finally, the yellow (in web version) area refers to polymeric researches on electricity transfer and power conversion efficiency that entails the emerging field of conjugated polymer [63]. Here, research streams cover a large number of organic photovoltaic polymers like pc60bm, pc71bm, polithiophene derivatives and related alternative reactive molecules, ultra-thin films of deposited oligomers, etc. More than in other RESs, this relevant related variety of

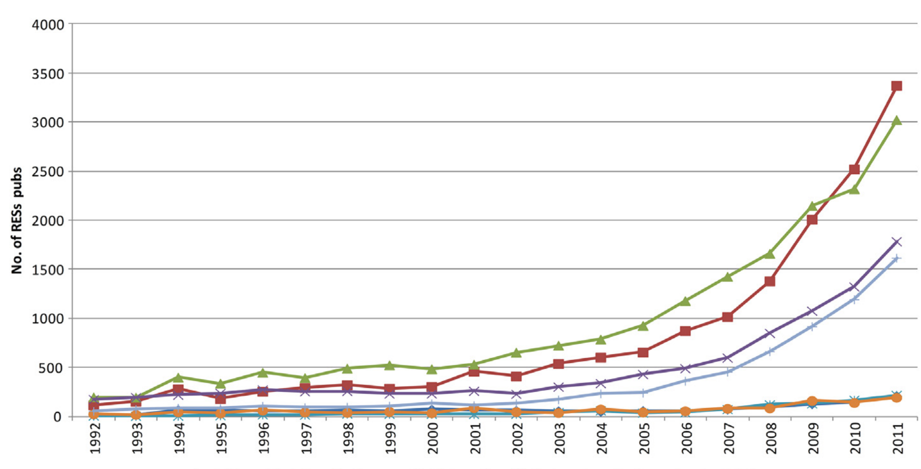

Fig. 6. Geographical publication trends for the field of RESs.

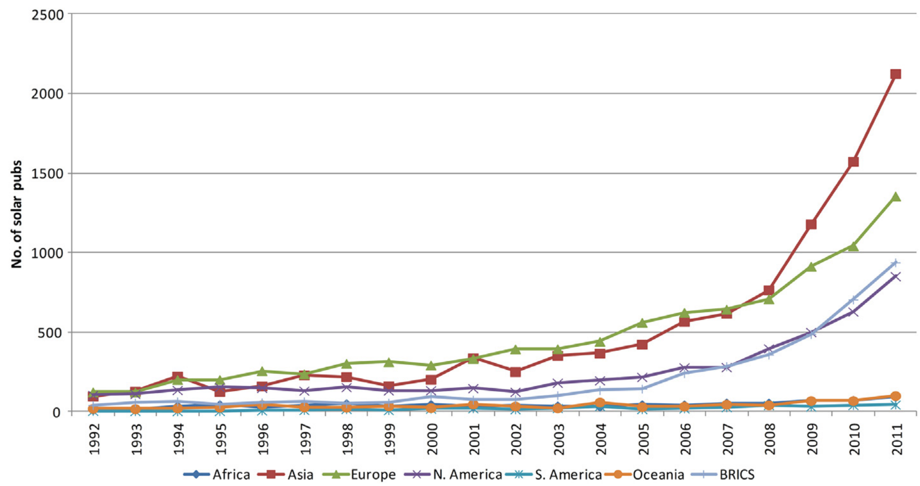

Fig. 7. Geographical publication trends for the field of solar energy.

technological trajectories stresses a certain lack of directionality within the scientific community and, in turn, poses questions about the geographical distribution of the different streams of research. This dimension of knowledge development is even more relevant if we consider, on the one hand, the huge amount of research efforts in the field and, on the other, the fact that an overlay-map similar to the one in Fig. 5 seems to suggest that the diversification of technological frontiers (i.e. the development of new technological trajectories) is attracting more researches than system integration and design issues (i.e. the improvements of current market technologies). Based on our data, what we can argue is that the way research communities interact with policy makers and industries will be soon determinant for boosting the competition for the creation of new market niches, e.g. organic solar films for functionality-improved products.

4.4. Resource efficiency in biomass research

A certain polarization of research clusters is present also in the field of biomass, where four clusters cover energy conversion issues and two other clusters cover policy and planning issues (Fig. 14). The dynamism of studies in energy conversion issues can be considered particularly high because keywords have a low density but have a large number of connections (i.e. are used in a high variety of contexts). In detail, the cyan (in web version) cluster concerns the assessment of a number of biodiesel alternatives to fossil oil, with particular attention to the comparison of engine performances and environmental impacts. The pink (in web version) cluster, which refers to catalysts and reactions for biofuel production, is characterized by the presence of a certain number of alternatives in biodiesel trans-esterification processes and in the production different sets of fuels. The later field is highly linked with the yellow (in web version) cluster, which is about the development of different pyrolysis and gasification techniques, an alternative that seem more investigated than the blue (in web version) cluster on anaerobic digestion and fermentation processes (of sludge, waste, etc.). In sum, even though it is clear that the interest in biofuels is increasingly prevailing over other gaseous and solid derivatives (thus confirming the analysis from Kajikawa et al. [62]), there is a high dispersion of efforts among a large variety of technological alternatives. This is in line with some industrial diversification strategies (e.g. the biofuels from algae are being heavily invested in by US and Chinese producers) [32].

From the side of policy and planning issues, a high concentration of studies characterizes both the green (in web version) cluster concerning rotation and harvesting techniques for biomass

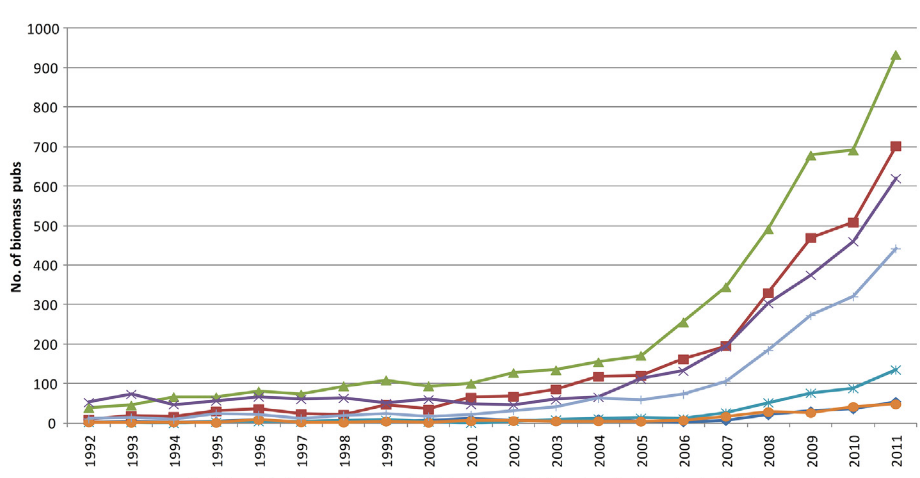

Fig. 8. Geographical publication trends for the field of biomass energy.

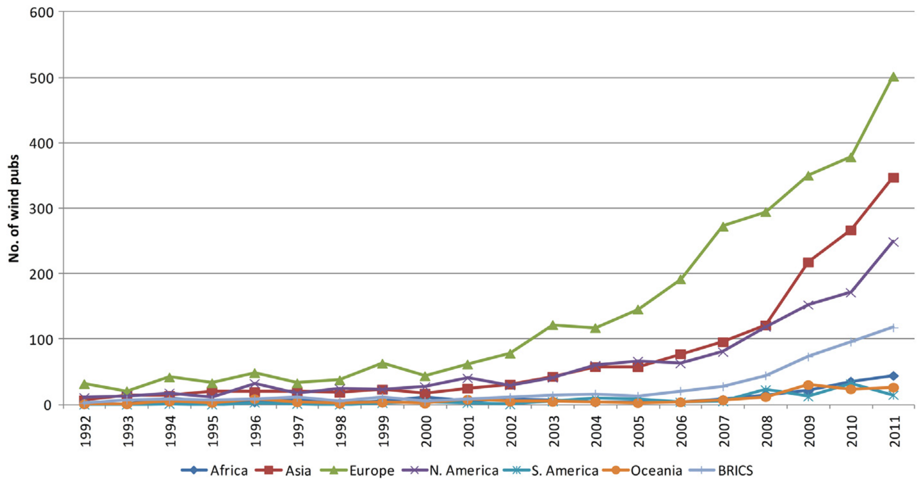

Fig. 9. Geographical publication trends for the field of wind energy.

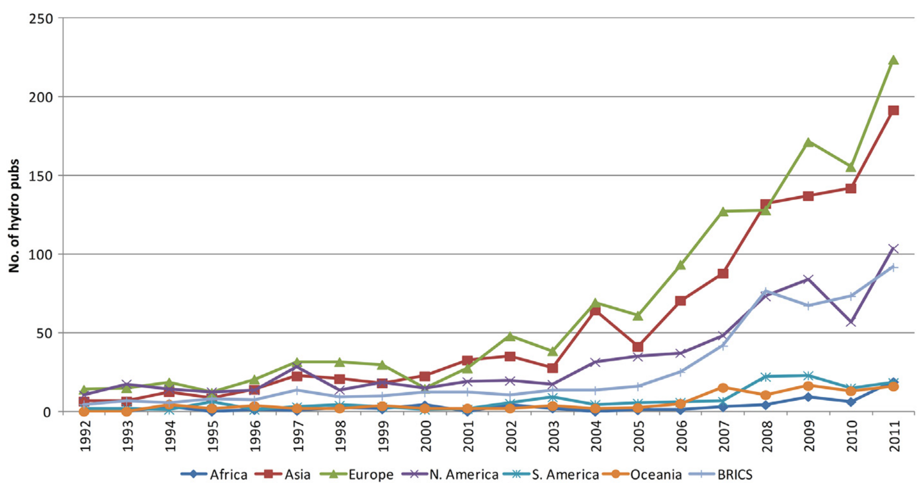

Fig. 10. Geographical publication trends for the field of hydro energy.

production, and the red (in web version) cluster concerning environmental impacts of biomass energy policies, especially of those that refer to energy crops. Here, quite surprisingly, the need for a systemic perspective on biomass energy supply chain management results in a prevalent attention to climate change and life cycle assessment than on local socio-economic issues.

Further insights come from a dive in the overlay map based on biomass manuscripts between 1992 and 2011 (Fig. 15). In sum, from a dive into the maps, while requirements and constraints placed on bio-energy systems are widely accepted (i.e. there is a low dispersion in streams of investigation), the community of bioenergy researchers – inspired by resource efficiency ambitions – seems to be still underway in exploring new technological trajectories. From this perspective, production of bio-fuels and bio-diesel is attracting more research than conversion technologies and biomass supply. Furthermore, it is worth noting that studies in biomass processing are more focused on laboratory scale reactions than on industrial scale up.

Country-specific overlay maps provide this framework with interesting insights on some geographical research peculiarities. As an example, Brazilian research environment displays a strong directionality on supply- and demand-side sustainability of bio-fuels and bio-diesel for automotive industry, that is much more influential here than in the world-wide framework.[1] In fact, in Brazil it is recognized as an interesting exchange of knowledge and technique (bioethanol industries) with the advanced economies [32]. In this search for green technologies, particular attention is paid to the capitalization of local biomass potentials and, in detail, to sustainability of soybean, sunflower, canola, and *Jatropha curcas* supply and conversion.

4.5. Towards an improved reliability of wind installations

Studies in the field of wind energy are less dispersed than in other RESs (Fig. 16). Apart from a small yellow (in web version) cluster about multiple RESs integration, researches are grouped in only three main clusters. The red (in web version) one presents a high concentration of interest on policy issues. In particular, social acceptance and infrastructural scenarios (including transportation systems and hydrogen storage) seem to be central topics for the evaluation of technologies that are subject to improvements mainly in terms of design capabilities. Not surprisingly, there are strong

[1] An interactive version of the map is available online at www.neesjanvaneck.nl/renewable_energy/biomass/brazil/.

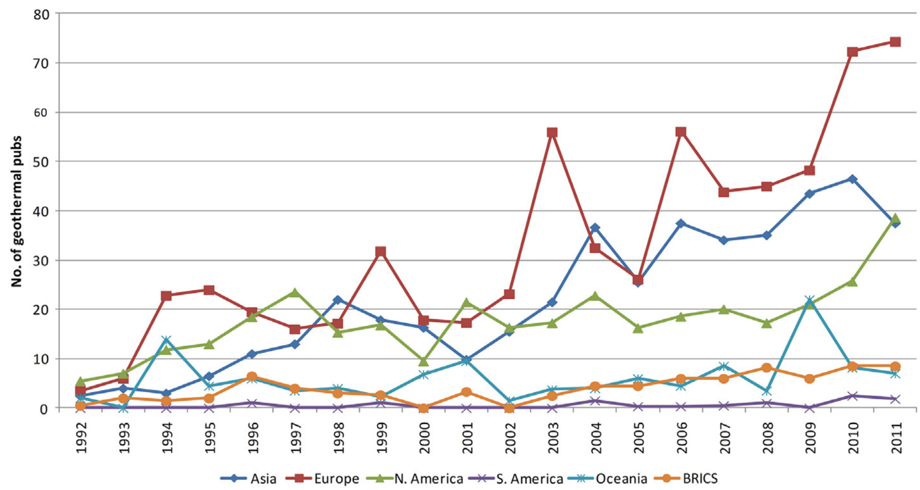

Fig. 11. Geographical publication trends for the field of geothermal energy.

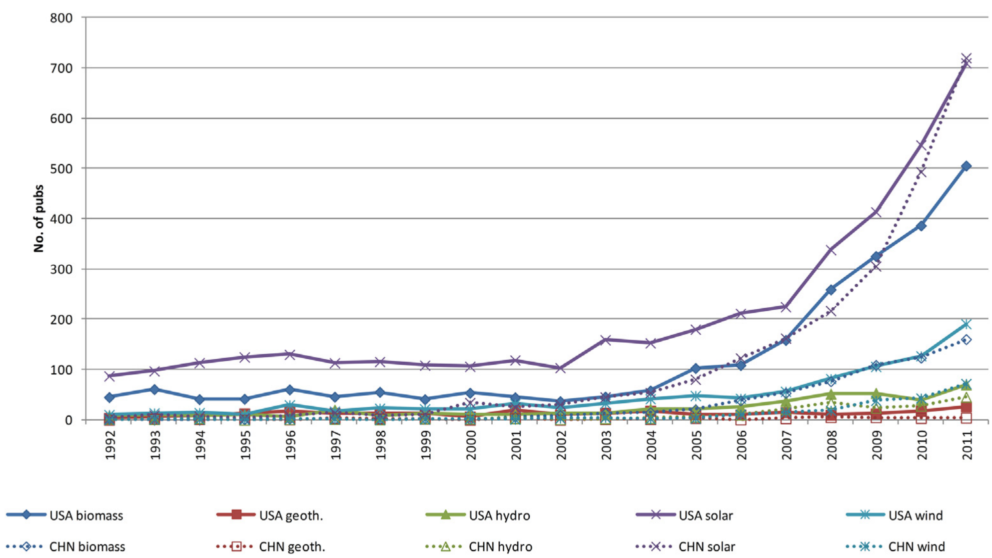

Fig. 12. Comparison between the publication trends of the USA and China for the field of RESs.

links with the green (in web version) cluster, covering design-related studies that range from wind data prediction to simulation accuracy, and with the blue (in web version) cluster, covering technological advancements in operation control. This cluster, in detail, collects studies on incremental knowledge in the field of electrical engineering, with particular reference to improved induction generation performances.

The overlay map built on wind manuscripts between 1992 and 2011 (Fig. 17) clearly shows that landscape and habitat protection are a key topics in policy issues, while generation control and grid connection (including storage) are emerging key topics in technical research.

Country-specific overlay maps highlight some geographical peculiarities in wind research trends. In particular, it is worth noting that in Denmark, where there is a large prevalence of wind research activity over solar and other RESs, wind technologies are covered through improvements for each component, from blades, to rotor, to turbine, converters and controllers.[2] Beside the integration with a related variety of information and communications technology and complementary green technologies [64], particular attention is paid to aerodynamic design and components fatigue in extreme conditions (e.g. sea applications). Habitat protection and mortality of birds for collisions are well covered as well.

4.6. From local electrical case studies to diffused geothermal direct uses

Also in the field of geothermal energy the dispersion of RESs is thematically low. In fact, only three main clusters can be identified (Fig. 18). The green (in web version) one entails keywords related to energy policy, with a specific focus on market barriers, availability of resources, and environmental footprint in energy mix design. The blue (in web version) one illustrates two main aspects: one refers to the design and the energy performance of geothermal district heating systems, an issue which is attracting an increasing interest from the geothermal community thanks to its potential impacts on new urban energy efficiency debates; the other refers to several studies on the new turn of green (in web version) energy strategies in Turkey for a sustainable integration of this technology into the national energy mix. The red (in web version) cluster,

[2] An interactive version of the map is available online at www.neesjanvaneck.nl/renewable_energy/wind/denmark/.

Table 4
Evolution in country's RES research focus (percentage of the specific RES on total RESs researches).

State years	China (solar)	Germany (solar)	Japan (solar)	Iran (wind)	Malaysia (biomass)
1992–2001	69.0%	84.5%	81.2%	5.9%	39.1%
2002–2011	66.1%	67.8%	72.1%	31.7%	57.5%
Key driver	Institutional environment	Intellectual capital	Intellectual capital	International cooperation	Natural resources
State Years	USA (solar)	Finland (solar)	Sweden (solar)	Denmark (wind)	Brazil (biomass)
1992–2001	58.8%	52.4%	43.6%	36.9%	27.6%
2002–2011	51.3%	55.5%	41.7%	48.0%	51.5%
Key driver	Intellectual capital	Natural resources	Intellectual capital	Natural resources	Natural resources

which concerns high enthalpy exploration, well drilling, and reservoir management, is still occupying the largest room for discussion on geothermal science.

Differences in these clusters are not only in target markets. Surfing through the network of research items, it is worth noting that while the blue (in web version) cluster is about non site-specific design-oriented studies, the red (in web version) one is mainly about site-specific empirical studies. Because of the site-dependency of outcomes (i.e. uncertainties in their generalization), it is thus not surprising that, in contrast with the more dynamic RESs, risks reduction in resource exploration and cultivation prevails over the development of either new or dominant technology paradigms. Additionally, it is worth noting that technical contents are mainly from on-field experiences carried out (with similar frequencies of occurrence) in Larderello (Italy), Geysers (Nevada), Wairakei (New Zealand), Philippines, Soultz (Germany), Krafla (Iceland) and Kyushu and Kakkonda (Japan). Finally, just examining in depth this geographic perspective, the decline of the share of Italian contributions (from 10.3% between 1992 and 2001 to 3.9% between 2002 and 2011) suggests that availability of resources and the presence of market leaders is not a condition sufficient for preserving scientific leadership.

4.7. New applications of well-established technologies in hydro energy

Together with geothermal energy, hydro energy shows the lower dynamism among RESs in terms of openness to new disciplines and technological frontiers.

Table 5
Coefficient of variation in RESs relative number of publications in leading European countries (in bold: Belgium, Denmark, France, Germany, Greece, Italy, The Netherland, Spain, Sweden, Switzerland, United Kingdom) and emerging regions (in italic: World regions with the exclusion of Europe, North America, West Asia).

	Wind		Hydro		Solar		Biomass		Geothermal	
1992	**1.06**	*0.98*	**1.69**	*1.70*	**0.38**	*0.80*	**0.83**	*0.58*	**2.56**	*1.58*
1993	**0.98**	*1.48*	**0.95**	*1.31*	**0.41**	*0.95*	**0.93**	*1.06*	**1.99**	*2.45*
1994	**1.32**	*0.97*	**1.54**	*0.84*	**0.39**	*1.13*	**0.76**	*1.00*	**1.32**	*2.02*
1995	**1.07**	*0.75*	**1.41**	*0.91*	**0.47**	*0.82*	**0.98**	*1.10*	**0.93**	*1.27*
1996	**1.27**	*0.76*	**1.54**	*0.87*	**0.44**	*0.73*	**0.89**	*0.54*	**1.85**	*0.60*
1997	**1.04**	*0.72*	**1.07**	*0.84*	**0.45**	*1.11*	**1.08**	*0.82*	**1.60**	*1.38*
1998	**0.99**	*0.96*	**0.64**	*0.94*	**0.28**	*0.92*	**0.66**	*0.75*	**1.36**	*1.40*
1999	**0.83**	*0.79*	**0.72**	*0.88*	**0.36**	*0.73*	**0.70**	*0.66*	**0.94**	*1.28*
2000	**0.98**	*0.83*	**1.03**	*0.93*	**0.29**	*0.88*	**0.54**	*0.84*	**1.79**	*1.26*
2001	**1.04**	*0.66*	**0.90**	*1.22*	**0.27**	*1.30*	**0.56**	*0.91*	**1.57**	*1.22*
2002	**0.94**	*0.72*	**0.93**	*1.09*	**0.34**	*1.09*	**0.57**	*0.74*	**2.19**	*1.34*
2003	**0.63**	*0.65*	**0.93**	*1.02*	**0.30**	*1.38*	**0.45**	*0.80*	**0.93**	*1.01*
2004	**0.83**	*0.72*	**0.57**	*1.46*	**0.26**	*1.06*	**0.57**	*0.87*	**0.97**	*0.85*
2005	**0.87**	*1.14*	**0.68**	*1.25*	**0.21**	*1.31*	**0.54**	*1.04*	**1.33**	*0.96*
2006	**0.84**	*1.29*	**0.44**	*1.32*	**0.29**	*1.36*	**0.59**	*1.13*	**0.97**	*1.01*
2007	**0.58**	*1.20*	**0.38**	*1.05*	**0.26**	*1.33*	**0.37**	*0.91*	**0.88**	*1.14*
2008	**0.55**	*1.02*	**0.35**	*1.04*	**0.34**	*1.44*	**0.25**	*0.78*	**0.54**	*0.87*
2009	**0.68**	*1.00*	**0.49**	*0.82*	**0.27**	*1.49*	**0.21**	*0.77*	**0.88**	*1.22*
2010	**0.74**	*1.04*	**0.44**	*1.06*	**0.25**	*1.57*	**0.30**	*0.71*	**0.94**	*0.90*
2011	**0.59**	*1.13*	**0.37**	*0.97*	**0.26**	*1.63*	**0.28**	*0.71*	**0.73**	*0.66*

In the field of hydro energy (Fig. 19), besides a significant cluster of multi-RESs planning studies (red (in web version) cluster), incremental improvements of efficiency of traditional technologies are clearly the focus of the blue (in web version) cluster, that is in turn connected with a cluster concerning conventional hydropower sources (green (in web version)) and storage management (yellow (in web version)). Conventional sources consist of river basins and –with a higher independence from the other hydro studies – marine tides and waves. Storage capacity based on reverse pumping represents a relatively novel approach for improving economic efficiency of hydro-systems because of the prevalence of energy price volatility on physical energy losses.

It is worth mentioning that, looking into the data, after a certain equilibrium between scientific production in Nord America, Europe and Asia during 1992–2003, these last two regions have experienced a higher growth in scientific production during 2004–2011. From a geographical perspective, besides the United States and United Kingdom, which are the countries with the highest tradition in hydro researches, China, Turkey, Spain, Japan, India, Canada, Brazil and Italy represent recent but important newcomers.

5. Conclusions and policy implications

The present paper opens with a review on technology transition that demonstrates the importance of knowledge development dynamics in informing decision-making processes on behalf of the actors involved. Focussing on the scientific domain, our analysis uses a bibliometric approach to compare the advancement of knowledge among different RESs, both in time and in space. As a result, from a longitudinal perspective, solar, biomass, and wind energy clearly emerge as the research fields attracting most interest; in particular, such interest appears to be proportional to the distribution of resources (e.g. solar energy is widely used worldwide) as well as to the flexibility and scalability in terms of demand side actors. In this sense, other characteristics – e.g. being programmable source or not – do not seem to systematically play a relevant role.

From a vertical perspective, while strategies of specialization (e.g. East Asia, South America, Central Asia, etc.) or diversification (e.g. Europe and North America) give a boost to regional peculiarities (which are often expression of socio-economic conditions and needs), globalization of markets and of explicit scientific knowledge does not seem to give the expected directionality to research streams within each RES. In fact, atomization and variety of research alternatives increase according to the same ranking above (i.e. from wind to biomass to solar energy). This means that the more R&D and energy policies can build on large volumes of scientific knowledge, the more social constructivism [41] can emerge as useful to orient researchers, industries and public authorities towards a limited set of technological goals that are embedded in priorities that are shared among stakeholders. In practical terms, considered the soar of research streams in some sectors and the associated threat of the "paradox of choice" (i.e. the loss of

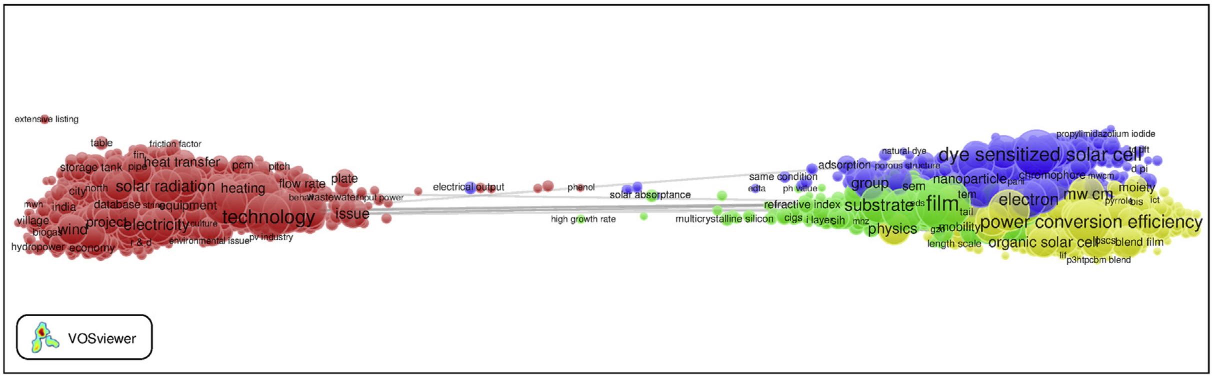

Fig. 13. Term map based on solar manuscripts from the period 1992–2011. An interactive version of the map is available online at www.neesjanvaneck.nl/renewable_energy/solar/.

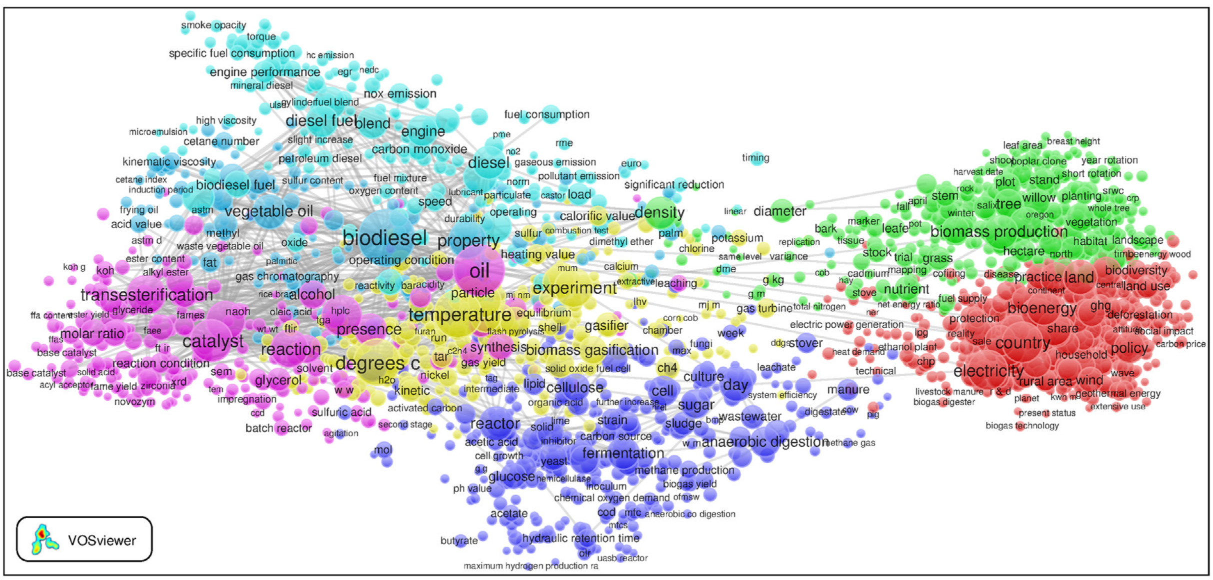

Fig. 14. Term map based on biomass manuscripts from the period 1992–2011. An interactive version of the map is available online at www.neesjanvaneck.nl/renewable_energy/biomass/.

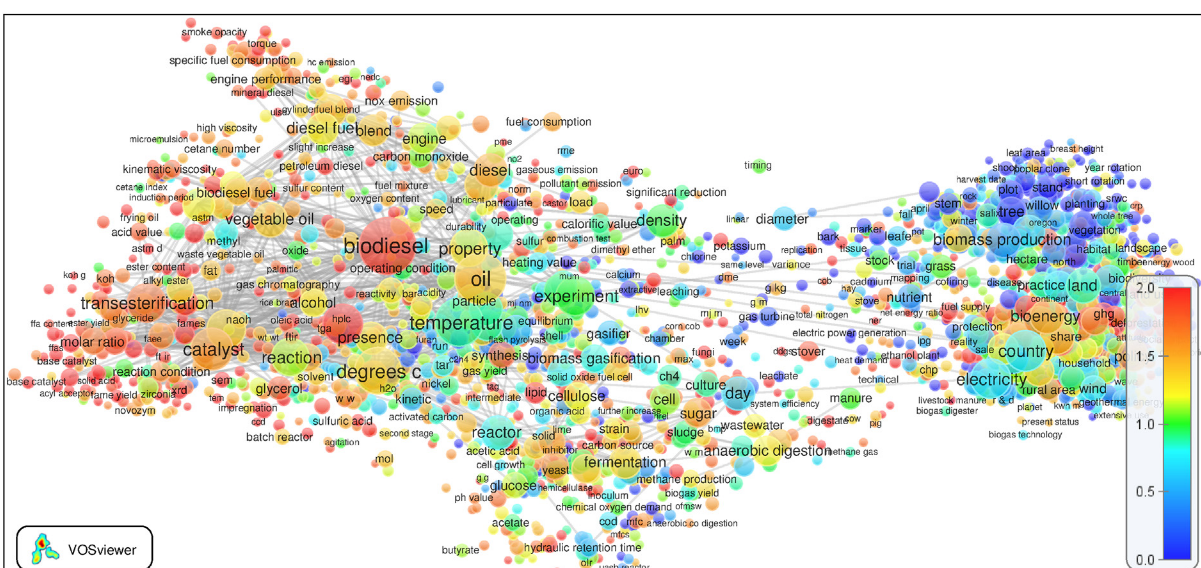

Fig. 15. Overlay map based on biomass manuscripts from the period 1992–2011. The colour of a term indicates the average publication year of the publications in which the term occurs (closer to red is more recent). An interactive version of the map is available online at www.neesjanvaneck.nl/renewable_energy/biomass/trend/. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

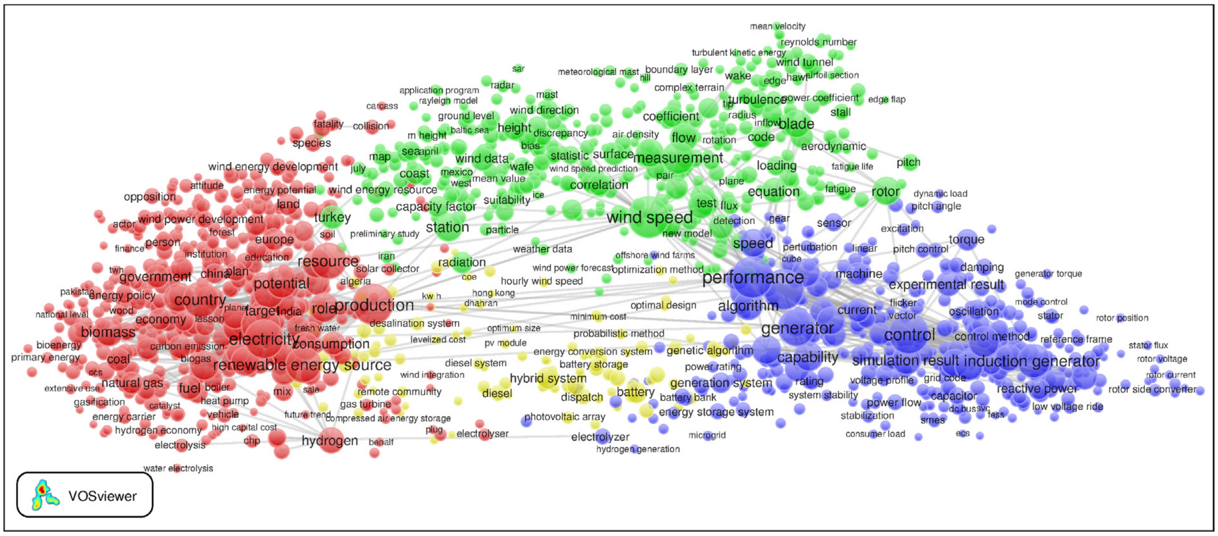

Fig. 16. Term map based on wind manuscripts from the period 1992–2011. An interactive version of the map is available online at www.neesjanvaneck.nl/renewable_energy/wind/.

confidence and productivity in front of an unmanageable number of alternatives), our data show how the energy research planner is increasingly asked to maintain the control over the worldwide picture of scientific and technological research. Such condition is particularly important to grasp effective investments in promising and emerging technologies that, especially with limited resources, respond to the need to limit the local number of failures and lock-ins. In so doing, monitoring and benchmarking worldwide research production could help in the transition from uncertainty to risk management.

Regarding the other RESs (i.e. hydro and geothermal), well established real or virtual innovation systems seem to introduce barriers to radically new solutions. In these cases, energy and research policy makers may, therefore, find it useful to (i) strengthen some existing (or even latent) advocacy coalitions by creating favourable conditions for private capital, and (ii) support the work of various interest groups associated with alternative technologies, in order to prevent incumbents from delaying (incremental and, even more, fundamental) scientific development.

Relevant implications for R&D and energy policies and related technology transitions emerge also in terms of key competences required for creating value from progress in scientific knowledge. In fact, our representation of the contrast between international isomorphism and national specialization sheds light on the importance of determining the appropriate directionality in research, energy and industrial policies integration. Based on our findings, we recommend that policy makers and R&D managers recognize the importance of achieving a deep understanding of the forces that shape local energy research mix.

Of course, some limitations in our research should be considered. Firstly, delineation of publications can present some limitations despite it being cross-checked by experts. Additionally, considering that term maps are a simplified representation of the contents of manuscripts, this could lead to a partial representation

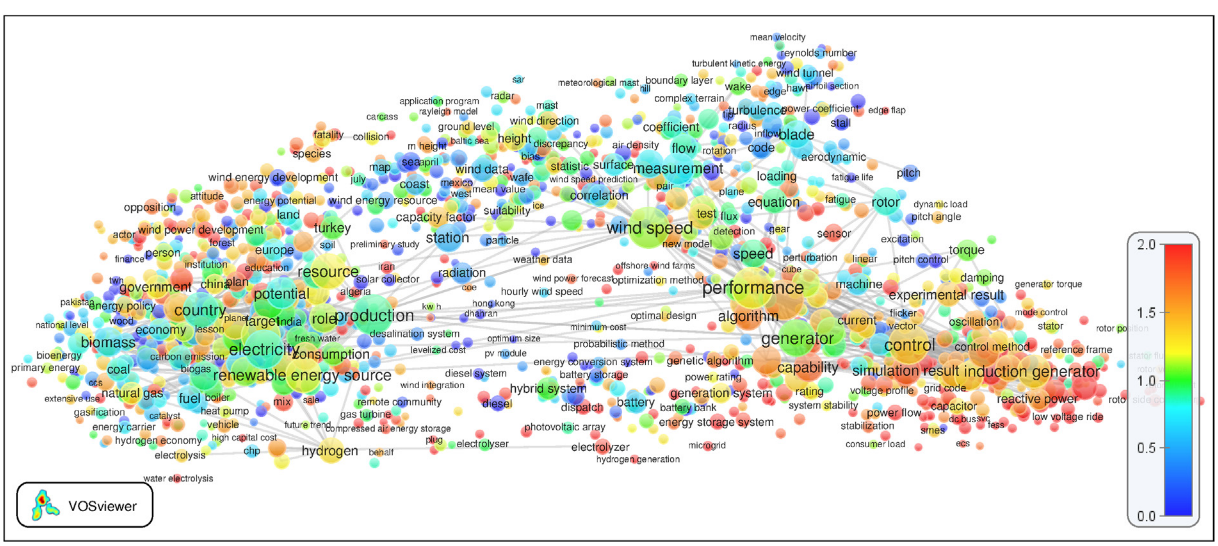

Fig. 17. Overlay map based on wind manuscripts from the period 1992–2011. The colour of a term indicates the average publication year of the publications in which the term occurs (closer to red is more recent). An interactive version of the map is available online at www.neesjanvaneck.nl/renewable_energy/wind/trend/. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

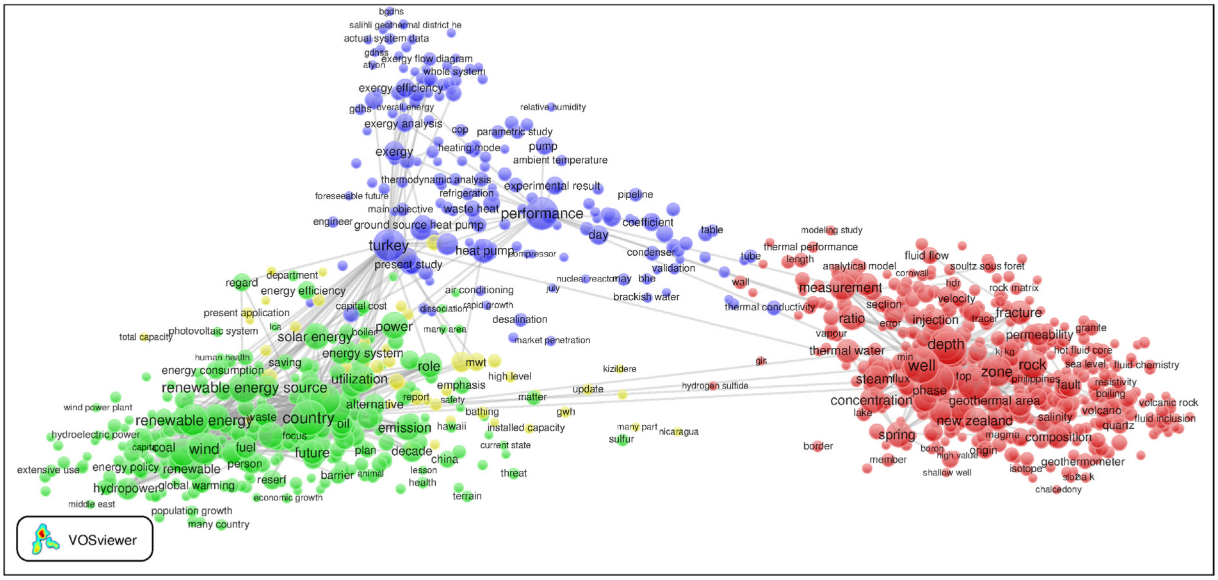

Fig. 18. Term map based on geothermal manuscripts from the period 1992–2011. An interactive version of the map is available online at www.neesjanvaneck.nl/renewable_energy/geothermal/.

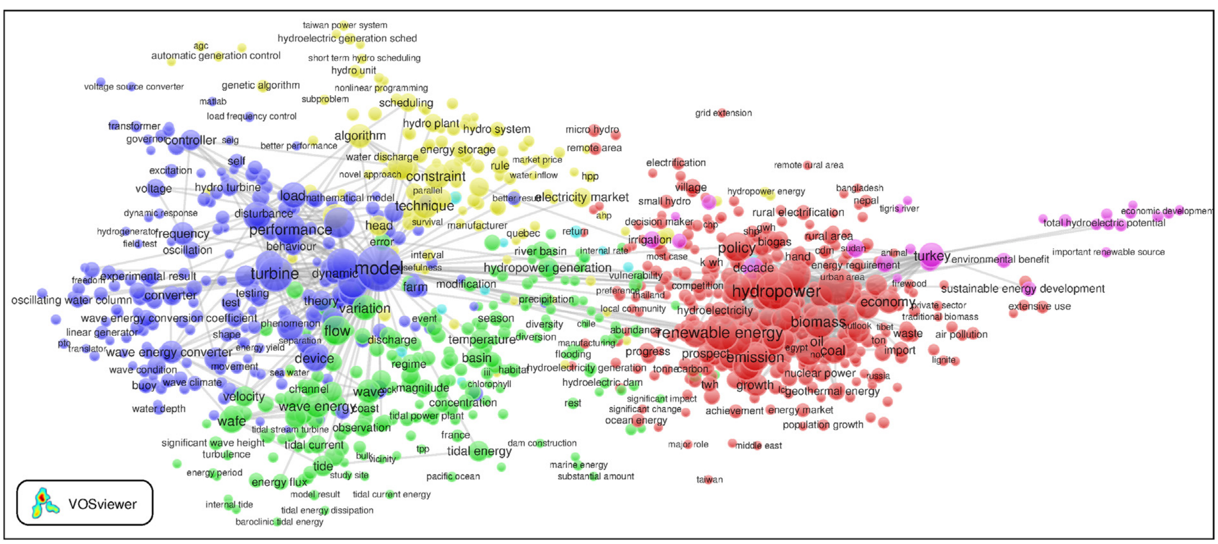

Fig. 19. Term map based on hydro manuscripts from the period 1992–2011. An interactive version of the map is available online at www.neesjanvaneck.nl/renewable_energy/hydro/.

of the scientific knowledge. Finally, expert based interpretations can be subject to the fashion of the time (e.g. bias in implicit knowledge). Nevertheless, the bibliometric approach we propose offers powerful ways to view the overall structure of research in a manner that an expert cannot perform. Thus we consider this exercise a useful incipit – not a conclusion – to a wider discussion which, given the continuously evolving nature of the topic, simply aims at increasing the understanding of energy and research policy implications.

Thus a number of studies could be usefully developed building on our results. First, further insights on the correlation between scientific production and technology transitions could be achieved through a deeper examination of specific (sectorial or regional) R&D and energy policies. Patent analysis and investigations on best available technologies could be usefully performed to this end. Second, the value chain of scientific information could be explored in order to inform better the integration of energy, research, and industrial policies.

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