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

Francesco Rizzi [a, b, *], Nees Jan van Eck [c], Marco Frey [a]

[a] Scuola Superiore Sant'Anna, Istituto di Management, 24 Piazza Martiri della Libertà, Pisa, Italy
[b] Università Europea di Roma, 190 Via degli Aldobrandeschi, Roma, Italy
[c] Leiden University, Centre for Science and Technology Studies, 62A Wassenaarseweg, Leiden, The Netherlands

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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.

* Corresponding author. Scuola Superiore Sant'Anna, Istituto di Management, 24 Piazza Martiri della Libertà, 56127 Pisa, Italy. Tel.: +39 (0)50 883972; fax: +39 (0)50 883936.
E-mail address: f.rizzi@sssup.it (F. Rizzi).

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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