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Hydropower development trends from a technological paradigm perspective

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ABSTRACT

Hydropower has long been considered the backbone of the power generation sector in low-carbon and sustainable energy systems. Yet, as reliance on hydropower has been generally declining, the world is awakening to the need to fundamentally rethink the way hydropower is developed and managed. The paper proposes a systematic methodology to research the development trends and find a more sustainable hydropower path. Literature mining using the data analysis system and the technological paradigm theory were adopted to conduct the research. The keyword visualization results were found to meet the laws for the three phases of the technological paradigm. Specific key areas, such as small hydropower plants, hybrid power systems, and hydropower from seawater were identified as past, present and near future trajectories. To further accelerate hydropower development, specific subsidies and incentives need to be provided in areas such as capital costs and technological support. The study paves the way for a soft path solution which complements the hard path in hydropower field.

1. Introduction

Hydropower does not only remain a backbone of the power sector, but is also one of the most ambitious emission reduction paths for low-carbon and sustainable energy system. In 2011, statistics from the World Bank showed that hydropower generated 23,210 terawatt-hours (TW h) of electrical energy accounting for 78.19% of renewable energies (including hydropower, geothermal, solar, tides, wind, biomass, and biofuels) and 15.74% of total electrical energy production worldwide, approximately 1.4 times larger than the 17,245 TW h generated using nuclear power in the same year. If calculated using the gross coal consumption rate of 349 grams per kilowatt-hour, the production of hydropower generation was able to save nearly 8100 million tonnes of standard coal and reduce CO_2 by approximately 20,695 million tonnes.

Yet reliance on hydropower is declining. The share of hydropower in renewable power generation drops from 99.37% in 1961 to 78.19% in 2011 and that in total power generation from 40.25% to 15.74% (Fig. 1). Under the Reference Scenario presented by the IEA, if the governments make no changes to the existing policies and measures, the share of hydropower in total power generation will drop to 14% in 2030 [1]. No single factor is responsible for this state of affairs. Social barriers, environmental sensitivity, remote locations, misdirected development efforts and rapid population growth are just some of the many contributing problems.

Current hydropower resources were observed to have a significant development potential. When the amount of economically available hydropower resources were divided by the electricity production from hydropower, the potential development degree became apparent. In 2010, 3410 TW h was generated from hydropower worldwide, which accounted for about 39% of the available 8721 TW h. Statistics from the World Atlas Industry Guide 2008 imply that future hydropower installed capacity is expected to increase in Africa (the Nile and Congo rivers), Asia (such as China) and South America (such as Brazil) (Table 1). Therefore, in order to continue to be a mainstay in the low-carbon and sustainable energy system to achieve a cost optimized scenario for stabilizing CO_2 emissions at 450 ppm by 2050, studies which fundamentally rethink the evolution and management of hydropower are required.

A soft path solution was proposed for global freshwater resources by Gleick [2], which is reference for hydropower resources either. It complements the hard path through investment in decentralized facilities, and the development of efficient technologies, associated policies, and human capital. Compared

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with the hard path, the soft seeks to improve the management of hydropower sources rather than finding new technologies or sources [3]. These two paths attempt to look for innovations that are able to offer a marked improvement on today's approaches or provide an entirely new perspective. However, what should be done to follow the soft path has not been studied.

A systematic methodology is needed to identify a more sustainable development for hydropower in the low-carbon and sustainable energy system. The technological paradigm, which is a classical concept in the literature on innovation and technological change, is employed to determine the hydropower development technological road map [4–6]. Based on Kuhn's notion of scientific paradigms [7], Dosi defined the technological paradigm further as a "model for the solution of selected technological problems, based on highly selective principles derived from the natural sciences, together with the specific rules designed to acquire new knowledge, and to safeguard them as far as possible against rapid dissemination to competitors" [8].

The technological paradigm is mainly applied to analyze technological change and innovation in engineering fields [9–11]. It provides a method for the investigation of past trends as well as being able to predict future possibilities. By demonstrating how the various factors interact, such as scientific advancement, economic development, and organizational structural change, blocks that are unable to be solved using existing technologies are exposed and future technological trajectories identified. Technological trajectories are the external forms of technological paradigms to express continuous changes. For example, when targeting technologies, the trajectory develops along *S*-curves. Thus, researching on historical background of technologies is a starting point for an in-depth analysis.

However, thousands of literatures block the way. A data analysis system is created to summarize the trends, which is composed of the ISI Web of Science, NoteExpress and NodeXL. Networks are built between the keywords and publication years to visualize the internal relationship. Whether the development of hydropower technologies meets the laws of technological paradigm could be found. Compared with simple statistical tools, this method has the ability to show the mutual relationships between keywords and time.

The technological road map could pave the way to the expansion of supply and an increase in efficiency for the hard path, while the policy framework, which includes four broad themes: capital, costs and risks, subsidies and penalties, and technological support, in the technological paradigm is indispensable to follow the soft path. If the technological paradigm is deeply researched, by following the two paths, hydropower development could develop beyond

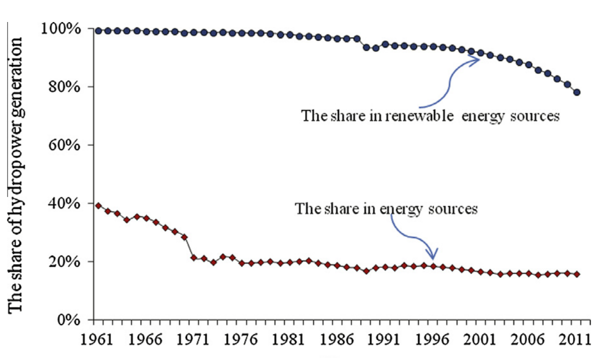

Fig. 1. The share of hydropower in power generation, 1961–2011. In addition to renewable energy sources, energy sources cover generation by coal, oil, gas, nuclear. Date are collected from the World Bank and analyzed by authors.

the current situation and continue to play a significant role in low-carbon and sustainable energy systems.

The remainder of this paper is structured as follows. Section 2 uses the data analysis system (DAS) to identify the main technological trajectories and uncover hydropower field development trends. The hydropower development technological paradigm is given in three stages in Section 3. Section 4 compares two curves and discusses the relationship between the technological paradigm and the soft-hard paths. Conclusions are given in Section 5.

2. Literature mining

Hydropower has a long extensive and wide ranging history. The technological road map starts from technological sources. However, a large body of literature in this field makes it difficult to determine the knowledge gaps and to explore future research possibilities. Literature mining from the published scientific literature is useful for the discovery of key areas and trends [12]. Through this process, the networks built from the keywords and publication years nodes were easily visualized and effectively identified [13]. Our primary goal for the literature mining is to confirm the hydropower development trends.

2.1. The data analysis system buildup

The data analysis system (DAS) was organized as shown in Fig. 2. The ISI Web of Science was chosen as the primary database, as it is able to provide researchers, governments, and academics with prompt and effective access to the world's leading citation databases. NoteExpress was then applied to review the general characteristics of the relevant research, by conducting a knowledge management interrogation which includes knowledge acquisition, management, application, and data mining. Scholars in China have used NoteExpress to achieve important research results in different fields [14–16]. NodeXL was designed to facilitate the learning of the concepts and methods in a social network analysis using visualization as its key component [17], and plays a critical role in the analysis of the keywords in the DAS. Therefore, the DAS, as a comprehensive integrated approach, can guide the research and point to a potential hydropower development direction.

2.2. Search strategies

Since the ISI Web of Science is rich in knowledge, a great deal of relevant information has been archived. Therefore, it would be very difficult to identify useful articles if there were not appropriate searching strategies. To ensure no important documents are overlooked or duplicated, the searching methodology we used needed to be in accordance with the following rules.

Rule 1: To guarantee an accurate and efficient search process, a hydropower and technologies focus was selected.
Rule 2: The results were firstly refined using field tags, and then sorted by document type.
Rule 3: Duplicate checking work was conducted to remove unnecessary or irrelevance research through a reading of the titles and abstracts in NoteExpress.
Rule 4: The selected articles were optimized in NodeXL by paying attention to spelling, and other similarities to ensure an accurate keyword classification.
Rule 5: The keywords were presented visually by years to determine the specific research focus.

Following this DAS methodology, 4985 initial hydropower records were refined to 1778 articles. Proceedings papers and