Sustainable Energy Technologies and Assessments 28 (2018) 30–42

Contents lists available at ScienceDirect

Sustainable Energy Technologies and Assessments

journal homepage: www.elsevier.com/locate/seta

Original article

Sustainable electricity generation mix for Iran: A fuzzy analytic network process approach

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ARTICLE INFO

Keywords:
Electricity generation mix
Sustainable development
Multi-criteria decision making (MCDM)
Fuzzy analytic network process (FANP)
BOCR

ABSTRACT

Electricity supply in Iran has been heavily dependent on fossil fuels. In light of the government's emphasis on reducing the consumption of conventional energy sources, combined with the worldwide attention to environmental issues, it is necessary for Iran to revise its current energy mix policy in power sector and move towards a more diversified energy portfolio. This paper aims to contribute to energy management studies through developing a new framework for assessing the mix of energy sources for producing electricity in Iran from the perspective of sustainable development. Multiple qualitative and quantitative criteria with conflicting nature need to be taken into consideration for evaluating competing energy options for electricity production in Iran. In order to address this issue and also to consider the complex interdependence among criteria and alternatives, this paper adopts a fuzzy analytic network process (FANP) method. Seven criteria and nineteen subcriteria are defined and structured in the form of benefits, opportunities, costs and risks (BOCR) to evaluate the share of six energy resources. The results indicate that the best energy mix for the power sector in Iran is as follows: renewable energies (31.6%), natural gas (25%), coal (12.3%), fuel oil (12.6%), nuclear (8.7%) and gas oil (9.7%).

Introduction

During the last 60 years, the global population has grown by the factor of 2.5, whereas the global primary energy consumption has increased by a factor of 4.5 [9]. Also, the worldwide demand for energy is expected to increase even more over the next 30 years [23]. A short glance at the world's energy architecture reveals that fossil fuels have remained as the dominant sources of electricity generation. The extensive consumption of fossil fuels has had negative global consequences such as climate change, depletion of fossil energy resources, and environmental pollution. In this sense, electricity sector has been the focal point in mitigating these issues mainly for two reasons [105]: first, electricity sector, especially in developing countries, is often highly carbon-intensive and is considered as a major source of greenhouse gas emissions. Therefore, moving towards generating electricity in lower carbon intensity units is a highly effective emission reduction strategy. Second, electricity sector is a relatively easy target for mitigating environmental effects because it is a large and concentrated sector.

In order to achieve long-term sustainable development and energy security, it is imperative for all the countries to diversify their energy portfolio and seek for exploiting a combination of various energy sources for generating electricity [53]; [109]. In fact, each source of energy has its own advantages and disadvantages and, as expressed by Li [53, p. 2240], "the dominance of a single energy source and system, no matter how "perfect" it might be at a time, would be unsustainable in the long run."

In this context, due to the large population and rapid economic growth of developing countries, their patterns of energy production and consumption might considerably affect the overall global energy consumption and environmental concerns. As a rapidly-growing developing country, Iran's energy demand is continuously increasing. The consumption of primary energy in Iran has grown by almost 50% since 2004 and it is expected that in the coming decades this figure would continue to grow at a rate of approximately 6% per year [22]. According to the latest Iran energy balance sheet in 2013, about 92% of electricity has been generated in fossil fuel based power plants [36]. It is estimated that by maintaining the current trend of electricity generation, the demand of power sector for fuel would be more than doubled over a 30 years period [7]. In order to address twine challenges of long-term energy security and environmental sustainability in the next decades, it is of crucial importance for Iran to revise its energy

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https://doi.org/10.1016/j.seta.2018.04.001
Received 6 December 2016; Received in revised form 13 September 2017; Accepted 2 April 2018

policy and ensure its energy security by reducing the dependence on fossil fuels. In this line, Iranian government is planning to gradually decarbonize the country's electricity generation mix and shift to a more diverse portfolio of clean, reliable and renewable sources of energy [58].

In view of the above discussion, the purpose of current research is to propose a comprehensive decision-making framework for evaluating alternative energy sources for supplying electricity in Iran and determining the best energy mix according to different aspects of sustainable development. A sustainable approach to energy planning requires a solution that simultaneously addresses multiple and potentially conflicting objectives such as economic viability, social acceptability and environmental protection [48]. The necessity of incorporating multiple inter-related goals and criteria from different perspectives in energy planning of Iran makes multi-criteria decision making (MCDM) approach as the preferred assessment method for this study. This approach is suitable for analyzing complex problems that involve high degrees of uncertainty, conflicting goals and criteria, as well as multiple actors with diverse interests. This study proposes a fuzzy group analytic network process (ANP) framework to assess the potential benefits, opportunities, costs and risks associated with exploiting different sources of energy for generating electricity in Iran.

The remainder of this paper is organized as follow: in Section "Energy status of Iran", energy status of Iran and the challenges in energy supply are described. Section "Electricity generation in Iran", outlines the electricity production and consumption in Iran. Following this, ANP and its fuzzy extension are briefly explained in Section "Literature review". In section "Methodology", the steps of the proposed BOCR–fuzzy ANP model are explained. Finally, conclusions and avenues for future research are presented in Section "Proposed fuzzy ANP model".

Energy status of Iran

Iran is the second-largest economy in the Middle East and North Africa, and also is ranked as the second most populous country in this region [101]. Compared with other oil producers in Middle East, the economy of Iran is more diversified; however, oil and gas still remain the major source of government revenues [93]. Iran has the third largest crude oil (approximately 10% of the global crude oil reserves), and second largest proved gas reserves in the world (17% of the world's reserves) [22,74]. With this huge hydrocarbon reserves, the current oil and gas production levels of Iran are well below its maximum potential. Therefore, Iran has a huge potential to increase its outputs massively [67].

The consumption of primary energy in Iran has grown by almost 50% since 2004 and is continuing to increase each year [102]. It is estimated that the energy demand in Iran continue to grow for the coming decades [22]. Iran has the highest primary energy consumption in Middle East. With the energy intensity about 2.5 times the Middle East's average, Iran is considered as the most energy intensive country in this region, and one of the world's most energy inefficient countries [67,100]. In 2013, about 244 million tons oil equivalent of primary energy was consumed in Iran, of which more than 98% came from natural gas and oil [22]. The highest energy consumption sectors in Iran are residential and power plant, which together consumes half of total country's energy [59].

Iran's energy sector has been profoundly affected by the broad range of international sanctions, which have led to a substantial decline in oil and gas production over the past few years. In the energy sector, not only sanctions slowed the progress of projects, but also it affected the investment in upstream in oil and gas projects [21]. International sanctions and inappropriate investment terms are among the important barriers to developments in the energy sector of Iran.

Electricity generation in Iran

Along with its fast-growing population and economy, production and consumption of electricity in Iran have rapidly grown recent years. By producing 239.2 billion kWh, and consuming 195.3 billion kWh, Iran is ranked 17th in the world in terms of electricity production, and 21st with regards to electricity consumption [19]. Studies on forecasting future electricity demand have shown that Iran's electricity consumption will continue to increase in the coming years [10,58]. Findings of recent studies suggest that Iran has the potential to add about 15,000–20,000 MW to its current electricity production capacity [57,66].

According to the latest energy balance sheet in 2013, more than 92% of electricity is generated in thermal power plants (consisting of steam turbine, combined cycle, gas turbine and diesel engine). The majority of electricity generated in thermal power plants, is produced by natural gas and oil (69% and 25% respectively). Only 8% of electricity is generated by renewable sources which are mainly produced from hydropower. Non-hydro renewables (e.g. wind, geothermal or solar) comprise less than 2% of produced electricity.

The extensive fossil fuels consumption in power plants has led to major challenges. Among other issues, Iran is now facing increasingly serious environmental problems. The CO_2 emissions from power plants have grown sixfold over the last three decades and currently, power plants account for almost one-third of the total CO_2 emissions [36,98]. These issues highlight the need to revisit the current carbon based electricity generation in Iran and to use more sustainable and clean sources of energy.

Although the contribution of nuclear and non-hydroelectric power is marginal for the time being, they are parts of the Iran's fourth development program and 20-year development outlook for meeting future electricity demand [67]. Iran aims to further develop its nuclear capabilities to produce 7000 MW of nuclear electricity over the next 20 years [102]. Also, by 2025, the Iranian government aims to increase the proportion of non-hydro renewable energy sources in its electricity generation mix to 10% [20].

Literature review

As a result of ever increasing demand for energy along with multitude of social, environmental, economic, and technological challenges that need to be considered for energy production and planning, decision makers are forced to use more and more complicated methods for energy planning.

The formal scholarly efforts to energy planning and identifying efficient supply options started after the oil crisis in 1970s [54]. The early studies on energy planning were mainly based on single objective decision making that were primarily oriented towards identifying the best energy supply options with maximum efficiency and minimum cost [62,86]. Although such traditional single objective models may be useful for studying a small system, they prove inefficient for studying complex systems that typically involve multiple objectives, criteria, and stakeholders [48].

From 1980s, scholars started turning their attention to the necessity of incorporating environmental factors in energy planning frameworks [69]. In order to address the trade-off between environmental and economic factors in energy planning, a group of studies employed optimization models based on multi-objective linear programming to evaluate and the decision alternatives [44,45,88]. For example, [63] developed a multi-objective energy allocation model that addresses different economic and environmental objectives and employed this model in the case of Lebanon. Also, Oliveira and Antunes [72] developed a multiple objective model to evaluate sustainable energy strategies based on economic, social and environmental considerations. More recently, San Cristóbal [87] developed a goal programming model to evaluate five different renewable energy plants for electric generation