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Pinch analysis for the planning of power generation sector in the United Arab Emirates: A climate-energy-water nexus study

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ABSTRACT

The United Arab Emirates has recently announced its 2050 Energy Plan, which aims for a 50% clean energy supply. The plan requires diversifying the nation's energy mix and adoption of more renewable energy sources. In addition, climate change and water scarcity issues are key factors to consider towards building an environmentally sustainable future in the country. Therefore, this paper uses Pinch Analysis to examine the 2050 target, focusing in three key aspects (i.e., carbon emissions, energy return on investment, and water footprint) of the country's power sector. Different scenarios for achieving the 2050 target are studied, accounting for demand growth, energy resource availability, and finally technology feasibility and cost projections. This approach provides a holistic assessment of the impact of each of the three aspects on the power generation sector. By constraining United Arab Emirates carbon emissions to 2012 levels, with maximum energy return on investment and minimum water footprint, the electricity sector in 2050 will be dominated by renewable energy, and particularly solar power. Furthermore, the interdependencies of energy and water policy issues are discussed.

1. Introduction

Climate change and fossil fuel resource depletion have driven many countries to look for more sustainable energy resources. This trend is true even for countries in the Middle East that are known for their huge reserves of hydrocarbons, such as the United Arab Emirates (UAE), which is currently the world's third largest net oil exporter (EIA, 2017). Since last decade, UAE has enjoyed robust economic development, which coupled with population growth has resulted in a sharp rise in energy demand (Mondal et al., 2014). UAE electricity generation has increased dramatically in recent years, and is generated almost entirely by natural gas-fired power plants (Juaidi et al., 2016). The UAE government has realized that renewable energy should play a more prominent role in the future energy mix to ensure sustainability of the country's development in the long term. This is reflected in the nation's agenda, in which the share of natural gas in the power mix will be reduced from 98% to 76% by 2021 (Ministry of Energy, 2016), and further down to 38% by 2050 (Gulf News, 2017).

Besides ensuring energy security, reduction of CO_2 emissions through diversification of the energy mix is also part of the UAE's priorities as contribution to the global climate change problem, as communicated to the United Nations Framework Convention on Climate Change (UNFCCC) in the country's Intended Nationally Determined Contribution (INDC) report (UNFCC, 2015). According to the latest statistics, the CO_2 emissions of the UAE increased by 63% between 2000 and 2010 (Ministry of Energy, 2015). Although the UAE is categorized by the UNFCCC as a non-Annex I Party that has no legal obligations to reduce emissions, the government has nevertheless committed to reduce CO_2 emissions by 15% by 2021 (Ministry of Energy, 2015). Since electricity generation from fossil fuels is responsible for almost half of the country's total emissions (Mondal et al., 2014), the primary focus for the country's emission reduction is the electricity generation sector.

The UAE is in a unique situation in terms of energy and water

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resources. It is estimated that the Gulf Corporation Council (GCC) region in which it belongs has two-thirds of global crude oil reserves, but only 1.4% of the world's fresh water supply (Griffiths, 2017). Water planning is thus an important criterion in the country's development roadmap; the UAE ranks in the top 25 among countries for usage of water, primarily due to its petrochemical production and electricity generation (Spang et al., 2014). Thus, water footprint needs to be considered even in energy planning problems due to the inherent interdependencies of these two aspects in the water-energy nexus (Siddiqi and Anadon, 2011). While renewable energy offers the advantage of sustainability, some techno-economic drawbacks hinder its wide integration into the grid energy mix. Some of these issues are low reliability and availability, as well as high capital cost. For the latter issue, the metric known as *energy return on energy investment* (EROI) provides a thermodynamically-based index that can serve as a proxy for economic value (Cleveland et al., 1984).

Clearly, a major shift is currently taking place in the UAE energy sector towards increased use of low-carbon technologies. Energy planning considering carbon emissions, EROI and water footprint are important to ensure the sustainable generation of electricity in the UAE. The country's energy diversification is a high-level policy goal, but detailed analysis of the combination effect from the emissions to the energy expended and water use has not yet been thoroughly studied. As such, this paper utilizes *Carbon Emissions Pinch Analysis* (CEPA) (Tan and Foo, 2007) and its extensions to examine the implications of the proposed energy mix targets on the carbon emission levels, as well as energy expended for capital investments, and water consumption. Two scenarios are analyzed based on official UAE government projections. This work thus serves as a platform to provide insights into the UAE electricity sector for the provision of sustainable energy. While this paper deals specifically with the UAE, many of the lessons drawn from the analysis can apply to other countries in the GCC, as well as in other regions where long-term availability of water resources may be threatened by climate change.

2. Methodology and data

2.1. CEPA theory and methods

Process Integration may be formally defined as "*a holistic approach to design and operation that emphasizes the unity of the process*" (El-Halwagi, 1997). Process Integration techniques such as *Pinch Analysis* were originally developed in the 1970s to address energy conservation problem in the process industry (Linnhoff et al., 1982). In the 1980s, this framework was extended to address industrial waste minimization problems (El-Halwagi and Manousiouthakis, 1989). Many of the developed techniques are now available in textbooks, such as those for heat integrated processes (Smith, 2016), material resource conservation (Foo, 2012), as well as a handbook (Klemeš, 2013) and encyclopedia chapter (El-Halwagi and Foo, 2014).

CEPA is an extension of the Pinch Analysis technique that focuses on carbon-constrained sectors, where specific carbon footprint limits are imposed on the planning of different energy resources (Tan and Foo, 2007). In particular, CEPA and its variants have been widely studied for electricity generation sector at regional and national levels, including California (Walmsley et al., 2015), China (Jia et al., 2016), Ireland (Crilly and Zhelev, 2008), New Zealand (Atkins et al., 2010) and India (Krishna Priya and Bandyopadhyay, 2013). Furthermore, the basic CEPA framework has been extended to account for other sustainability metrics, such as land footprint (Foo et al., 2008), water footprint (Tan et al., 2009a), *emergy* transformity (Bandyopadhyay et al., 2010), and EROI (Walmsley et al., 2014). Recent works have been reported to account for financial aspects in the CEPA problems, such as the case for India (Chandrayan and Bandyopadhyay, 2014) and Philippines (Tan et al., 2017a). Structural similarities of different footprint-constrained energy planning problems are discussed in a book chapter by Tan and Foo (2013). Recent attempts to extend the CEPA framework to simultaneously account for multiple metrics have been reported by Jia et al. (2016), and more recently in conjunction with the Analytic Hierarchy Process (AHP) by Patole et al. (2017). Other variants of CEPA take into account technological issues, including deployment of carbon capture and storage (CCS) at scale (Tan et al., 2009b). Key developments are surveyed in a recent review paper (Foo and Tan, 2016), while a brief tutorial can be found in a recently published encyclopedia chapter (Tan and Foo, 2017).

The most commonly used graphical tool in CEPA is the *energy planning pinch diagram* (EPPD) (Tan and Foo, 2007), with a generic version shown in Fig. 1. As shown, the EPPD consists of the demand and source composite curves. The source composite curve is plotted with cumulative quantity of total carbon dioxide equivalent emissions (CO_2-e) generated from the several fuel sources on the y-axis against the total electricity generated from these sources on the x-axis. Each energy source is plotted as a segment so that its electricity output (in TWh) and carbon emissions (in Mt CO_2-e) lie along the horizontal and vertical axes of the diagram. Consequently, the slope of each segment corresponds to its carbon emission factors (EF), measured in Mt-CO_2-e/TWh. The energy source with the lowest carbon EF is plotted first, followed by the next highest, and so on. The demand composite curve is also plotted in the similar fashion, to represent the regions or sectors that require the electricity.

For a feasible EPPD, the source composite curve has to stay entire below and to the right of the demand composite curve. For cases where this condition is not met, the source composite curve has to be shifted horizontally to the right, so that it only touches the demand curve at the Pinch Point. The resulting gap on the left is the minimum amount of clean (i.e., zero-carbon) energy resources that need to be added in order to meet the system's specified emissions limits. The overhang of the source composite curve on the right corresponds to the amount of excess resources. The equivalence of CEPA to mathematical programming is well known (Tan and Foo, 2007), and recently the P-graph equivalent has also been proposed (Tan et al., 2017b). While mathematical programming is a well-established tool for planning, there remains a need for simplified representation of complex problems to facilitate

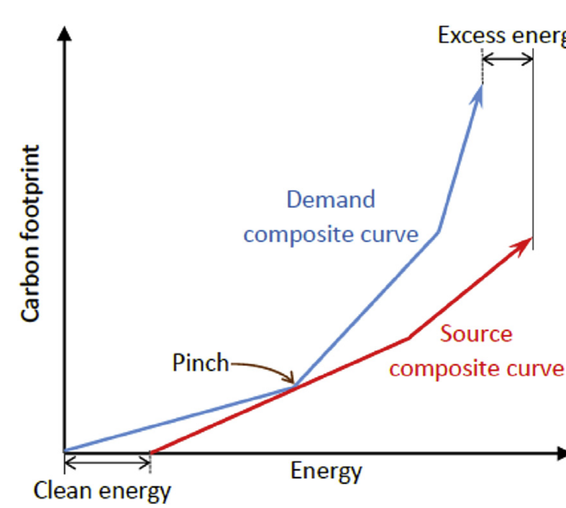

Fig. 1. Energy planning pinch diagram (EPPD) (Tan and Foo, 2007).