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Toward supplying food, energy, and water demand: Integrated solar desalination process synthesis with power and hydrogen coproduction

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ABSTRACT

The increase in population coupled with rising per capita income and associated change in consumption habits will put unprecedented stress on food, energy and water (FEW) resources. Sustainable and reliable fresh water supply is central for life and also for all sectors that support our existence. Uncertainty on water security prompted interest in investigation of renewable energy driven desalination processes. One particularly promising option is to produce fresh water from the two most abundant resources on earth: solar energy and seawater. In this study, using Solar Electricity, Water, Food and Chemical (SEWFAC) process synthesis concept, we explore and identify synergistic integration alternatives of multi stage flash desalination, solar thermal power, and hydrogen production processes. The promising options have been analyzed by detailed process simulation and optimization using an integrated Aspen Plus and MATLAB modeling environment. The proposed process designs can meet the water and electricity demand with rather high conversion efficiencies. Furthermore, integration of solar hydrogen production and hydrogen-fired power plant can enable continuous production of fresh water and electricity in solar-rich water-poor regions. In addition to other metrics, we have evaluated the performance of the desalination process from power point of view with a new metric, Electricity Equivalent Water (EEW) to demonstrate the marginal energy penalty of desalination. Integration of thermal desalination processes with electricity and hydrogen production is a synergistic alliance and can play a pivotal role in approaching FEW nexus.

1. Introduction

Population growth coupled with rising per capita income and shift toward resource intensive consumption habits create unprecedented stress on food, energy and water (FEW) resources. The grand challenge is to develop and implement solutions to sustainably meet humanity's increasing FEW needs with scarcer resources (Gençer et al., 2017). To put into perspective, the current annual global food consumption is 29.6 EJ (converted to equivalent energy number for comparison) (Alexandratos and Bruinsma, 2012), primary energy consumption is 556 EJ (BP, 2017), and water consumption is more than 9 trillion m^3 (Hoekstra and Mekonnen, 2012). The projected increase in FEW demand by mid-century are 70% (FAO, 2015), 50% (EIA, 2015; IPCC, 2014), and 55% (FAO, 2011), respectively.

Given the scale of the challenge, the solution will include a mix of options such as efficient and low CO_2 emission fossil fuel processing (Ramapriya et al., 2014; Tock and Maréchal, 2015), biofuel production from hybrid conversion processes (Mallapragada et al., 2014; Gençer et al., 2014b), waste management and conversion (Hernández and Martín, 2017; Garcia and You, 2017), utility scale energy storage (Gençer and Agrawal, 2016). Solar energy conversion pathways are particularly attractive due to the tremendous potential of solar energy hitting the earth surface. Of course, intermittency, variations in availability and being dilute in nature are challenges to be addressed (Agrawal and Mallapragada, 2010; Gençer et al., 2014a). Our objective is to optimize the utilization of solar energy through process synthesis and integration to supply FEW needs. We adopt the Solar Electricity, Water, Food and Chemical (SEWFAC) concept, which entails systematic synthesis of energy efficient, synergistic processes for optimal utilization of resources (Gençer and Agrawal, 2017a). The FEW production processes are connected by hydrogen, electricity, and fresh water. SEWFAC approach utilizes these connecting elements to complement individual processes by synergistic integration.

In this study, we explore integrated fresh water production processes. Fresh water is an essential, ever-growing need to sustain life on earth. Moreover, water has an indispensable role for numerous sectors

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such as agriculture, industry and energy. Global agriculture accounts for 75–86% of humanity's consumptive water use (Field and Michalak, 2015; Molden, 2007). Moreover, energy sector uses great quantities of water for hydropower, thermal electric plants, biofuel production, and oil and gas extraction via fracking (Maupin et al., 2014; Larsen et al., 2016). Currently, surface and underground fresh water resources supply the majority of global water demand (Vorosmarty et al., 2000). The availability and consumption trends significantly vary depending on socio-economic state and geographical location of a region (Lam et al., 2016; Carlton et al., 2016). Water resources are becoming scarcer in many geographical locations (Wallis et al., 2014; Liu et al., 2017). This has raised questions on access to water (The Water Project, 2017) and various aspects of water security such as environmental footprint of man-made water management systems (Palmer et al., 2015). Although access to fresh water is an emerging issue for many countries, it has already been a great problem for arid areas of the world such as Middle East and North Africa (MENA) region (Jemmali and Sullivan, 2014). These countries have been relying on production of fresh water form the seawater and brackish water resources using various desalination technologies for decades (MENA, 2011). In 2015, there were almost 20,000 desalination facilities worldwide with total daily fresh water production capacity of about 85 Mm^3 (Voutchkov, 2016).

2. Background on desalination and process integration

Based on the form of the energy used, we can classify current desalination technologies in two categories: (i) Thermal energy driven desalination processes that include Multi Effect Humidification (MEH), Multi Effect Distillation (MED), Multi Stage Flash (MSF), and Membrane Distillation (MD), and (ii) Electricity-driven processes, which is composed of Mechanical Vapor Compression (MVC), Thermal Vapor Compression (TVC), Reverse Osmosis (RO) and Electro Dialysis (ED). RO has the largest share among the installed desalination plants. RO and ED are the two mainly electricity-driven desalination techniques. Both can be used for brackish water (BW) that has a typical salinity level of 0.05–3%. The energy consumption of ED for BW is 3–4 kWh/m^3 while RO requires 0.5–1.5 kWh/m^3. RO process is also used to desalinate seawater, which has a typical salinity level of 3–5%, by consuming 4–10 kWh/m^3 of electricity (Kucera, 2014). Electricity-driven processes work solely with electricity where as heat-driven processes need energy in the form of electricity for driving pumps. For heat driven desalination processes the feed water quality does not change the energy demand dramatically. Thermal processes needs 60–200 kWh/m^3 heat and up to 2–5 kWh/m^3 electricity depending on the process (Kucera, 2014).

Although currently installed desalination capacity is primarily powered by fossil-based energy sources, there is a growing interest in the development of renewable desalination processes. Solar energy amongst other renewable energy sources has a particular advantage with the ability to directly supply thermal energy for heat-driven desalination technologies. However, depending on the temperature level requirement of the process, solar concentrators may be needed.

2.1. Process integration

Process systems engineering tools and techniques are widely used for synthesis and integration of chemical processes to produce fuels, chemicals, and electricity from a combination of resources. This is achieved by developing frameworks for heat integration (Duran and Grossmann, 1986; El-Halwagi, 2006), mass integration (Shenvi et al., 2013; El-Halwagi and Manousiouthakis, 1989), integration of various feedstocks (Floudas et al., 2012; Agrawal and Singh, 2010), and supply chain integration (Guerra et al., 2016). Some of the measures used to evaluate improvements in the performance of integrations include energy efficiency (Hamed, 2005), exergy efficiency (Favrat and Marechal, 2015; Al-musleh et al., 2014), technology selection (Palenzuela et al., 2015). Single or multiple of these objectives are applied to the problem of interest using process simulation tools, equation oriented modeling techniques, and/or a combination of both and solved/optimized.

2.2. Desalination for solar-rich water-poor regions

Considering most of the arid areas have high insolation, utilization of solar energy for desalination has drawn attention in the literature (Li et al., 2013; Shatat et al., 2013). Different desalination techniques, solar collector design and steam generation methods have been examined to investigate solar desalination alternatives (Kalogirou, 1998). Qiblawey and Banat reported an overview of solar thermal desalination processes (Qiblawey and Banat, 2008). It has been also reported that among the desalination techniques humidification–dehumdification, MD desalination techniques are attractive alternatives for renewable energy integration (Mathioulakis et al., 2007; Gonzlez-Bravo et al., 2015). Gude et al. reviewed different renewable energy alternatives and desalination techniques including hybridization of different desalination processes (Gude et al., 2010). Bacha et al. modeled different configurations of thermal storage for continuous operation of solar desalination (Ben Bacha et al., 2007). Various energy recovery configurations for solar Rankine cycle RO desalination plant was studied with identified potential to significantly reduce the cost of the recovery system (Ben Bacha et al., 2007). A low temperature, low pressure desalination system has been proposed that can be operated by waste or solar heat (Chang et al., 2012). A multi objective MINLP that considers the simultaneous minimization of cost and environmental impact of a solar Rankine cycles coupled with RO desalination plant has been developed (Salcedo et al., 2012).

Integration of desalination technology with Concentrated Solar Power (CSP) for simultaneous power and fresh water production is an attractive route to meet energy and fresh water demand. This concept has been proposed in a number of publications with detailed configurations presented in Gonzlez-Bravo et al. (2017), Moser et al. (2010) and Palenzuela et al. (2011a). Gonzlez-Bravo et al. present an optimization approach for designing water desalination systems involving heat integration and waste heat recovery to reduce the desalination cost, energy consumption, and overall greenhouse gas emissions (Gonzlez-Bravo et al., 2017). Moser et al. analyzed possible integration schemes for simultaneous power and fresh water production from solar energy. Two types of solar fields (parabolic trough and linear Fresnel reflector) and two types of desalination technologies (MED and RO) have been included in the study with thermal storage and fossil fuel added as backup energy sources (Moser et al., 2010). Palenzuela et al. presented a detailed study for production of 50 MWe net power and ~49 km^3/day fresh water with four different configurations. These configurations include various combinations of RO, low temperature (LT)-MED, Thermal Vapour Compression (TVC), and Parabolic Trough (PT)-CSP (Palenzuela et al., 2011a). Desalination integrated with CSP has been discussed in detail in this study and alternatives have been evaluated for Middle East and North Africa (MENA) region (Palenzuela et al., 2011a). A techno-economic feasibility analysis was performed by the Cyprus Institute for Concentrating Solar Power and Desalinated Water (CSP-DSW) Project in 2010. The study proposed to use CSP on Demand (CSPonD) technology, which is a combined solar collection and thermal storage technology (Slocum et al., 2011).

In addition to the above studies, various cogeneration solutions have been proposed by integrating desalination technologies such as multi stage flash or Multi Effect Distillation with the traditional steam cycles or gas turbines (Palenzuela et al., 2011b; Wang and Lior, 2007a,b). However, to the best of our knowledge, a thorough study of solar power integration has not been previously reported on the process level. The overall solar energy conversion efficiency can be increased by judiciously integrating processes that have complementary attributes. Here, we present integrated solar thermal process designs for (i) efficient fresh water and electricity production, and (ii) fresh water,