Resources, Conservation and Recycling 104 (2015) 181–193

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

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

Involving integrated seawater desalination-power plants in the optimal design of water distribution networks

Ramón González-Bravo [a], Fabricio Nápoles-Rivera [a], José María Ponce-Ortega [a,*], Mahmoud M. El-Halwagi [b,c]

[a] Chemical Engineering Department, Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Michoacán 58060, Mexico
[b] Chemical Engineering Department, Texas A&M University, College Station, TX 77843, USA
[c] Adjunct Faculty at the Chemical and Materials Engineering Department, King Abdulaziz University, Jeddah, Saudi Arabia

ARTICLE INFO

Article history:
Received 11 April 2015
Received in revised form 14 August 2015
Accepted 24 August 2015
Available online 15 September 2015

Keywords:
Seawater desalination
Macroscopic water networks
Water scarcity
Optimization
Aquifer water recharge
Sustainable water management

ABSTRACT

Water and energy consumption has increased substantially over the last decades. Water scarcity has led to an increase in the extraction of fresh water from aquifers, dams and lakes, and it has produced serious overexploitation problems. Furthermore, the population growth in urbanized areas and the increase in water and energy demands in industry, agriculture and households have amplified this problem. As consequence, there are several regions where is almost impossible to satisfy the water demands using the available water resources. In this context, the use of alternative water resources such as reclaimed water, rainwater harvesting and the potential use of desalinated water can be an option. However, desalinated seawater is very expensive because the high energy consumption, and this way to integrate a seawater desalination plant to a power plant to simultaneously produce clean water and power can be an attractive option. This way, this paper proposes an optimization formulation for synthesizing water networks to satisfy water and energy demands in a macroscopic system involving the use of existing water resources and the installation of integrated seawater desalination-power plants. A case study from Mexico (where satisfying the water demands has become a serious problem) is presented. Results show that the integrated system is able to satisfy the current water demands, the excess desalinated water can be used to recharge the overexploited aquifers and interesting profits can be obtained from the sales of power.

1. Introduction

Water scarcity occurs when the demand of fresh water exceeds the natural recharge in a specific place, this condition increases as a result of excessive water extraction from all sectors (domestic, industrial and agricultural users) compared to the available supply, according to the existing institutional arrangements (water irrigation rights) and available infrastructure. Water scarcity is presented as partial or no satisfaction of water demands, this situation causes economic competition for the quality and quantity of water, disputes between users, irreversible depletion of groundwater, as well as negative impacts on the environment (e.g. overexploited dams, rivers and aquifers) (FAO, 2012). The global water demand is projected to increase around 55% by 2050, mainly caused by water demands in industry (400%), thermal electricity generation (140%) and domestic users (130%). As a result, water availability will decrease and as consequence 40% of the world population will live in water-stressed areas by 2050. There is clear evidence that groundwater reserves are declining, currently about 20% of the aquifers are overexploited, some others are in critical conditions. Deterioration of wetlands worldwide is reducing the capacity of ecosystems to purify water. This challenge is becoming steeper as demands increase, especially in emerging economies, where agriculture, industry and urban development are evolving quickly. This way, there is needed to find sustainable ways to ensure access to fresh water for all (UN-Water, 2014).

Recently several strategies have been reported to solve the water distribution problem. In this context, Oliveira-Esquerre et al. (2011) proposed a methodology for minimizing the water use considering water reuse involving geographical and hydrogeological information, the proposed model is based mainly on water balances. Nápoles-Rivera et al. (2013) proposed a mathematical model for the sustainable water management in macroscopic systems, in which water demands are satisfied by rainwater and reclaimed water, where a multi-period model including storage and distribution schedule was reported. Gao et al. (2014) presented

* Corresponding author.
E-mail address: jmponce@umich.mx (J.M. Ponce-Ortega).

http://dx.doi.org/10.1016/j.resconrec.2015.08.010
0921-3449/

an optimization approach to integrate water management systems considering the reduction of fresh water consumption and water supply cost. Zheng and Zecchin (2014) introduced a multi-objective optimization method for designing water distribution systems in which multiple supply sources are taken into account, where the minimization of the entire network cost is subjected to the selection of pipe diameters and the optimization of the pressure across the network. Alnouri et al. (2015) presented a mixed-integer nonlinear programming (MINLP) model to integrate macroscopic water networks for water integration within industrial cities, in which centralized and decentralized water treatment options were introduced. Georgescu and Georgescu (2014) presented an optimization framework for scheduling pumping stations for water distribution networks in the city of Oradea in Romania. Nápoles-Rivera et al. (2014) proposed a mathematical programming model for the efficient and sustainable use of water under parametric uncertainty, in which public, agricultural and industrial demands are satisfied, furthermore this work introduced desirable levels of water in the natural reservoirs as part of the model to reduce the pressure over natural resources. Rojas-Torres et al. (2014) reported an optimization model for water storing and distribution in cities in a multiannual framework, it involves reclaimed water, harvested rainwater, dams, springs and deep wells to satisfy industrial, agricultural and domestic demands, and then this model was extended to include multiple objectives by Rojas-Torres et al. (2015). Hadadin et al. (2010) proposed an initiative to solve the problem of lack of water in Jordan, this approach is focused on reducing the overdrawing water from aquifers by the development of new supplies of water, rainwater harvesting, seawater desalination and reclaimed water reuse.

On the other hand, water and energy are extremely linked. Water is necessary for the production, distribution and use of energy, whereas energy is crucial for the extraction and transportation of fresh water to the final users. People everywhere, but especially the most vulnerable and marginalized, face great risks when access to either water and/or energy is limited or compromised. Currently, about 90% of energy production is based on not sustainable methods yielding huge amounts of non-reusable water. The International Energy Agency estimated the global water withdrawals for energy production in 2010 as 583 billion m^3. By 2035, it is expected that the water withdrawals will increase by 20% and the consumption by 85% (UN-Water, 2014). This way, several works focused on the optimization and utilization of water in power plants have been published (coupling power and desalination plants), where the produced water has been used to satisfy different demands. In this context, Hajeeh et al. (2003) proposed a dual-purpose plant for power generation and desalination using multi-stage flash distillation (MSF). Agashichev and El-Nashar (2005) developed an optimization model for the techno-economic evaluation of a triple hybrid reverse osmosis (RO), MSF and power generation, where the unit cost for electricity production and water desalination were minimized. Sanaye and Asgari (2013) proposed a multi-objective optimization model for combining a power generation cycle with a MSF desalination unit, where it was implemented an energy analysis based on mass an energy conservation equations. Almansoori and Saif (2014) presented a model to find optimal osmosis arrangements for seawater desalination and power generation, where it was presented a complete analysis about the optimal operating conditions for power production and desalination through reverse osmosis stages. Najafi et al. (2014) presented a model for integrating hybrid power generation systems with a MSF desalination unit, this approach presented an integrated thermodynamic, economic and environmental model, where the total costs are minimized, and the results showed that the initial investment and operating costs are paid back in 9 years. Esfahani and Yoo (2014) proposed a systematic approach for power generation coupled with a multi effect thermal vapor compression desalination system, the study was based on the net fresh water production and net power generation, the results indicated that the proposed configuration reduces the unit fresh water cost by coupling power and water generation.

Water scarcity, especially in arid regions, has driven the widespread use of desalinated seawater associated to power generation. This way, Muginstein et al. (2003) analyzed the possibility of implementing power desalination plants to satisfy energy and water demands in Israel, their results shown benefits in water and electricity supply with similar costs to the market. Liu et al. (2011) presented an optimization approach for integrating water resources including desalinated water, where the optimization task was split the regions to propose an optimal water management including potable and non-potable water systems, location of desalination plants, wastewater treatment and reclamation plants. Atilhan et al. (2011) introduced an optimization model to design desalination and distribution networks for water supply in arid regions, the model determined the technology (reverse osmosis or multiple-effect distillation) as well as the location and capacity of the desalination plant. Atilhan et al. (2012) introduced an optimization approach for designing macroscopic water networks taking into account desalination plants, it was presented a mathematical formulation involving desalination plants, groundwater, aquifers and recyclable water to supply industrial, agricultural and residential demands, where the authors used sources, sinks, interceptors and storage to represent the macroscopic water network.

From the above mentioned reports, the importance to satisfy the water and energy demands in arid regions has been highlighted. However, none of the above mentioned papers has proposed a systematic methodology to synthesize a macroscopic water network that simultaneously considers seawater desalination plants integrated to power plants and considering the available water resources (dams, wells, rivers, etc.) and alternative sources such as rainwater harvesting and reclaimed water reuse, neither the option to recharge the overexploited aquifers to improve the sustainability of the system. Therefore, this paper presents an optimization formulation for designing water networks in places with water scarcity, one important point is that the proposed model incorporates seawater desalination plants integrated with power plants. This way, the energy required in the desalination plant is provided by the heat excess from the power plant and the associated cost is absorbed by the sale of the electricity produced in the power plant. The proposed model incorporates traditional (dams, wells, river, etc.) and alternative (desalinated seawater, harvested rainwater and reclaimed water) water sources to satisfy the water demands. Furthermore, to improve the sustainability of the system, the proposed optimization formulation considers the recharge of overexploited aquifers. In addition, the proposed model accounts for the variation of the water demands through the year. Important challenges such as the optimal location for installing new units, and the scheduling and operation of the system are considered to maximize the overall benefit. The proposed optimization formulation is applied to a region of Mexico (in the State of Sonora), where the water scarcity has yield important social problems between different cities and users. The results show that the proposed approach can yield attractive solutions.

2. Problem statement

The problem addressed in this paper can be described as follows. Given a macroscopic water distribution system with:

- Three different types of users (i.e., domestic, agricultural and industrial); each one of these users has different water and