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Nuclear-Renewable Hybrid Energy System for Reverse Osmosis Desalination Process

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INTRODUCTION

The leading cause of global climate change is generally accepted to be growing emissions of greenhouse gas (GHG) as a result of increased use of fossil fuels [1]. Among various sources of GHG, the global electricity supply sector generates the largest share of GHG emissions (37.5% of total CO_2 emissions) [2]. Since the current electricity production heavily relies on fossil fuels, it is envisioned that bolstering generation technologies based on non-emitting energy sources, i.e., nuclear and/or renewables could reduce future GHG emissions.

Integrated nuclear-renewable hybrid energy systems HES) are very-low-emitting options, but they are capital-intensive technologies that should operate at full capacities to maximize profits. Hence, electricity generators often pay the grid to take electricity when demand is low, resulting in negative profits for many hours per year. Instead of wasting an excess generation capacity at negative profit during off-peak hours when electricity prices are low, nuclear-renewable HES could result in positive profits by storing and/or utilizing surplus thermal and/or electrical energy to produce useful storable products to meet industrial and transportation demands. Consequently, it is necessary (1) to identify key integrated system options based on specific regions and (2) to propose optimal operating strategy to economically produce products on demand.

In prioritizing region-specific HES options, available resources, markets, existing infrastructures, and etc. need to be researched to identify attractive system options. For example, the scarcity of water (market) and the availability of abundant solar radiation make solar energy (resource) a suitable option to mitigate the water deficit the Central-Southern region of the U.S. Thus, a solar energy-driven desalination process would be an attractive option to be integrated into a nuclear power plant to support the production of fresh water in this region.

In this work, we introduce a particular HES option proposed for a specific U.S. region and briefly describe our modeling assumptions and procedure utilized for its analysis. Preliminary simulation results are also included addressing several technical characteristics of the proposed nuclear-renewable HES.

REGIONAL CASE STUDY

The state of Arizona is one the drought-prone regions in U.S., suffering from freshwater shortage [3]. On the other hand, significant solar photovoltaics (PV) capacity is expected to be installed in this region due to the abundant solar energy input and the rapidly decreasing cost of PV technology. Thus, solar PV is an appropriate option within a nuclear-renewable HES to bridge the gap between drinking water supply and demand. We propose an integrated nuclear-solar PV HES as a regional option in Arizona to support the production of fresh water via brackish water reverse osmosis (BWRO) desalination process.

System overview

A configuration of the proposed HES is shown in Fig. 1. Steam is produced from a nuclear small modular reactor (SMR), which drives the steam turbines to generate electricity for the grid. Additional electricity is generated via solar PV arrays during the period when the solar radiation is available. As shown in Fig. 1, the PV power is not inputted directly to the electricity distribution center but via a grid-scale battery. This battery is installed in order to dampen excessive unsteadiness due to high variability in available PV power. The combined electricity produced from both a SMR and PV modules is sent to the power grid. The amount of required generation to meet the demand is subtracted from the total electricity generation, yielding an excess generating capacity that could be utilized to produce new energy currencies. This excess electrical power is directed to an RO plant, from which the fresh water is produced.

RO process utilizes a semi-permeable membrane, which allows water to pass through but not salts, to separate the fresh water from the saline feed water. As illustrated in Fig. 2(a), a typical BWRO plant consists of four main components: feed water pre-treatment, high-pressure (HP) pumping, membrane separation, and permeate post-treatment. In this work, our modeling efforts are focused on the two components (i.e., high pressure pumping and membrane separation) enclosed in the dashed box shown in Fig. 2(a). Fig. 2(b) depicts the configuration of an RO vessel used in BWRO, which typically comprises of seven membrane models connected in series. These pressure vessels are arranged in rows in each membrane stage, with two-stage membrane separation is being typical.

Assumptions and procedure

The SMR is modeled as a dynamic physics-based component and is operated at full thermal generation rate (600 MWth), generating equivalent electrical power of 180

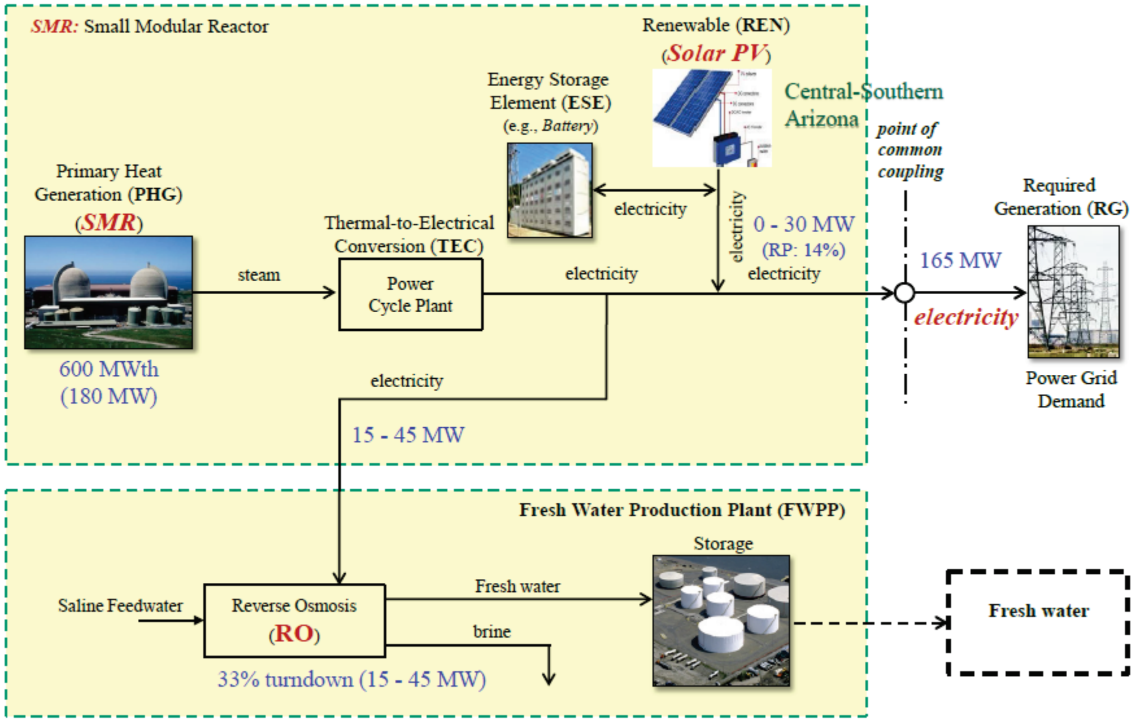

Fig. 1. Architectural topology of the proposed nuclear-renewable HES.

MW with Rankine cycle. On the demand side, a constant electricity profile of 165 MW delivered from the nuclear-renewable HES to the grid is assumed, ensuring that the BWRO plant is operated continuously with a minimum load of 15 MW, even when no renewable power is provided to the system.

The PV power generation is modeled as a time-series input signal to the battery based on solar irradiance as wells as ambient temperature data [4]. Historical data of solar irradiance and ambient temperature at Southwest Solar Research Park in Phoenix, Arizona were obtained from National Renewable Energy Laboratory database[2] and used in the case study. Each individual PV module is sized such that it can provide maximum of 4 MW rated power at the standard test condition (i.e., 25 °C and solar radiation of 1000 W/m^2). A linear scaling in renewable power with the number of PV modules is assumed. There are total of nine PV modules, providing the total nominal capacity of 36 MW.

With the historical weather data and battery size considered as the bases of this study, at the highest solar irradiance, the maximum amount of renewable power that can be delivered to the BWRO desalination plant is reduced to 30 MW due to the power smoothing effect introduced by the battery. With nuclear power generation, the total electric power input to the BWRO desalination system swings from 15 to 45 MW, yielding the turndown ratio of 33%.

The BWRO desalination plant is sized for 44,900 m^3/hr (284 million gal/day (MGPD)) capacity, about three times the size of one of the current largest seawater RO desalination systems [5]. The plant with this capacity consumes 45 MW of electrical power to generate the required feed pressure (15.15 barg) for desalting the brackish water, containing 2,200 part per million (ppm) of total dissolved solids (TDS). The assumed values for the simulation parameters used in the case study are listed in Table I. The FilmTech BW30-400 membrane, a spiral-wound membrane manufactured by Dow Chemical, is chosen for simulation and its specifications can be found in Ref. [6].

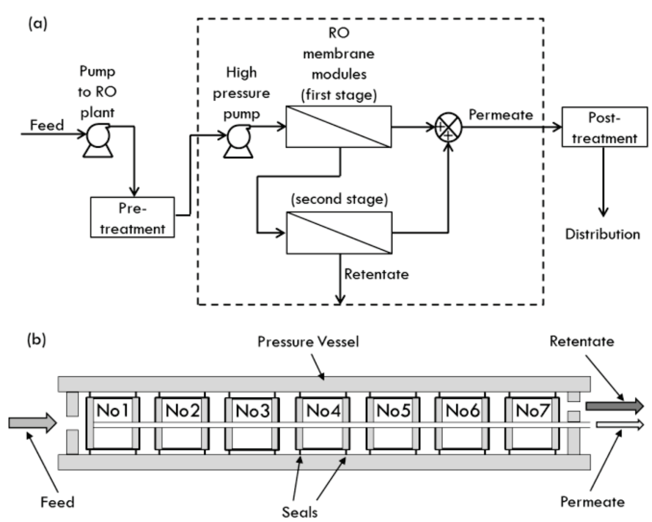

Fig. 2. BWRO desalination process: (a) Process flow diagram for a two-stage BWRO plant. (b) Schematic of an RO vessel.

Table I. Parameters for the RO process simulation.

Parameter	Value
Number of HP feed pumps, each of which is rated at 1MW	45
Pump efficiency	0.75
Pump speed [RPM]	1,800
Number of stages	2
Number of pressure vessels	10,260
Number of RO elements in a pressure vessel	7
Fouling of an RO membrane due to scale formation [%]	5
Feed temperature [°C]	25
Feed salinity[2] [ppm]	2,200
Feed pressure [barg]	15.15
Permeate flow rate [m^3/hr] (MGPD)	44,900 (284)
Average permeate salinity [ppm]	21
Recovery ratio (ratio of permeate flow rate to feed flow) [%]	75

In this work, the emphasis is on dynamic simulation and control of RO desalination process over the full range of operating conditions. We extend the work shown in Ref. [6] and develop an 1-D dynamic model to describe flow in the axial direction on both the feed and permeate sides by incorporating the overall fluid and solute mass balance equations as follows:

$$V_B \frac{d\rho_b}{dt} = Q_f \rho_f - Q_r \rho_r - Q_p \rho_p \qquad (1)$$

$$V_B \frac{dC_b}{dt} = Q_f C_f - Q_r C_r - Q_p C_p \qquad (2)$$

where Q, C, and ρ refer to the volumetric flow rate, salt concentration, and density of the solution, respectively. Subscripts f, r, p, and b refer to the feed, retentate, permeate, and bulk (average between the feed and retentate) streams, respectively. V_B is the brine channel volume of an RO element. Also, the solution-diffusion model modified with the concentration polarization theory is applied to predict RO performance. The goal is to control the electrical power consumption of the HP RO pump with variable electrical load (VEL) in order to maintain the grid stability and reliability.

RESULTS

The proposed HES was modeled dynamically with the object-oriented Modelica language using the Dymola tool and *Modelica.ThermoPower* library [7].

Plant responses to the step change made in VEL

Fig. 3(a) compares the amount of electrical power consumed in the BWRO system ($P_{I,\,RO}$) to the step change made in electric load (L_E) from 0.8 to 1.0 per unit value, pu (per unit value is the decimal equivalent of percent value). The results show that the RO pump exhibits a fast dynamics (settling time of about 20 seconds), assuring that the integrated nuclear-solar PV HES can absorb local and instantaneous variability in the renewable power source while operating the nuclear reactor at near steady state.

Fig. 3(b) and 3(c) show the RO-elements responses for the selected membrane module numbers (1st, 7th, and 14th) to step change in L_E. It can be seen from Fig. 3(b) that as the power set-point increased, so did permeate production rates in all three membrane modules. This is because as the energy requirement increases at a fixed feed pressure, the feed flow rate increases, resulting in a higher solvent flux (permeate flow rate). In Fig. 3(c), the results also show that the solute concentration in permeate (permeate quality) is inversely proportional to a permeate flux (flow rate).

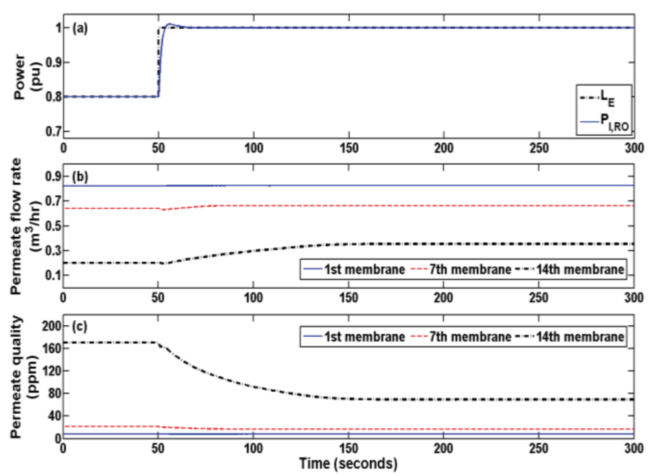

Fig. 3. RO elements responses to L_E change from 0.8 to 1.0 pu: (a) L_E vs. $P_{I,\,RO}$. (b) Permeate flow rate, Q_p. (c) Permeate salinity, S_p.

Plant responses with varying PV penetration

For the considered regional case study, available solar irradiance and ambient weather data were sampled at time intervals of 60 seconds. The simulation was conducted for a time period of one week (6.048×10^5 seconds), for a total of 10,080 time steps in the simulation. Figs. 4(b) and 4(c) represent the permeate flow rate and quality, respectively, in response to set-point variations in VEL over an one week (see Fig. 4(a)). As seen in the previous case, the freshwater production rate increases and the water quality is improved with increasing power requirement. The highest solute concentration in permeate observed was 111 ppm, which is far less than a drinking water taste threshold set by the U.S. Environmental Protection Agency (TDS of 500 mg/L), ens-

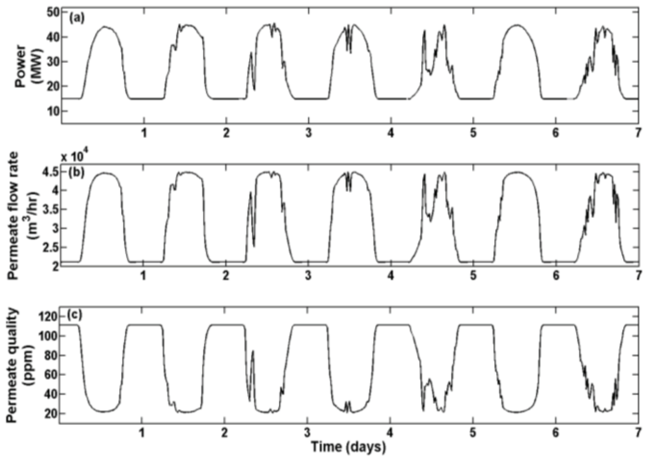

Fig. 4. BWRO plant responses to L_E change over an one week in early July, 2013: (a) L_E. (b) Q_p. (c) S_p. Note that $P_{I, RO}$ and L_E are essentially the same when plotted on the same figure, so we do not show $P_{I, RO}$ here.

uring acceptable salt rejection rates over the entire operating conditions. Based on the assumptions listed in Table II, the proposed HES can supply the fresh water of 48.3 billion gallons per year. This amount could meet about 70% of the current total water consumptions in Phoenix and Tucson, Arizona (68.7 billion gallons per year).

Table II. Parameters used to estimate the total water demands in Phoenix and Tucson, Arizona

Parameter	Value
Population in Phoenix[3]	1.56×10^6
Population in Tucson[3]	5.29×10^5
Daily water usage by an average American [gallons]	90
Plant operating factor [%]	95
Yearly average Q_p [million gallons per year]	199

The results suggest that higher overall profits are expected from utilizing greater capital assets of the proposed HES at times of low or negative electricity prices and producing "clean" energy currency for the combined electric grid and industrial manufacturing sector. Furthermore, the potential of nuclear-renewable energy as low-carbon energy resources is obvious.

NOMENCLATURE

C = salt concentration in the stream, kg/m^3
L_E = variable electrical load in the BWRO system, MW
$P_{I, RO}$ = electrical power consumed in the BWRO system, MW
Q = volumetric flow rate, m^3/hr
S = quality (or salinity) of the stream, ppm
t = time, hour
V_B = brine channel volume of an RO element, m^3

Greek Letter

ρ = density of the solution, kg/m^3

Subscripts

b = bulk (average between the feed and retentate) stream
f = feed stream
p = permeate (or product) stream
r = retentate (or reject) stream

ENDNOTES

[1]Accessed on Jan. 5, 2015 at http://www.nrel.gov/midc/ssrp/
[2]Of the various possible dissolved components in feed stream, the only components considered in this study were Na^+ and Cl^-, i.e., in the feed stream, the mass concentration of TDS is the same as that of NaCl.
[3]Accessed on Jan. 15, 2015 at http://quickfacts.census.gov/qfd/

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