Unit-Commitment Framework for Estimating the Operational and Economic Impact of Grid-Level Solar PV Generation in Kuwait

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***Abstract*—This study uses a unit-commitment framework to optimize the scheduling of power generation and desalination assets in Kuwait with the objective of minimizing the cost of primary energy consumed by these assets. This framework can be used to estimate the operational and economic impact of adding new solar PV capacity to Kuwait's power grid. Based on the results of this analysis, adding solar PV to Kuwait's power grid has an impact on the optimal operating schedule for thermal power plants and desalination plants and reduces the cost of primary energy for fueling the power and desalination plants. However, when the capital cost for the solar PV capacity is also considered, the energy savings alone are not sufficient to justify the investment cost.**

I. Introduction

Demand for electricity and water in Kuwait more than doubled between 1995 and 2014 [1]. All of Kuwait's grid-level power generation assets, including steam turbine cogeneration plants, combined cycle gas turbine power plants, and open cycle gas turbines, use fossil fuel energy sources, including domestically produced natural gas, imported liquified natural gas (LNG), heavy fuel oil, gas oil, and crude oil. As for water, as much as 98% of demand for fresh water is met through desalination. Desalination plants are highly integrated with Kuwait's power generation systems, with nearly 700,000 m^3/day of desalination capacity being thermal distillation units, e.g., multiple stage flash (MSF), that are integrated with steam turbine cogeneration plants. Kuwait also has over 200,000 m^3/day of reverse osmosis (RO) desalination capacity.

In light of increasing demand for electricity and water, Kuwait is seeking ways of reducing the cost of primary energy for fueling their power generation and desalination systems. One way for Kuwait to reduce their primary energy consumption would be to install grid-level solar PV capacity. Solar PV is a good fit for Kuwait's power grid because of their high solar insolation and high demand for electricity for air conditioning over the course of the day. Adding solar PV capacity to Kuwait's power grid would decrease the cost of generating electricity from thermal generators during the parts of the day with sufficient solar irradiation. As solar PV capacity increases on Kuwait's power grid, thermal generators have to turn down or off while solar generation is on line. However, many of these power plants are cogeneration plants integrated with thermal desalination plants. Thus, because these thermal distillation plants are needed to meet daily demand for desalinated water, there is a limited extent to which these thermal generators can be turned off. Instead of turning off cogeneration plants, solar PV generation can be curtailed based on the assumption that tracking PV arrays can be turned away from the sun to reduce their power output. Taking curtailment into consideration along with the cost of investing in new solar PV capacity, the net savings, i.e., energy savings minus investment cost, can decrease with excessive new solar PV capacity. This study uses a unit-commitment framework to estimate the operational and economic impact of adding new solar PV capacity to Kuwait's power grid.

II. Methods

A unit-commitment model is used to determine the optimal hourly operating schedule for Kuwait's power generation and desalination assets on a daily basis. This model is run for each day of the year to estimate total annual cost of fuel consumption for power generation and desalination. The objective of this model is to minimize the daily cost of fuel consumed by the set of generators, G, summed over a defined time set, T, as defined by equation 1.

$$FC(d) = \sum_{g \in G} \sum_{t \in T} \bar{P}_{fuel}(g,d) \times Q(g,t) \quad (1)$$

Where Q is the fuel consumed [Btu] by a thermal generator g during hour t, and $\bar{P}_{fuel}$, is the daily weighted average of fuel cost [$/Btu] for each thermal generator. The steam turbine power plants run on a combination of domestically produced natural gas, heavy fuel oil, crude oil, and gas oil, and the gas turbine power plants run on a combination of imported natural gas and gas oil.

The gross electricity produced by the set of thermal generators on an hourly basis, $W_{thermal}$, plus the electricity produced by solar PV, W_{pv}, has to account for the auxiliary power needed to run the power stations, W_{aux}, the electricity needed to run the desalination plants, W_{desal}, and the consumer demand for electricity, W_{demand}, as shown in equation 2.

$$\sum_{g \in G} W_{thermal}(g,t) + W_{pv}(t) = \sum_{g \in G} (W_{aux}(g,t) + W_{desal}(g,t)) + W_{demand}(t) \quad (2)$$

In addition to meeting the hourly demand for electricity, the total volume of water desalinated by the set of desalination plants must be sufficient to meet daily demand for desalinated water as shown in equation 3.

$$\sum_{g \in G} \sum_{t \in T} V_{desal}(g,t) = V_{demand}(d) \quad (3)$$

The electricity produced from PV is a function of the incident solar irradiation, Q''_{isr}, the total area of solar panels, A_{pv}, and the net efficiency of the solar panels, η_{pv}, as shown in equation 4.

$$W_{pv} = \eta_{pv} A_{pv} Q''_{isr} \quad (4)$$

The electrical energy needed to run the power and desalination plants, W_{aux} and W_{desal}, is determined based on linear regressions with $W_{thermal}$ and V_{desal} as the independent variables, respectively, where V_{desal} is the hourly volume of desalinated water produced by each desalination plant. The fuel consumption from the plants that only generate electricity, i.e., open cycle gas turbine and combined cycle gas turbine power plants, is estimated using quadratic regression with $W_{thermal}$ as the independent variable. It is common for power plant fuel consumption to be modeled as a quadratic function in unit-commitment dispatch models [2]. The model uses a piecewise linear approximation of this quadratic regression so that the model can be solved as a linear program. The fuel consumption of the cogeneration plants is estimated using a multi-linear regression of the hourly gross electricity production and desalination volume as shown in equation 5.

$$Q(g,t) = c_0(g) + c_1(g) W_{thermal}(g,t) + c_2(g) V_{desal}(g,t) \quad (5)$$

Each power and desalination plant is also constrained by its minimum and maximum hourly output. This formulation is straightforward for the power-only plants and desalination plants using a binary on/off variables as is typical of unit-commitment models [2], [3]. The maximum output constraints for each cogeneration plant is also limited by how much steam is removed from the power cycle and used for distillation. The derivation of this constraint is shown in equations 6 – 8. Equation 6 determines the max rate of fuel consumption, Q_{max}, when the cogeneration plant is not distilling any water and is generating electricity at full capacity, $W_{gen,cap}$. Using the same value for the max fuel consumption, equation 7 can be rearranged to determine the maximum electricity generation for the cogeneration plant, $W_{cogen,max}$, based on the volume of distilled water, resulting in equation 8.

$$Q_{max}(g,t) = c_0(g) + c_1(g) W_{gen,cap}(g) \quad (6)$$

$$Q_{max}(g,t) = c_0(g) + c_1(g) W_{cogen,max}(g,t) + c_2(g) V_{desal}(g,t) \quad (7)$$

$$W_{cogen,max}(g,t) \leq W_{gen,cap}(g) - \frac{c_2(g)}{c_1(g)} V_{desal}(g,t) \quad (8)$$

The minimum fuel consumption of the cogeneration plants is constrained to generate enough steam for the distillers in addition to a minimum flow rate of steam through the turbine. The minimum flow rate through the steam turbine is defined as 15% of the flow rate of steam when the turbine is operating at max capacity. The corresponding fuel consumption, $Q_{min,ST}$, can be calculated using the definition of Q_{max} from equation 6 assuming a linear relationship between steam production and fuel consumption as shown in equation 9.

$$Q_{min,ST}(g,t) = 0.15 \times x_{gen}(g,t)(c_0(g) + c_1 W_{gen,cap}(g)) \quad (9)$$

Where x_{gen} is the binary on/off variable for the steam turbine. The minimum fuel consumption required to produce steam for the distiller can be estimated as a function of the "gained-output ratio" (GOR) of the distiller, i.e., the mass of distillate produced per mass of steam input to the distiller. A GOR of 11 is assumed for this analysis based on data provided by the Kuwait Foundation for the Advancement of Science. Equation 10 estimates the minimum fuel consumption required to produce steam for distillation, $Q_{min,dis}$.

$$Q_{min,dis}(g,t) = \frac{V_{desal}(g,t)\rho_{water}}{q(g)GOR} \quad (10)$$

Where $q(g)$ is the ratio of the mass flow rate of steam to the rate of fuel consumption by the cogeneration plant. The total minimum fuel consumption for each generator is the sum of equations 9 and 10 as shown in 11.

$$Q_{min}(g,t) \geq Q_{min,ST}(g,t) + Q_{min,dis}(g,t) \quad (11)$$

The last constraint specific to the cogeneration plants is that a distillation plant associated with a steam turbine power plant can only run if the associated steam turbine is also running. This model includes constraints on the minimum up and down time for the power and desalination plants as described by Carrion and Arroyo [2]. This model also includes startup cost constraints for each power plant modeled as piecewise linear functions of the time each generator has been turned off as described by Kumar et al. [3]. Estimates for the startup fuel consumption are taken from [4].

The model is run for each day, d, of an entire year, Y, and repeated with a range of values for solar PV capacity. The total annual cost is defined by equation 12.

$$AnnualCost = \sum_{d \in Y} FC(d) + cfr \times C_{pv} \times S_{pv} \quad (12)$$

Where the daily fuel cost, FC, is calculated using equation 1, S_{pv} is the rated solar PV capacity [MW], C_{pv} is the overnight capital cost of new solar PV [$/MW], and cfr is the annual cost of financing the solar PV capacity as defined in [5].

III. Results

The unit-commitment model was run for each day of 2014. The sum of hourly solar generation for the entire year is shown in Figure 1. Based on these results, the average capacity factor for solar PV in Kuwait would be approximately 14%. The average curtailment of solar PV generation is less than 1% when solar PV capacity is less than 8 GW and is over 4% for 8 GW of solar PV capacity. The corresponding change in hourly power output from cogeneration power and desalination plants is shown in Figure 2. As more solar PV capacity is added to the grid, less electricity is generated by cogeneration power plants during the hours when solar PV generation is on line. At the same time, hourly desalination volume from cogeneration plants tends tends to flatten out, that is, the peak hourly desalination volume is reduced, when less than 8 GW of solar PV are added to Kuwait's power grid. When 8 GW of solar PV are added to Kuwait's power grid, peak desalination volume starts to increase again, likely the result of cogeneration plants turning off while solar PV generation is on line. Note that electricity demand for desalination accounts for 4–6% of total electricity demand.

The net additional cost for solar PV, i.e., the annual financing cost minus the savings from reduced energy consumption, is shown in Figure 3. These calculations used two different estimates for the capital cost of utility-scale solar PV, 1160 and 2710 $/kW for the low and high end, respectively. In all cases considered, the difference between financing cost and savings increased as more solar PV was added to Kuwait's power grid. These results would have been more favorable for the cost effectiveness of solar PV if the variable O&M costs for thermal power generators were also included in the unit-commitment model. Similarly, a price on carbon emissions would also improve the cost effectiveness of new solar PV capacity in Kuwait. Because demand for electricity in Kuwait is increasing, future work should also include comparison of the cost new solar PV capacity and new thermal power generation capacity.

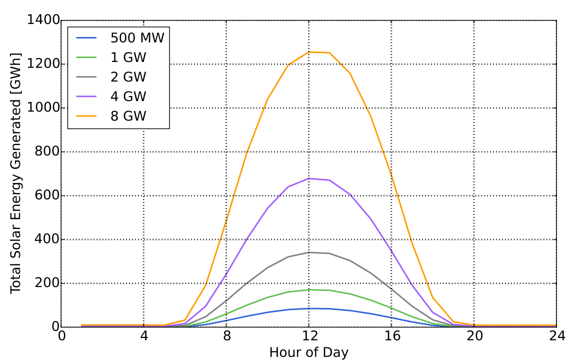

Fig. 1. For the capacity of solar PV considered, the average capacity factor for solar generation is approximately 14%. For all cases below 8 GW, average curtailment is less than 1%, whereas average curtailment is more than 4% when 8 GW of solar PV are added to Kuwait's power grid.

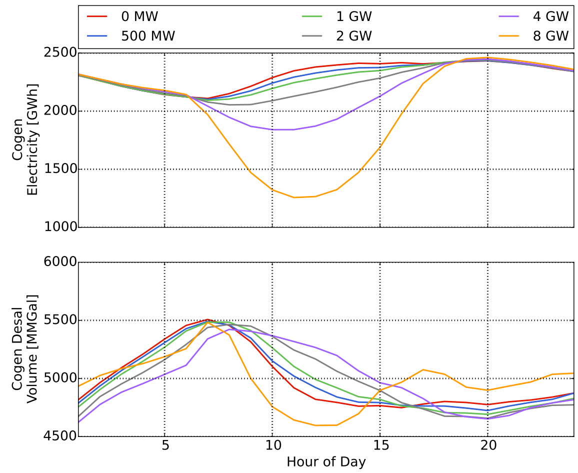

Fig. 2. As more solar PV capacity is added to the grid, less electricity is generated by cogeneration power plants during the hours when solar PV generation is on line. At the same time, hourly desalination volume from cogeneration plants tends tends to flatten out, that is, the peak hourly desalination volume is reduced, when less than 8 GW of solar PV are added to Kuwait's power grid. When 8 GW of solar PV are added to Kuwait's power grid, peak desalination volume starts to increase again, likely the result of cogeneration plants turning off while solar PV generation is on line.

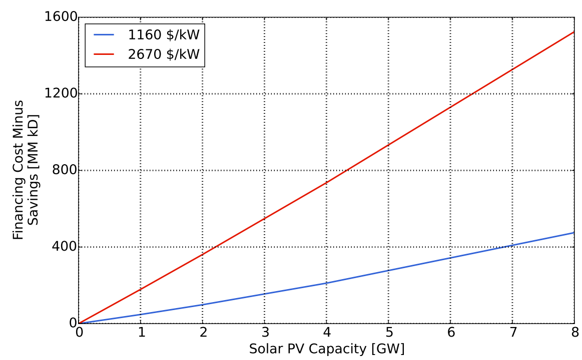

Fig. 3. For both high and low estimates of the capital cost of solar PV, 1160 and 2670 $/kW, respectively, the difference between the cost of financing the solar panels and the savings from reduced energy consumption increases.

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References

[1] "Statistical yearbook," tech. rep., Kuwait Ministry of Electricity and Water, 2015.

[2] M. Carrion and J. M. Arroyo, "A computationally efficient mixed-integer linear formulation for the thermal unit commitment problem," *IEEE Transactions on Power Systems*, vol. 23, August 2006.

[3] J. Sumbera, *Modeling generator constraints for the self-scheduling problem*. PhD thesis, University of Economics, Prague, 2011.

[4] N. Kumar, P. Besuner, S. Lefton, D. Agan, and D. Hilleman, "Power plant cycling costs," tech. rep., National Renewable Energy Laboratory, April 2012.

[5] "Simple levelized cost of energy (lcoe) calculator documentation." http://www.nrel.gov/analysis/tech_lcoe_documentation.html.