Paper ID APEN-MIT-2022_2545
Applied Energy Symposium: MIT A+B
July 5-8, 2022 • Cambridge, USA

ASSESSING THE POTENTIAL AND OPTIMAL SCHEDULING OF AN INTEGRATED PUMPED HYDRO REVERSE OSMOSIS SYSTEM FOR EGYPT

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Abstract— Energy storage and water desalination are two fields where Egypt is intensively investing in to plan for the current and future energy and water demands as well as commit to its sustainability targets, Integrated Pumped hydro Reverse osmosis System "IPHROS" is a system that combines both water production and energy storage, its operating schedule in studied in multiple scenarios that represent current status and future trends. The system is modeled as an unconstrained price taker, this revenue scheme starts yielding a positive re-turn on investments when higher renewables penetration are added to the grid but also in-creases the overall grid emissions, the IPHROS was also modeled in an off-grid scenario to provide energy and fresh water to a hydrogen electrolyzer, which proved to be the most profitable scenario for IPRHOS.

I. Introduction And Literature Review

Climate change is arguably the most serious challenge facing the global community during the 21st century, the scale of its threat should not be debatable nor should the proactive measures to mitigate it be a partisan issue. Rather actionable items must be developed by the scientific and engineering communities in partnership with political, business, and community leaders as the future of all depends on taking action now by all.

A. Literature Review

Energy storage can disrupt markets by exponentially increase the market penetration of renewables and transform power supply towards green energy sources. Researchers have presented many different methodologies to optimize energy storage, especially pumped hydro storage, operation and scheduling in numerous situations and formations.

Some papers modeled energy storage as a price taker and discussed their operation scheduling to maximize revenue. For example, the authors in [1] present methods for optimum daily operational strategy of pumped hydro storage, simulated on a real case study with the objective of maximizing revenue, additionally the paper also provides storage sizing models. Similarly, the authors in [2] also provide a dispatch model for energy storage as a price taker, while increasing penetration of renewable energy sources beside investigating the storage-induced emissions.

Another modeling objective is maximum peak power reduction achieved by energy storage, and authors in [3] introduce a parameter called the F-Factor to evaluate the potential peak reduction by a specific energy storage technology by modeling the energy storage with the objective of minimizing the maximum demand.

Network security has also been an important topic, and authors in [4], present a unit commitment model to account for storage reduction in wind power curtailment in high and low wind power outputs in order to maximize the plant's capacity credit.

All of the previously cited work, model pumped hydro storage solely as an energy storage device, few pieces of research include an integrated system of energy and water supply systems, Authors in [5] provide an optimal strategy and optimal sizing of such system based on S. Vicente island's grid with a 30% wind power injection limit using a multi-objective derivative free method to achieve minimum cost, maximum RES share and minimum curtailed wind power.

Finally, article [6] introduced a stand-alone integrated pumped hydro reverse osmosis system (IPHROS) that reduces the overall capital cost by sharing some of the infrastructure as compared to the two separate systems, the authors also provided a methodology for the site selection and assessment to construct such system and eventually proposing a sizing methodology dependent on the number of people which such system serves.

B. Power Demand and Energy Mix

Over the past decade, Egypt's power demand had consistent growth, recording an annual growth rate of 6%. In 2016, the peak load demand was near the installed capacity. [7]
Electricity is consumed by different end users in the economy, divided between residential (47%), industrial (25%) and commercial (12%), with the remainder used by government, agriculture, pub`
For many years, the Egyptian government granted subsidies for energy prices. This has naturally led to rapid increase in demand, with the subsidy bill increasing at a compound annual rate of 26% between 2002 and 2013.
In 2015, Egypt began a plan to cut back electricity subsidies by July 2019 with full cancellation of subsidies, the plan was later extended to 2025. [8]

1) Renewable Energy Penetration in The Energy Mix

Egypt sustainable development strategy (SDS): Vison 2030 aims to achieve a diversified energy mix where Renewable energy has a central role to play, as detailed in the Integrated Sustainable Energy Strategy to 2035, released by the Ministry of Electricity and Renewable Energy in 2015
The total installed capacity of renewable energy sources is expected to reach 19.2 GW by 2021/22 and increase to 49.5 GW and 62.6 GW in years 2029/30 and 2034/35 respectively. [8]

II. Integrated Pumped Hydro Storage Reverse Osmosis System

Egypt's Pumped hydro-storage feasibility had been studied before, In 1979 a Joint Egypt/United states report investigated the feasibility for pumped hydro-storage on the Red Sea and found large potential at areas near Suez [9] and In 1989 a pumped-hydro plant was proposed [10] those pumped storage schemes that have been conceived in Egypt included some technical problems such as corrosion of pipe and turbine system [11]
Pumped hydro storage and reverse osmosis were found to have similar ideal pressure height requirements [6], and they were found to be feasible if large mountains were close to large bodies of water. The topology along the Gulf of Suez provides this requirement in addition to the abundance of renewable energy sources in that area as mentioned before, all that make the Gulf of Suez an ideal habitat for the IPHRO System.

Fig. 1. Shows a schematic diagram of the proposed IPHROS in [6], where Pumped hydro Storage and Reverse Osmosis systems are co-located and they share the water inflow/outflow infrastructure and therefore eliminating costs for high pressure pumps used for the reverse osmosis system. In addition, since 20x water is needed for the energy storage and power generation than for desalination, the high outflow out to the sea when generating power can dilute the brine outflow from desalination thus eliminating the need for a costly long outflow pipe and potential brine poising of delicate ecosystems. This symbiotic approach thus potentially reduces costs due to sharing of some elements between the two systems.

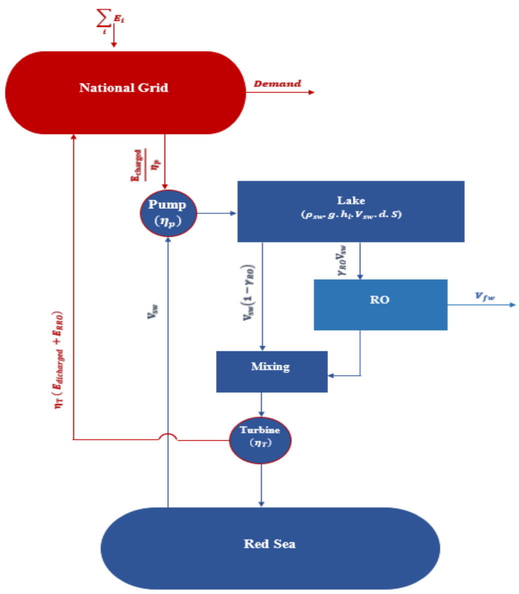

Fig. 1 Schematic Diagram Of IPHROS

A. System description

The IPHROS is coupled with the utility grid to manage the intermittent nature of renewable energy technologies by storing energy at periods of energy surplus (Supply > Demand) and discharging power at periods of energy deficit (Supply < Demand), the Sea body (e.g. Red Sea) acts as the lower reservoir while sea water is pumped to an upper reservoir to store its potential energy, water from the upper reservoir could flow down to a pretreatment unit and flow further downhill in pipes to directly supply the RO membrane. This operation is practical if fresh water is needed near sea level. Else aqueducts can be designed and built to deliver the water to where it is needed. If pumped over a mountain range, energy can be recovered on the downhill side as is done in the LA aqueduct.

DEM Data were downloaded through United Stages Geographical Survey (USGS) website, and was later analyzed using elevation contour maps for each region using ArcMap tool.

B. Ataqa Pumped Storage Power Plant

Ataqa pumped hydro storage plant is a 2.1 GW (phase 1) pumped hydro project that is being developed in Suez, Egypt at the Ataqa mountain

The project is designed to operate as a freshwater pumped hydro storage only, but as Egypt plans to spend 8.6 billion dollars until 2030 in doubling the quantities of desalinated water used in the country's drinking water [12]. Thus, it could make sense to use the symbiotic approach of the IPHROS to integrate a reverse osmosis plant with the pumped hydro plans by adding a companion pumped seawater hydro system next to the freshwater system, and share grid tie in and engineering and construction resources.

TABLE 1. Model Map

Model / Scenario	Economic Dispatch without IPHROS	Grid Connected IPHROS without Carbon Tax	Grid Connected IPHROS with Carbon Tax
Load Profile: 1 Energy Mix: 1	Scenario 11	Scenario 11I	Scenario 11IC
Load Profile: 2 Energy Mix: 1	Scenario 21	Scenario 21I	Scenario 21IC
Load Profile: 3 Energy Mix: 1	Scenario 31	Scenario 31I	Scenario 31IC
Load Profile: 4 Energy Mix: 1	Scenario 41	Scenario 41I	Scenario 41IC
Load Profile: 1 Energy Mix: 2	Scenario 12	Scenario 12I	Scenario 12IC
Load Profile: 1 Energy Mix: 3	Scenario 13	Scenario 13I	Scenario 13IC
Load Profile: 1 Energy Mix: 4	Scenario 14	Scenario 14I	Scenario 14IC

1) Technical Specifications of Ataqa

. The technical specifications of the pumped hydro plant according to the government's requirements are listed in Table 2. (Data here is shared by the Egyptian Energy Authority).

C. Site Selection For Modeling

Ataqa is chosen for modeling herein since it has the highest A* - Index as well as it is very applicable and already in the Egypt's plan for the near future. Region EGY-C will be modeled in some scenarios as well for comparison purposes between different scales of IPHROS as EGY-C has dramatically more energy and power ratings.

TABLE 2. Ataqa Technical Specifications

Item	Dimensions
Upper Reservoir Level (m)	832
Lower Reservoir Level (m)	258
Power Rating (GW)	2.1
Energy Capacity (GWh)	8.72
Water volume at upper reservoir (m3)	7330000
Water volume at lower reservoir (m3)	7330000
Overall System Efficiency	76%

III. MODELING

The General Algebraic Modeling System (GAMS) is used for the optimization models of IPHROS that will be discussed in this paper.

A. The Base Scenario

For the status quo, the load profile used for simulation is the Peak Load Day (25th of July, 2018) provided in the annual report 2018 / 2019 by the ministry of electricity [13] Shown in Fig. 2.

The Energy Mix is also provided in [13] is a mix of different technologies mostly thermal stations shown in Fig. 3.

B. Model Scenarios

The IPHROS behavior will be modeled under different scenarios with increasing demand or increasing renewables penetration in the energy mix to analyze how the IPHROS system operation schedule would change under each scenario compared to the economic dispatch models (formulated through set of equations listed below) without IPHROS system.

A model map is shown below illustrating the different scenarios that would be run to test effect of introducing IPHROS as well as carbon tax on system parameters and feasibility.

1) Load Profiles

These profiles include the base load profile shown in Fig. 2 [13] and three other profiles based on the base load with a 20% increase each to study how would the IPHROS system behave at higher demand levels.

Higher demand scenarios are reasonable to consider with Egypt's consistent population growth which will lead to higher energy and fresh water needs.

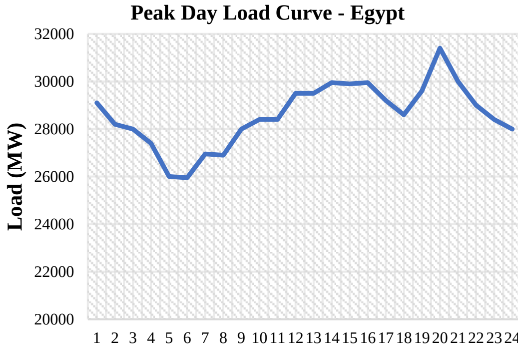

Fig. 2 Load Profile In Peak Load Day, July 2018, Egypt

2) *Energy Generation Mix Scenarios*

These Scenarios are representative of the transition of energy mix (years: 2018/19, 2025, 2030, 2035) towards sustainable sources according to Sustainable development strategy (SDS): Egypt Vision 2030 shown in Fig. 3 [8]. The energy mix in each of the four scenarios is representative of the percentages of the energy sources of the corresponding year in the SDS plan maintaining the total installed capacity of the original scenario (59.093 GW).

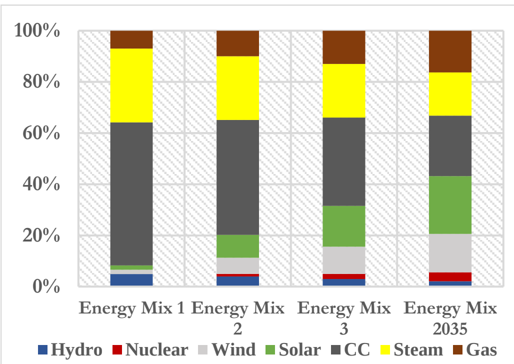

Fig. 3 Energy Generation Capacity Mix According To Egypt's SDS

IV. Off-Grid Scenario With Hydrogen Electrolyzer

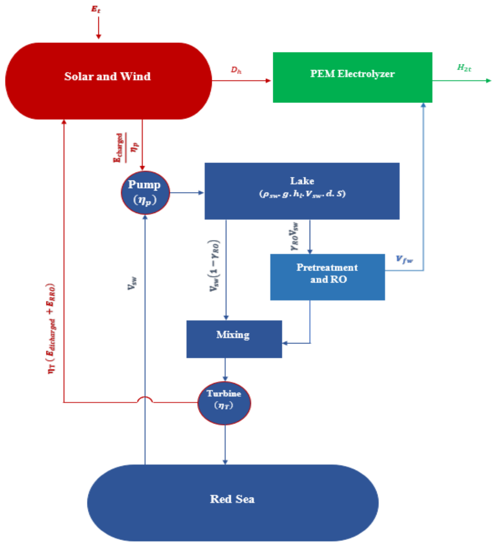

Fig. 4 Off-Grid Model

V. Results

These results are based on the modeled IPHROS according to Ataqa storage technical specifications.

TABLE 3. Daily Fresh Water Output

Daily Fresh Water Output: MCM (Million Cubic Meters)		
Model / ***Scenario***	***Grid Connected IPHROS without Carbon Tax***	***Grid Connected IPHROS with Carbon Tax***
Load Profile: 1 Energy Mix: 1	0.476	0.06
Load Profile: 2 Energy Mix: 1	0.357	0.12
Load Profile: 3 Energy Mix: 1	0.06	0.06
Load Profile: 4 Energy Mix: 1	0.06	0.06
Load Profile: 1 Energy Mix: 2	0.31	0.36
Load Profile: 1 Energy Mix: 3	0.356	0.366
Load Profile: 1 Energy Mix: 4	0.4	0.47

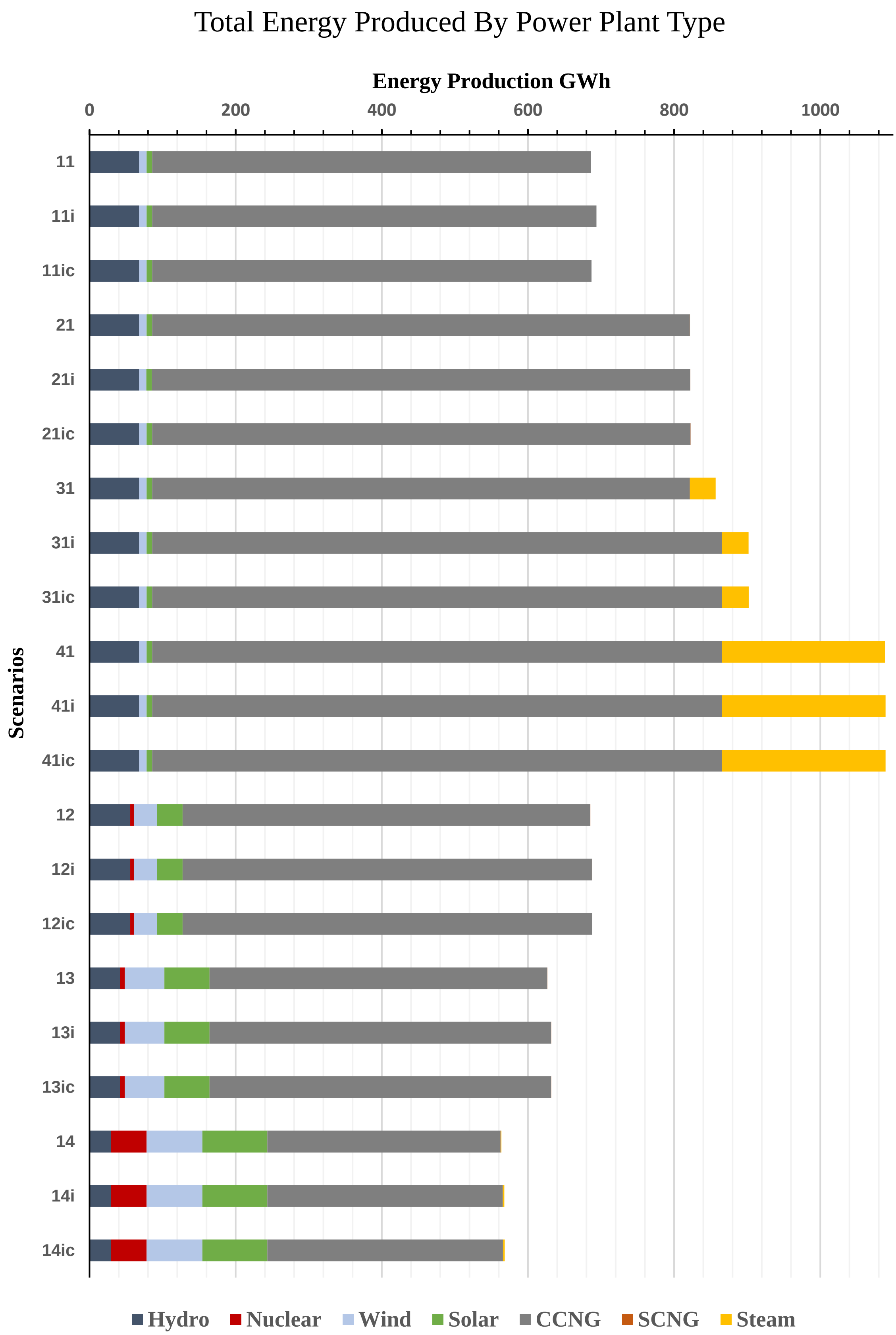

Fig. 5 Energy Production By Power Plant For Each Modeled Scenario

VI. Discussion

This paper shows the results of modeling an integrated pumped hydro storage reverse osmosis system that is grid tied to Egypt's national grid and provides a base of how a free energy market system may be schemed and how energy can be priced in order to offer basis for an arbitrage business model that secures a revenue for an IPHROS, a number of scenarios were proposed for modeling to resemble Egypt's planned transition in its energy mix according to its sustainable development strategy in addition to other scenarios that explores other technical options as coupling IPHROS to renewable plants only or economical situations where a carbon tax is imposed and finally taking into account expected increase in energy demands. The site qualitative assessment parameter provided in 7 was developed to include another criterion that adds weight to the proximity of the IPRHOS plant to the nearest grid coupling point.

Furthermore, an off-grid scenario was modeled in which IPHROS is used in conjunction with a green hydrogen electrolyzer plant where IPRHOS meets not only the energy demand but the fresh water requirements of the electrolyzer plant as well.

The results show that the price taker IPRHOS starts yielding a positive return on investment when more renewables are introduced to energy grid (energy mix 2) and increases with increasing renewables penetration due to higher gaps on energy prices that incentivizes the arbitrage practice.

Introducing IPHROS as a price taker increases emissions by increasing total produced power from conventional generation, this occurs as there is no curtailed power that exceeds demand at any energy mix up to the planned energy mix of the year 2035, furthermore imposing carbon tax reduces the total daily grid emissions for the current energy mix (energy mix 1) but increases emissions for other energy mixes where renewables penetration increases, this can be explained by the higher energy gap prices that the carbon tax amplifies where hours with high renewable penetration generation have much lower prices than hours with low renewables penetration.

Increasing renewable penetration increases water production as well, as the water production from the reverse osmosis process depends on γ_{ro_t}, which depends on the amount of discharged energy that increases with more renewables penetration.

The operation of IPHROS is less stable beyond the original energy mix (Energy Mix 1), the results shown here are the result of the 21st iterations, the iterations don't converge to a single solution for other energy mixes, the possible reason for this is the market configuration modeled here (Day Ahead Market), along with the revenue scheme (Arbitrage) where the prices is fed to the model ahead of operation scheduling.

On the other hand, utilizing IPHROS in an off-grid scenario in conjunction with a green hydrogen electrolyzer proves to be economically feasible as well as it would provide a stable operation for the electrolyzer, the electrolyzer could produce green hydrogen for the industrial economy or transportation, while fuel cells can generate electricity when required. However, electricity would then have to be spent on desalination, using IPHROS with the hydrogen electrolyzer can achieve the best of both worlds, which could expand the production of hydrogen that is used by some of Egypt's main industries, needles to mention the capability of Egypt to export its hydrogen production globally, that makes hydrogen the fuel to power Egypt's future economy.

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