Seawater PHES to Facilitate Wind Power Integration in Dry Coastal Areas – Duqm Case Study

M. H. Albadi*‡, A. S. Al-Busaidi**, E. F. El-Saadany***

*Department of Electrical and Computer Engineering, Sultan Qaboos University, PO Box 33, Muscat 132, Oman

**The Research Council, PO Box 1422, Muscat 130, Oman

***Department of Electrical and Computer Engineering, University of Waterloo, ON, N2L 3G1, Canada

*** Department of Electrical Engineering, Petroleum Institute, Abu Dhabi, United Arab Emirates

(mbadi@squ.edu.om, ahmed.albusaidi@trc.gov.om, ehab@uwaterloo.ca)

‡ Corresponding Author; M. H. Albadi, Department of Electrical and Computer Engineering, Sultan Qaboos University, PO Box 33, Muscat 132, Oman, T: +968-24142664, Fax: +968-24413454

Received: 23.02.2017 Accepted:26.04.2017

Abstract- Currently, the contribution of renewable energy resources, such as wind power, in power systems is increasing in large, interconnected systems. However, the intermittent nature of renewable energy poses a profound challenge to power system operation and planning. Using energy storage systems can facilitate wind power integration in isolated systems. Pumped hydro energy storage (PHES) plants are by far the most established technology for energy storage on a large-scale. In dry coastal areas, seawater PHES can be used to facilitate the integration of large scale renewable energy resources. In Oman, the potential of renewable energy resources has not been exploited yet. This article presents a techno-economic evaluation case study of using a combined wind power and PHES power plant to highlight its economic feasibility. PHES systems can enable higher penetration of renewable energy in isolated systems, therefore reducing the dependency on fossil fuels.

Keywords Wind Power; Energy Storage; Pumped Hydro Energy Storage; Techno-economic Evaluation; Isolated Power System.

1. Introduction

Nowadays, renewable energy resources have become one of the world's main sources of energy. The rapid growth of the renewable energy contribution in the power sector is attributable to several reasons. These include reduction in the cost of renewable technologies, implementation of policies that promote the utilization of renewable energy, regulations that provide better access to financing, energy security, growing demand, and environmental concerns related to other energy resources. Subsequently, new markets for both large- and small-scale renewable energy are evolving around the globe [1]. According to REN21, the year 2015 witnessed several developments related to renewable energy. These developments include a substantial decline in global fossil fuel prices; announcements about the lowest-ever prices for renewable power long-term contracts; a substantial growth in energy storage; and a historic climate agreement in Paris [1]. New facilities for wind and solar PV systems represented about 77% of all new renewable energy installations in 2015 [1].

However, wind and solar power are known to have intermittent natures. A lot of research has been conducted to analyze wind speed intermittency [2, 3]. Wind speed experiences both spatial and temporal variations. Spatial variations are a function of geographical location and the type of terrain [4]. The temporal variation can be classified into annual, seasonal, synoptic, and diurnal variations in addition to short term turbulences. This intermittency has negative implications on power system operation. However, aggregating the output of different wind turbines can reduce the negative implications of variability on power systems through two options: 1) increasing the number of turbines within a wind farm and 2) wider geographical dispersion of wind farms [4-6]. Another solution to output variability is to combine wind energy systems with storage facilities, which will be discussed in this article.

A new coastal city is being developed in the Duqm area of Oman. Currently, the diesel-based power system in Duqm is isolated and the area has a high potential of wind power [7, 8]. This current article empathizes on the importance of wind power in that area and proposes the utilization of a combined wind-seawater PHES plant. The main contributions of this article include the followings:

- Conducting a survey about energy storage for renewable energy applications.
- Identifying Duqm as a potential site for seawater PHES facilities in Oman.
- Conducting a techno-economic evaluation of five alternatives for future electricity generation in Duqm including a combined wind-PHES and fossil fuel-based electricity.
- Demonstrating that potential fuel saving and environmental benefits of both a wind power project and a combined wind-PHES project in Duqm economically justify investing in renewable energy considering the opportunity costs of fossil fuels.

After this introduction, this article proceeds by presenting a review of energy storage options for wind power facilities in section 2. Section 3 presents power systems in Oman, wind power potential as well as generation and load data of Duqm. Section 4 discusses the case study of using combined wind and PHES power plant and highlights its economic feasibility over other fossil fuel-based options. The main conclusions are summarized in section 5.

2. Energy Storage Systems for Wind Power

With the global interest in renewable energy and the highly-increased installation capacity, the challenge of the intermittency of these renewables is still the main technical challenge. The intermittent nature of wind speed negatively affects the power production and, consequently, the grid stability. The instantaneous wind energy penetration limits in isolated electricity grids are discussed in [9]. For an isolated grid, the maximum instantaneous output contribution of wind power in the grid should be within 25–50%, as recommended by Risø National Laboratory [10]. The minimum load should be considered when planning the capacity of intermittent wind power generators. This value will limit the installation capacity of wind turbines before output curtailments, which obviously makes the increase in renewable capacity economically not feasible. However, the presence of a storage facility can maximize the installation capacity of intermittent renewable energy in isolated grids [11-13]. There exist different techniques to optimize energy storage capacity in power systems that have intermittent energy resources [14-16].

2.1. Storage Technologies

Energy storage facilities are required to minimize the wind energy curtailment, safeguard the investors’ interest, and establish wind power as a reliable electricity generation source [17-19]. This section will present an overview of the different storage technologies that can be used to facilitate wind energy integration. Generally, the energy storage technologies can be classified according to the form of stored energy into two types: electrical energy and thermal energy storage technologies. Refer to Fig.1.

Electrical energy storage can be in different forms. Electrical energy can be stored as mechanical energy, such as PHES; chemical energy, such as the generation of hydrogen; electrochemical energy, such as in batteries; magnetic energy when using superconductors; and cryogenic energy when using liquid air. Thermal energy storage can be achieved using sensible heat storage, such as when using molten salt; latent heat storage, such as when using ice; and thermochemical heat storage through redox cycles [20]. Below is a brief description of the commonly used electrical energy storage devices/techniques.

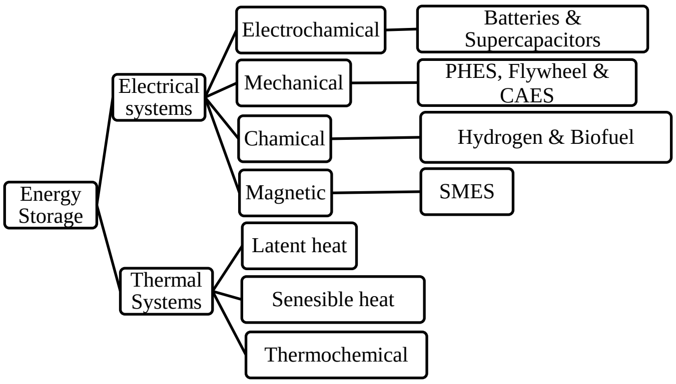

Fig. 1. Classification of energy storage technologies

2.1.1. Batteries

In batteries, energy is stored in the form of electrochemical energy, and it can be converted to electrical energy while discharging. Batteries’ technology can be classified into lead-acid, sodium-sulphur, nickel-cadmium, nickel metal hydride, lithium-ion, phosphate-based lithium-ion, cobalt-based lithium-ion, and redox flow batteries. The capital cost of the battery systems varies from \$350 /kWh for sodium-sulphur, to \$600 /kWh for vanadium redox. The efficiency can reach 80% for 2000 cycles for the lead acid batteries [21]. Different topologies of connecting batteries to the grid are presented in [22].

2.1.2. Superconducting Magnetic Energy Storage (SMES)

SMES maintains the superconducting state by using a superconducting coil, a power conditioning system and a cryogenic refrigerator [23]. SMESs have high and fast responses of 1-5 ms, high efficiency (up to 95%) and long life times, which can reach 30 years according to [24].

2.1.3. Supercapacitors

Supercapacitors are implemented at grid level for short power exchange. A comparison between different topologies of integrating the supercapacitors to a grid with wind power is presented in [25]. In [26], supercapacitors are used to mitigate short-term power fluctuation of wind turbines.

2.1.4. Flywheels

Flywheels store electrical energy in the form of rotational kinetic energy by using accumulators. These accumulators are comprised of composite flywheel coupled with motor-generators and magnetic brackets, with a low-pressure casing, which helps to reduce self-discharge losses [27]. An overview of flywheels energy storage applications and performance is presented in [28].

2.1.5. Compressed Air Energy Storage (CAES)

Different applications of CAES are reviewed in [29]. During the low-demand periods, excess energy can be stored in the form of compressed air by injecting the air into a reservoir, such as a depleted natural gas one. When the energy demand is high, the stored, compressed air energy can be released for power generation. This type of energy storage technique has low operational and maintenance cost and high efficiency [30].

2.1.6. Pumped Hydro Energy Storage (PHES)

At low energy costs and during the off-peak times, the energy can be stored in a hydraulic potential energy form by pumping the water into an upper reservoir. The power generation happens during the high peak by discharging the stored water from the reservoir. The authors in [31] presented a technical comparison between the rate of the discharging time versus the power rating and the efficiency for most of the energy storage systems. The PHES system has the highest discharging time at a high-power rating [32]. These characteristic makes PHES by far the most established technology for energy storage on a large-scale [33-35]. PHES can play an important role in reducing the scheduling costs of thermal generation facilities in isolated power systems with high wind power penetration [36].

2.2. Combined Wind-PHES for Isolated Systems

The authors in [37] presented a techno-economic comparison of various combination of renewable energy resources and storage for the Aegean Archipelago Islands. The study highlighted that the utilization of energy storage can contribute to reducing the energy production cost and wind energy curtailments. Six energy storage options were considered in the aforementioned study, namely PHES, compressed air, flywheel, batteries, flow batteries, and fuel cells. For small (1 MW < peak demand < 5 MW), medium (peak demand < 35 MW), and large-sized (peak demand > 40MW) islands, PHES appeared to be the best storage option given an autonomy period of 12 hours or more [37]. In addition to the long discharging time, PHES systems respond fast and can be turned on and off quickly; therefore, they can be used to improve frequency regulation and system stability [37]. The response time of PHES facilities is suitable for spinning reserve, renewable capacity firming, peak shaving, transmission congestion relief, as well as transmission and distribution upgrade deferral [32, 38].

The most cost-effective technique of using PHES is to pump water to an upper reservoir during the off-peak period and use it to produce electricity during peak periods. However, the capital cost of the system components and plant location must be studied. A model for component sizing of medium-sized wind-PHES systems was presented in [39], and a case study of component sizing of El Hierro island was presented in [40]. A 12-MW plant combined with an onshore wind farm has been in service since December 2013. The combination of wind and PHES significantly reduces the island dependence on imported diesel fuel [41].

2.3. Seawater PHES Systems

PHES systems require both water availability and height difference between upper and lower water reservoirs. In areas with scarce sweet water resources, seawater brings up new opportunities for PHES facilities. In Okinawa, a seawater PHES demonstration plant has been running since 1999 with an installed power of 30 MW [35, 42]. This plant is not combined with renewable energy production but performs balancing services for the grid. According to J-Power, the owner of the power station, the seawater PHES facility is fully functional and has operated trouble-free for 14 years [43]. The main challenges of seawater PHES plants include seawater intrusion into the ground and/or into ground water and corrosion of metal materials. To prevent seawater leakage from the upper reservoir, rubber sheet linings are used. Additionally, drainage system is used to detect and safely drain any leakage. To prevent seawater from spilling outside the reservoir, an embankment dam should be built around the reservoir. To prevent corrosion, fiberglass reinforced plastic pipes can be used in the penstock [44]. These measures will result in increased costs of seawater PHES systems. However, these costs are compensated since only one reservoir has to be built. For sweet water PHES facilities, authors of [45] estimated that the cost of reservoirs represents 26% of the capital cost.

Seawater PHES received a lot of attention in the past few years. For example, in [46] the authors address the technical details of designing seawater PHES systems using two case studies for the islands of Crete and Kasos. Through the two case studies, the authors discussed seawater PHES reservoir siting, components sizing, the pump station and the hydro power plant locations, and the corrosion-resistant material selection. In [47], a sizing of a photovoltaic system and a seawater PHES reservoir for a small system of 1MW peak load is conducted. In [48], the authors investigated the effects combining wind and seawater PHES in the Island of Rhodes considering low onshore wind speed and low head height. The authors considered a double penstock design that allows simultaneous power production and storage. Despite unfavourable conditions of wind and head height, the analysis show that such projects are technically and financially feasible.

3. Data of Duqm Power System

3.1 Market Structure of Electricity Sector in Oman

There are three power systems in Oman: the Main Interconnected System (MIS) in the northern part where most of the population is living, Dhofar Power System (DPS) in the south, and Rural Areas systems. Most of the electricity demand is in the MIS. In 2015, the electricity supply was 3,414.9 GWh in the MIS, 256.2 GWh in DPS, and 69.3 GWh in other rural systems [49]. The market structure of the electricity sector in Oman is shown in Fig.2 [49]. Rural Areas Electricity Company (RAEC) has a duty to provide electricity and potable water to rural areas throughout the Sultanate of Oman. The company was established through the unbundling of the sector in 2005, previously under the Ministry of Electricity and Water, following Royal Decree 78/2004 [50]. In 2014, RAEC had nine networks in Musandum, 16 networks in Al Wusta & Sharqiyah, and 36 networks in the Dhofar Governorate [51].

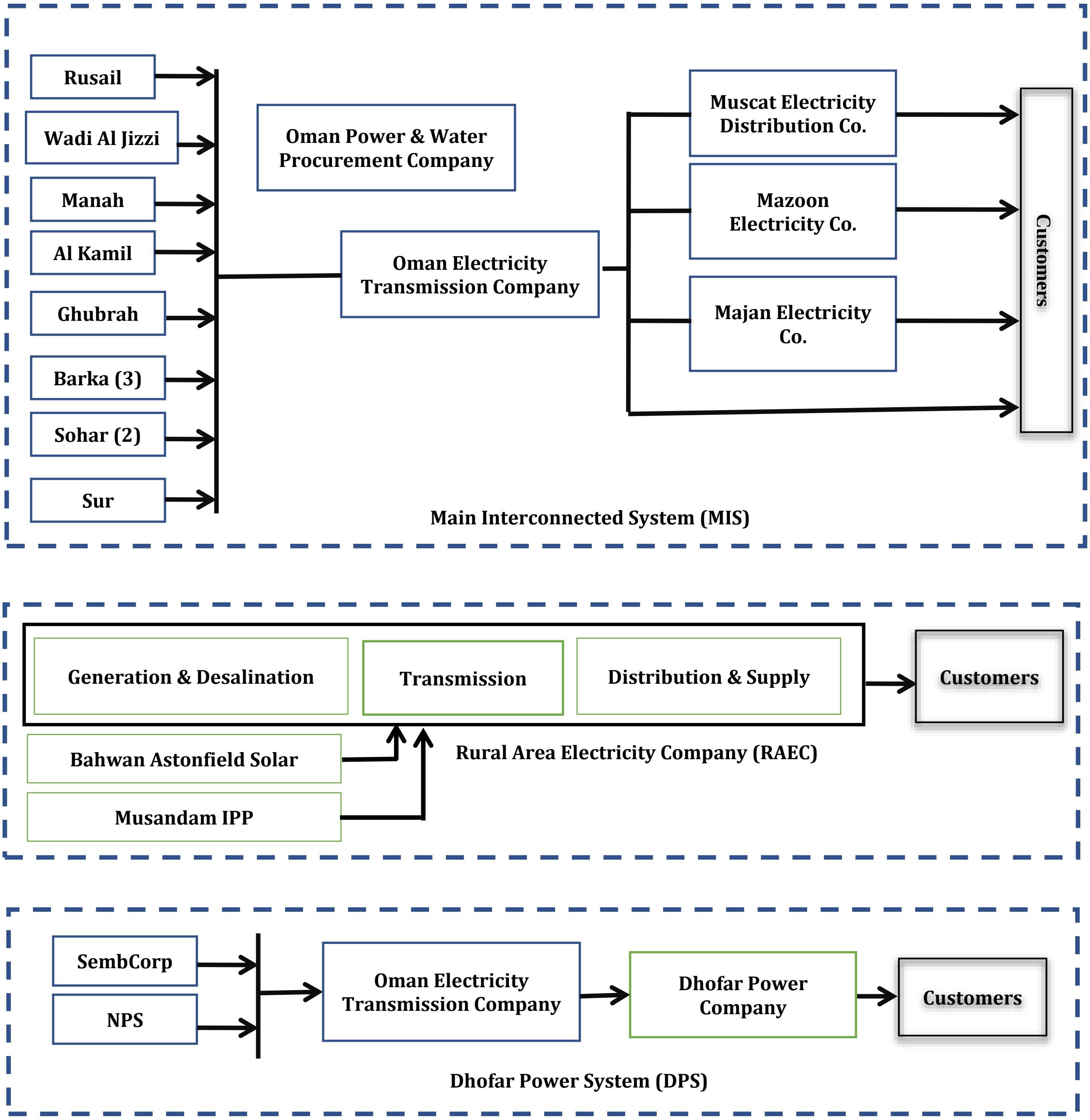

Fig. 2. Market structure of the electricity sector in Oman

The major challenges of the power sector in Oman are listed below:

- The steep growth in demand requires continuous addition of capacities. The MIS peak demand is projected to grow at 8% each year to reach 9,529 MW in 2022 [52]. High demand peaks driven by air-conditioning device challenges the cost-efficiency of combined cycle gas turbine (CCGT) and open cycle gas turbine (OCGT) generation facilities. With growing peak demand, more installed capacity is required, but with lower capacity factors.

- The power mix in Oman has been 100% depending on domestic fossil fuels, and diversification of primary resources is necessary for long-term security and affordability of the power supply. The first license for generation of electricity from renewable energy resources was issued on 1 July 2015 for a 303 kW PV plant [49].
- The sector is heavily subsidized through subsidies to electricity customers and fuel subsidies to power-generating facilities. The AER reported that the financial subsidies reached OMR 454.4 million in 2015 [49]. Subsidies range between 46% and 83% as a percentage of the electricity economic cost for MIS and RAEC, respectively [49]. This high subsidization level gives particularly low incentives for energy efficiency, and the burden on the state's budget keeps growing with the growing demand and lower income from the export of fossil fuels.
- These subsidies do not account for "hidden" costs of fossil fuels in terms of the impacts of emissions on health, environment, and climate. On the Paris COP21, Oman has committed to an unconditional 2% emissions cut in 2030, which will be achieved through reduction in gas flaring and "an unquantified increase in renewables" [53].

3.2 Load Developments in Duqm

Duqm is located in the Al Wusta Governorate on a coastal strip on the Arab Sea open to the Indian Ocean; refer to Fig.3. The new city is about 550 km from the Muscat Governorate [54]. The Special Economic Zone in Duqm (SEZAD) has been established per the provision of the Royal Decree No 119/2011 [55]. The establishment of SEZAD is among the efforts made by the government to diversify the national economy of the sultanate. Although the establishment of SEZAD was recent, the development of this city started in 1990s [7]. Currently, large projects such as Port of Duqm, the dry dock, the fishery harbour, hotels and resorts, and Duqm Airport are operational. Other projects such as refineries and a petrochemical complex are under development. Because of these projects, the load in Duqm is expected to increase. The long-term load forecast is done by Oman Power and Water Procurement Company (OPWP), which is the single buyer of power and water for all central power plants within the Sultanate of Oman. As part of the OPWP responsibility, it undertakes long-term generation planning and publishes a seven-year statement [56]. According to the seven-year statement of OPWP (2014-2020), peak demand in Duqm is expected to grow at an average of 19% per year, from 19 MW in 2014 to 65 MW in 2021. This expected demand scenario is generated considering the expected growth in residential and commercial demand due to population growth and development in the area [57].

3.3 Existing and Potential Future Generation Capacity in Duqm

The existing RAEC capacity in 2016 was 66.3 MW of diesel-based generators [58]. The capacity factor of these generators was 13% in 2014 and projected to be 16% and 22% in 2015 and 2016, respectively [58]. Table 1 shows the performance indices for the Duqm power station, and Table 2 shows the primary substations capacity and loading in 2014 [51]. It is worth mentioning that not all the loads are connected to the RAEC power system, as some loads are supplied by onsite generation facilities.

Table 1. Duqm power station indices

Year Index	2014	2015	2016
Energy Sent (kWh)	76,804,028	90,292,595	126,138,984
Fuel (Lt)	23,674,559	29,103,173	40,660,430
Capacity Factor (%)	0.13	0.16	0.22
Fuel Rate (L/MWh)	308	322	322

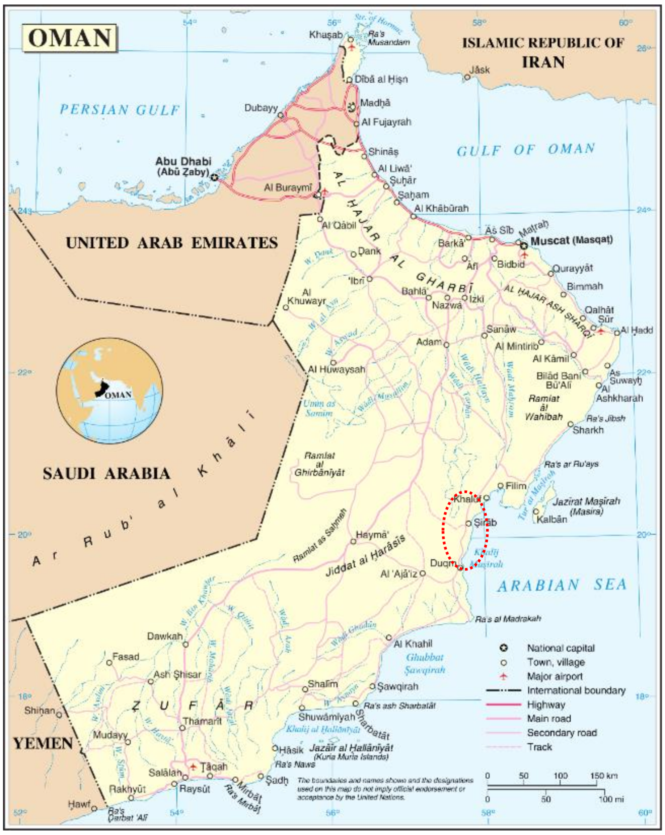

Fig. 3. Map of Oman and location of Duqm

In 2014, the utilization factors of distribution assets were low except for the Dry Dock and Old Duqm. However, these values are expected to increase with the expected load growth. In addition to the expected growth in RAEC generation capacity, the Central Utilities Company (CUC), a partnership of Takamul and Sembcorp Utilities, is planning to own and operate a gas power plant with an estimated capacity of 200-250 MW [59]. This power plant is to be commissioned before the operation of the refinery project that is targeted to begin operations in 2018 [59]. A gas pipeline is to be constructed to link CUC to upstream natural gas facilities [60].

Table 2. Duqm primary substations capacity and loading in 2014

Substation	Installed Capacity (MVA)	Max Load (MW)
Main SS	4x31.5	15.5
Old Duqm	1x6	1.53
Duqm Port	2x20	1.42
Duqm Beach	2x20	2.1
Duqm Town 1	2x20	0.01
Duqm Town 2	2x20	3.37
Duqm South	2x10	0.2
Dry Dock	2x20	7
Duqm Airport	2x10	0.5
Duqm Frontier Town	2x10	0.44

3.4 Renewable Energy Status and Potential in Oman

Despite numerous studies that have highlighted the potential of renewable energy resources in Oman [7, 61-64], the contribution of renewable energy in the electricity sector is very small. To-date, there is no published figure on the country's renewable energy share in the produced electrical energy or the installed capacity. However, Oman Electricity Transmission Company (OETC) suggested that 15% be reached by 2030 in the OETC master plan for 2014-2030 [65]. In May 2008, the Authority for Electricity Regulation (AER) published a Study on Renewable Energy Resources [61]. The study recommended the immediate implementation of certain types of wind and solar pilot projects. Later in 2010, AER confirmed a shortlist of six renewable energy pilot projects in rural areas. The first pilot project was commissioned in Al Mazyounah in May 2015 [49]. According to AER, the implementation of renewable energy pilot projects has been delayed because of two significant barriers: 1) the absence of a policy framework and policy instruments to encourage and support the economic deployment of renewable energy projects and 2) the fact that fossil fuel subsidies make renewable energy-based generation appear more expensive in comparison with fossil fuel–based electricity [66]. However, these barriers are now not as strong as before. In 2012, AER issued new regulations to encourage the implementation of renewable energy projects in rural area [66]. The AER is currently working on agency contracts to facilitate the purchase of electricity from small scale renewable facilities [49]. In 2015, the Public Authority of Electricity and Water (PAEW) completed the National Energy Strategy for Oman, which looks out to 2040. In the same year, PAEW completed a study about renewable energy and energy efficiency. As PAEW's role in the electricity sector is limited to policy overview, the recommendations were passed to the Ministry of Finance for a decision on how to take the various recommendations forward [67]. In 2015, the Council of Financial Affairs and Energy Resources approved the proposal raised by PAEW to allow the development of renewable energy projects in locations where renewable energy is economically competitive with the Omani gas price in the international markets [67]. The AER is responsible for the implementation of this proposal to facilitate the increasing use of renewable generation capacity. In addition, PAEW completed the wind atlas study during 2015. This study resulted in the selection of the best 15 sites for wind energy plants. In addition, PAEW completed a preliminary environmental critical analysis study for four selected sites, each with a minimum capacity of 100 MW. The second phase of the study involves the installation of wind monitoring masts to collect bankable wind speed data [67].

3.5 Wind Potential in Duqm

Although there exist no bankable data for wind speed in Duqm, similar to other high wind potential areas in Oman, several studies have highlighted the good wind resources. The authors in [7] reviewed the hourly wind speed for the period between September 2003 and December 2007 in Duqm. The monthly average mean wind speed ranges between 2.93 m/s in February and 9.76 m/s in July, with an annual average of 5.33 m/s. In addition, due to the effects of summer monsoons, higher capacity factors during summer months coincide with the peak demand season of the MIS [7]. The capacity factor of the wind turbines considered in the case study varies between 8% in November and 76% in August with an annual capacity factor of 36% [7].

In [63], the authors analyzed five years of hourly wind data from 29 weather stations to identify the potential location for wind energy applications in Oman. The article reported that the mean wind speed measured at 10 m above ground level reaches above 6 m/s in Duqm during summer. However, using the annual mean wind speed, a hub height of 70m is required to reach 6 m/s [63]. The authors in [8] used ensemble numerical weather prediction models for the initial wind speed assessment. Using a multi-criteria decision support system, it was concluded that Duqm area has a high potential for wind energy applications. The annual energy yield for the simulated 25 MW wind farm was 75GWh [8]. This annual energy yield corresponds to a capacity factor of 34%. The study recommended that SEZAD consider utilizing the wind power in Duqm. In fact, OETC considered the installation of 200 MW wind power capacity by 2030 in the adequacy assessment [65].

The existence of the cliff-shaped shoreline, with a plateau at 80-100m above the sea, facilitates building water reservoirs above these cliffs; refer to Fig.4.

Fig. 4. Cliff-shaped shoreline in Duqm

This reservoir can be connected to the sea by pipes equipped with pumps and hydro turbines. Surplus energy can be stored from the grid by pumping water from the sea into the reservoir, and re-injected again by letting the water flow again to the sea through the hydro turbines.

4. Techno-economic Evaluation

This study considers the following five alternatives for Duqm future generation.

- Alternative 1: 70 MW diesel power plant
- Alternative 2: 300 MW OCGT
- Alternative 3: 300 MW CCGT
- Alternative 4: 150 MW wind farm(s)
- Alternative 5: 150 MW wind farm(s) and 30 MW PHES facility

Below are the cost assumptions for this project and potential alternative projects.

4.1 Cost and Performance Assumptions

4.1.1 Wind Turbines

Wind turbines are a relatively mature technology. The International Renewable Energy Agency (IRENA) reported that the global weighted average installed costs declined from $4,766 /kW in 1983 to $1,623 /kW in 2014 and $1,560 /kW in 2015 [68]. The capital cost is expected to decrease further. In this study, a range of the capital expenditure (CAPEX) of the wind project is assumed to be between $1200 and $1500 /kW. 3% of CAPEX per year is considered as the annual operation and maintenance (OPEX). The CF ranges between 35% and 45%. A summary of wind power project assumptions is given in Table 3.

4.1.2 Seawater PHES Facility

The installation cost of PHES systems is site-specific. The U.S. Department of Energy estimated the capital cost of hydro power plants to vary from $2,000 to $6,000 /kW [69]. In another report, the average cost is estimated to be about $2,230 /kW for large PHES facilities [45]. For small-scale greenfield PHES projects, the estimated cost is about $ 4,000 /kW [38]. The authors in [31] estimated the capital cost to be in the range $600-2000 /kW. In general, lower specific costs are expected for larger plants as reported in [70]. However, the specific cost was estimated to be €1.94/kW and €5.11/kW for a 4.1MW facility in the Island Crete and a 6.5 MW project in the Island of Kasos, respectively [46]. In this study, the CAPEX is assumed to be between $3,500-4,500 /kW. Typically, the annual OPEX of PHES facilities is estimated to be 1% of the CAPEX [38]. In this study, 2-4% is considered to include additional maintenance for the usage of sea water and periodic refurbishment.

Table 3 summarizes the cost parameters for the 30 MW PHES facility. The round efficiency of PHES systems varies between 65% and 87% as stated in [31]. Authors in [66] reported that the round efficiency is close to 80% for facilities commissioned since 1985. In this study, the round efficiency is considered to be 75%.

Capacity factor in general is defined as the ratio of the average output power to the rated output power. In this study, a capacity factor (CF) of 18.75% is assumed considering six hours/day of full operation as a generator and the round efficiency.

Table 3. Wind power and PHES assumptions

Parameter	Wind Turbines	PHES
Installed Capacity [MW]	150	30
CAPEX [$/kW]	1200 -1500	3500-4500
Annual O&M costs [%CAPEX]	2-3	2-4
Capacity Factor [%]	35-45	18.75
Lifetime [Years]	25	>75

It is worth noting that in the case of Duqm, some costs are saved due to the fact that only one reservoir has to be built; but on the other hand, working with sea water, and in an open system probably raises issues of more intensive maintenance due to corrosion and abrasion of the electro-mechanical parts by suspended sediments and due to salinity [35].

4.1.3 Natural gas-based Generators

Currently, all central power plants are running on domestically available natural gas [49]. The existing power plants in Oman are based on both combined cycle gas turbines (CCGTs) and open cycle gas turbines (OCGTs). The cost parameters are similar to the ones in [45]. Currently, natural gas is sold to power plants in Oman at a regulated price of $3 /mmBTU [49]. However, the opportunity cost might be higher. The AER used $6 and $9 /mmBTU as the opportunity cost for natural gas for subsidies calculations [66]. Different scenarios for natural gas prices are considered and shown in Table 4.

Table 4. Natural gas-based generators assumptions

Parameter	CCGT	OCGT
Installed Capacity [MW]	300	
CAPEX/installed power [$/kW]	1000	650
Annual O&M costs [%CAPEX]	5	7
Fuel efficiency [%]	55	35
Gas Price [$/mmBTU]	3-9	
Lifetime [Years]	>25	

4.1.4 Diesel-based Generators

Currently, diesel-based generators are used in all RAEC networks including Duqm [58]. A 70-MW expansion of the existing diesel power plant is considered. The CAPEX of the expansion is considered to be $300 /kW. The value of fuel consumption is considered similar to that of the existing plant [51]. The fuel price is in line with opportunity cost considered by AER [66]. A summary of diesel-based power plant assumptions is given in Table 5.

Table 5. Diesel-based generators assumptions

Parameter	Value
Installed Capacity [MW]	70
CAPEX/installed power [$/kW]	300
Yearly O&M costs [%CAPEX]	5
Fuel consumption [L/MWhe]	330
Fuel Cost [$/bbl]	50-85
Lifetime [Years]	20

4.1.5 Financial Assumptions

To compare among different alternatives, the value of the levelized cost of energy (COE) is calculated considering the financial assumptions shown in Table 6.

Table 6. Financial assumptions

Parameter	Value
PPA-life [Years]	20
Equity/Debt ratio	20/80
Equity Return for thermal plant [%]	10
Equity Return for wind farm and storage plants [%]	12
Debt term for thermal plant [Years]	10
Debt term wind farm and storage [Years]	20
Interest rate [%]	4.5

The study considers a power purchase agreement (PPA) of 20 years for all types of electricity supply options. A 20/80 ratio for equity/debt is considered with a 4.5% interest rate [71]. The targeted equity internal rate of return (IRR) is 10% for thermal plants. A higher equity IRR of 12% is considered for renewables due to the probabilistic risk induced by the weather conditions.

4.2 Results and Discussions

For the considered alternatives, the COE per kWh is calculated with a “goal seek” financial model such that the target equity IRR is reached at the end of the PPA life. In all thermal power plant options, the COE ($/MWh or ¢/kWh) has two components: investment ($COE_{investment}$) and fuel (COE_{fuel}).

$$COE_{total} = COE_{investment} + COE_{fuel} \quad (1)$$

The $COE_{investment}$ is a function of the expected annual payment received from a PPA that covers the investment cost (PPA_{inv}) and the estimated annual energy yield (E_A).

$$COE_{investment} = \frac{PPA_{inv}}{E_A} \quad (2)$$

The annual energy yield is a function of the power plant capacity factor (CF) and capacity (P_{rated}).

$$E_A = CF \times P_{rated} \times 8760 \quad (3)$$

Equation (3) is used to estimate the annual energy yield of all alternative except for the combined wind-PHES (Alternative 5). For this alternative, losses due to PHES facility inefficiency need to be considered.

$$E_{A\_Wind+PHES} = E_{A\_Wind} - (1-\eta_{PHES})E_{A\_PHES} \quad (4)$$

where E_{A_Wind} is the annual energy yield of the wind power facility and η_{PHES} is the PHES plant round efficiency.

The annual energy yield of PHES facility is obtained considering the six hours/day of full operation as a generator.

$$E_{A\_PHES} = P_{rated} \times \frac{6h}{24h} \times 8760 \quad (5)$$

The COE_{fuel} is calculated using the below formula:

$$COE_{fuel} = NHR \times FP \quad (6)$$

where NHR is the net heat rate in mmBUT/kWhe and FP is the fuel price in $/mmBTU. In the case of a diesel generator, COE_{fuel} is calculated using the plant fuel consumption, in L/MWhe, and the price per liter.

The debt annuity payment (A) is obtained using the below formula.

$$A = D\frac{i(1+i)^N}{(1+i)^N - 1} \quad (7)$$

Where D is the debt value and i is interest rate and N is debt term.

The COE is calculated considering current regulated prices of fossil fuels as well as their opportunity costs.

4.2.1 COE Based on Current Regulated Fossil Fuel Rates

The calculated values of COE_{total} of all alternatives considering current regulated fuel rates ($50 /bbl and $3 /mmBTU) to power generators in Oman is given in Fig.5. The COE_{total} from diesel generators (Alternative 1) ranges between ¢23.34 and ¢14.28 /kWh. This variation is due to the $COE_{investment}$ that ranges between ¢0.53 and ¢9.59 /kWh for 5% and 90% capacity factors, respectively. The fuel component (COE_{fuel}) of this alternative is ¢13.75 /kWh. For Alternative 2 (OCGTs), the fuel component is ¢2.91 /kWh, and the COE_{total} ranges between ¢4.23 and ¢26.67 /kWh. These values are lower than those of diesel generators except for a capacity factor lower than 15%, beyond which the $COE_{investment}$ of OCGTs is very high (¢23.75 /kWh). As CCGTs (Alternative 3) are more efficient than OCGTs, their COE_{fuel} values are lower than those of OCGTs. The COE_{fuel} for CCGTs is 1.85 ¢/kWh and COE_{total} ranges between 4.07 and 41.77 ¢/kWh. It is worth noting that the COE_{total} of CCGTs is slightly lower than that of OCGTs at high-capacity factors. For lower-capacity factors, the COE_{total} of CCGTs is much higher than that of OCGTs. This result is due to the fact that CCGTs are more capital intensive than OCGTs. In addition, low fuel prices ($3 /mmBTU) result in low contribution of COE_{fuel} in COE_{total}, which in turn dilutes the effect of the fuel efficiency difference.

For wind power (Alternative 4), the calculated COE varies between ¢3.65 and ¢5.53 /kWh. This variation is due to the difference in wind power capacity factors (35-45%) and the difference in operation and maintenance (O&M) cost. This range of COE demonstrates that wind power is always cheaper than diesel-based plants considering the current price of fuel. The same result is true for OCGT and CCGT for capacity factors lower than 50%.

With a PHES facility (Alternative 5), the COE increases to be between ¢5.84 and ¢9.83 /kWh. The COE from the combined wind-PHES alternative is lower than the fuel cost (COE_{fuel}) of diesel power with the current market price. Therefore, Alternative 5 can be used as a diesel fuel saver. The COE of this alternative is also competitive with Alternative 2 (OCGT) and Alternative 3 (CCGT) for low-capacity factor values considering the subsidized fuel price ($3 /mmBTU).

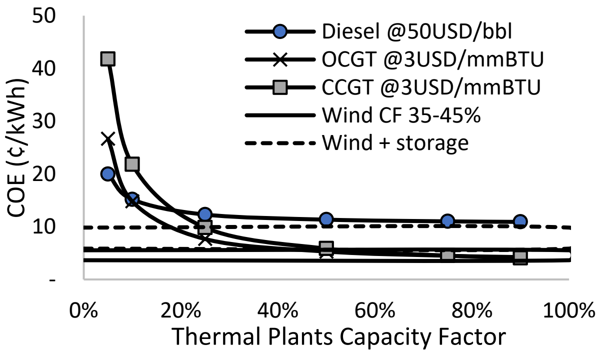

Fig. 5. COE with current fuel prices

4.2.2 COE Based on Opportunity Cost of Fossil Fuel

The simulation results considering the opportunity cost of fuel ($9 /mmBTU for natural gas and $85 /bbl for oil) are presented in Fig.6 [66]. At these fuel prices, the fuel component (COE_{fuel}) of this diesel generator alternative is increased to ¢23.38 /kWh. Similarly, the COE_{fuel} of OCGTs and CCGTs increases to ¢8.74 and ¢5.56 /kWh, respectively. Since the COE for wind power (¢3.65-5.53 /kWh) is lower than the marginal cost (COE_{fuel}) for diesel generators and OCGTs, it can be used as a fuel saver. In addition, the increase in COE_{fuel} results in increasing COE_{total} to ¢10.06-32.50 /kWh for OCGTs, and ¢7.78-45.47 /kWh for CCGTs, respectively. With these values, wind power is always cheaper than natural gas-based power. Moreover, simulation results demonstrate that the COE from the combined wind-PHES alternative is lower than those of diesel power and OCGT for all capacity factors. In addition, the combined wind-PHES alternative is also economically competitive with CCGT for capacity factors lower than 55%. There exist other benefits of a combined wind-PHES including fuel saving and emission reduction which are discussed in the next section.

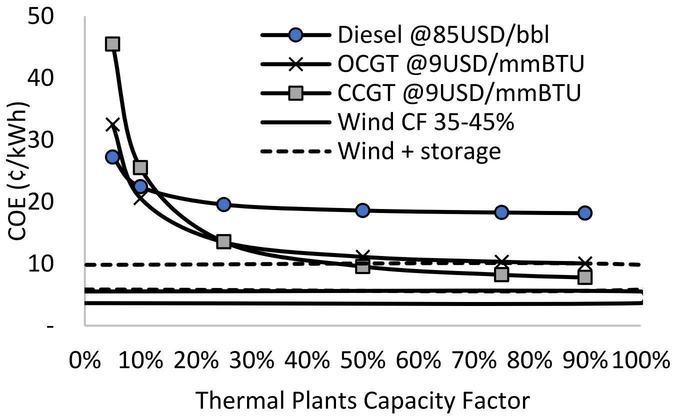

Fig. 6. COE considering the opportunity cost of fuel prices

4.3 Fuel Saving and Environmental Benefits

As renewable energy-based projects do not use fossil fuels to generate electricity, they have no greenhouse gas (GHG) emissions during the operations phase. Energy from such projects would replace a part of fossil fuels that would have been combusted in fossil-fuel based generation plants; it would therefore result in fuel saving and a reduction of GHG emissions. Carbon dioxide emissions (CO2) coefficients for natural gas and diesel fuel, obtained from the US Energy Information Administration (EIA), are presented in Table 7 [72]. Based on these emissions coefficients and power plant fuel consumption rate, avoided GHG emissions are calculated and presented in Table 8.

Table 7. Emission coefficients

Fuel Type	CO2 emission factors	
Diesel	0.2496 tCO2/MWhthermal	2.684 kg/liter
Natural Gas	0.1811 tCO2/MWhthermal	0.053 kg/cft

Table 8. Assumed fuel properties for GHG calculation

Power plant	Fuel Consumption	tCO2/MWh
Diesel-based	330 Liters/MWh	0.885756
OCGT	9.749 MMBtu/MWh	0.517382
CCGT	6.204 MMBtu/MWh	0.329243

Considering a CF of 40% for wind turbines, the annual energy yield of the wind power facility (Alternative 4) is 525.6 GWh. With the PHES facility (Alternative 5), this value is slightly reduced to 509.2 GWh. Using these annual energy yield values, annual fuel saving and emission reduction benefits are calculated as presented in tables 10 and 11, respectively.

The annual avoided fuel costs are calculated considering the opportunity cost of fuel ($9/MMBtu for natural gas and $85/bbl for diesel). If renewable energy is replacing diesel-based electricity, the annual fuel savings are between $92.7 million and $89.8 million. Considering an OCGT power plant, the annual natural gas avoided costs range between $46.1 million and $44.7 million. As CCGT power plants are more efficient, lower fuel savings benefits are expected to range between $28.4 to $29.3 million annually.

Table 9. Annual fuel saving benefits

Power plant	Fuel Saving (L/year or MMBtu/year)		Avoided cost ($/year)	
	Wind power (Alternative 4)	(Combined wind-PHES) (Alternative 5)	Wind power (Alternative 4)	(Combined wind-PHES) (Alternative 5)
Diesel-based	173,448,000 L/year	168,027,750 L/year	92,723,774	89,826,156
OCGT	5,123,849 MMBtu/year	4,963,729 MMBtu/year	46,116,670	44,675,524
CCGT	3,260,631 MMBtu/year	3,158,737 MMBtu/year	29,347,402	28,430,295

Table 10. Annual avoided GHG emissions benefits

Power plant	Avoided Emission (tCO2/year)		Avoided GHG emission credit ($/year)	
	Wind power (Alternative 4)	Combined wind-PHES (Alternative 5)	Wind power (Alternative 4)	Combined wind-PHES (Alternative 5)
Diesel-based	465,553	451,005	2,327,767	2,255,025
OCGT	271,936	263,438	1,359,680	1,317,190
CCGT	173,050	167,642	865,251	838,212

To quantify the benefits of GHG emission reduction, an average damage cost of $5/tCO2 is considered [73]. Based on this value and fuel consumption rate, avoided GHG emission cost is calculated for different fossil fuel-based power plants. The avoided cost of GHG emission reduction ranges between $2.3 million and $2.6 million if renewable energy replaces diesel-based electricity. This value is reduced to a range between $1.4 million and $1.3 million when renewable energy is replacing OCGT-based electricity. The avoided GHG emission benefits are between $0.9 and $0.8 million if renewable energy is replacing CCGT-based electricity. The total benefits of fuel saving and avoided GHG emissions are presented in Table 11. The required annual PPA payments for both Alternatives 4 and 5 are presented in Table 12.

Table 11. Annual fuel saving and GHG credit

Power plant	Total fuel saving and avoided GHG emission ($/year)	
	Wind power (Alternative 4)	Combined wind-PHES (Alternative 5)
Diesel-based	95,051,541	92,081,180
OCGT	47,476,349	45,992,713
CCGT	30,212,652	29,268,507

Table 12. Renewable energy PPA payments

Scenario	PPA payments ($/year)	
	Wind power (Alternative 4)	Combined wind-PHES (Alternative 5)
High cost	25,435,840	40,259,774
Low cost	21,555,501	33,158,790

The required annual PPA payment for Alternative 4 is between and $21.6 million and $25.4 million, while Alternative 5 requires an annual PPA payment between $33.2 million and $40.2 million, for low cost and high cost scenarios, respectively. The variation in PPA payments is due to the assumed difference in capital cost, operation and maintenance costs, and wind turbines capacity factor. The results show that the total fuel saving and GHG emission reduction benefits of Alternative 4 are more than the required PPA payments. With the PHES facility (Alternative 5), the total fuel saving and GHG emission reduction benefits of renewable energy are more than the required PPA payments in cases where renewable energy is replacing electricity that would have been produced by diesel generators or OCGT power plants. The required PPA payment for Alternative 5 is more than the total benefits of fuel saving and GHG emission reduction of a CCGT power plant.

5. Conclusions

There is a rapid growth of renewable-based power generation facilities, mostly wind and solar systems, in power systems around the globe. However, large scale integration of intermittent resources poses a profound challenge to power system operation and planning. In this article, an overview of solutions for wind power variability has been presented. PHES is the most established technology for large-scale energy storage in power systems. In dry coastal areas, seawater PHES can be used to facilitate the integration of large scale renewable energy resources. A techno-economic evaluation of using a combined wind-PHES plant in the isolated power system in Duqm-Oman has been presented. The study demonstrates that wind power in Duqm is significantly cost advantageous in comparison to diesel generators. Competitiveness of the combined wind-PHES plant is reached even without taking the social-environmental and opportunity costs of fossil fuels into account. When considering the opportunity costs of natural gas, the combined wind-PHES becomes economically competitive with open cycle gas-based generation facilities. The COE from combined cycle gas-based generation facilities that operate at capacity factors lower than 55% is higher than that of the combined wind-PHES. Considering the opportunity cost of fossil fuels, the combined wind power-PHES can be used as a fuel saver. For interconnected systems, such as the MIS network in Oman, PHES projects can help in transitioning to a more efficient power system with less dependency on fossil fuels. Integration of renewable energy in the Omani power sector would result in improved security of the supply, reduced subsidies, and lower social-environmental impact. Considering the current policy in Oman, such renewable energy projects are to be initiated by Oman Power and Water Procurement Company through a call for proposals and a tendering process.

Acknowledgments

The authors would like to acknowledge the support of Rural Areas Electricity Company (RAEC), Power and Water Procurement Company (OPWP), and the Public Authority of Electricity and Water (PAEW) for supporting this work and for providing data used in the simulation. Additionally, the authors would like to thank Rent-A-Port Green Energy (RAP-Energy) and Mr. P. Bayart, for the assistance and disclosure of some of project data.

References

[1] REN21, "Renewables 2016 Global Status Report," REN21 Secretariat, Paris2016.

[2] H. Holttinen, "Hourly wind power variations in the Nordic countries," *Wind energy,* vol. 8, pp. 173-195, 2005.

[3] M. Albadi and E. El-Saadany, "Comparative study on impacts of wind profiles on thermal units scheduling costs," *IET renewable power generation,* vol. 5, pp. 26-35, 2011.

[4] M. Albadi and E. El-Saadany, "Overview of wind power intermittency impacts on power systems," *Electric Power Systems Research,* vol. 80, pp. 627-632, 2010.

[5] L. Reichenberg, A. Wojciechowski, F. Hedenus, and F. Johnsson, "Geographic aggregation of wind power—an optimization methodology for avoiding low outputs," *Wind Energy,* vol. 20, pp. 19-32, 2017.

[6] M. Shahriari and S. Blumsack, "Scaling of wind energy variability over space and time," *Applied Energy,* vol. 195, pp. 572-585, 2017.

[7] M. Albadi, E. El-Saadany, and H. Albadi, "Wind to power a new city in Oman," *Energy,* vol. 34, pp. 1579-1586, 2009.

[8] S. Al-Yahyai and Y. Charabi, "Assessment of large-scale wind energy potential in the emerging city of Duqm (Oman)," *Renewable and Sustainable Energy Reviews,* vol. 47, pp. 438-447, 2015.

[9] D. Weisser and R. S. Garcia, "Instantaneous wind energy penetration in isolated electricity grids: concepts and review," *Renewable Energy,* vol. 30, pp. 1299-1308, 2005.

[10] P. Lundsager and E. Baring-Gould, *Isolated systems with wind power*: Wiley, 2005.

[11] A. Kumar and A. Biswas, "Techno-economic optimization of a stand-alone PV/PHS/battery systems for very low load Situation," *International Journal of Renewable Energy Research,* vol. 7, pp. 844-856, 2017.

[12] H. S. Das, A. Dey, T. C. Wei, and A. H. M. Yatim, "Feasibility analysis of standalone PV/wind/battery hybrid energy system for rural Bangladesh," *International Journal of Renewable Energy Research,* vol. 6, pp. 402-412, 2016.

[13] E. Hossain, R. Perez, and R. Bayindir, "Implementation Of hybrid energy storage systems to compensate microgrid instability in the presence of constant power loads," *International Journal of Renewable Energy Research,* vol. 7, pp. 738-750, 2017.

[14] A. K. Barnes and J. C. Balda, "Placement of distributed energy storage via multidimensional scaling and clustering," in *2014 International Conference on Renewable Energy Research and Application (ICRERA)*, 2014, pp. 69-74.

[15] S. Waiwong and P. Damrongkulkamjorn, "Optimal sizing for stand alone power generating system with wind-PV-hydro storage by mixed-integer linear programming," in *2016 IEEE International Conference on Renewable Energy Research and Applications (ICRERA)*, 2016, pp. 437-441.

[16] M. Moradzadeh, J. V. d. Vyver, and L. Vandevelde, "Optimal energy storage sizing based on wind curtailment reduction," in *2014 International Conference on Renewable Energy Research and Application (ICRERA)*, 2014, pp. 331-335.

[17] O. P. Mahela and A. G. Shaik, "Comprehensive overview of grid interfaced wind energy generation systems," *Renewable and Sustainable Energy Reviews,* vol. 57, pp. 260-281, 2016.

[18] A. Erduman and B. Uzunoğlu, "Storage commitment and placement for an interconnected island system with high wind penetration, Gotland," in *2014 International Conference on Renewable Energy Research and Application (ICRERA)*, 2014, pp. 605-609.

[19] S. M. Vaca, C. Patsios, and P. Taylor, "Enhancing frequency response of wind farms using hybrid energy storage systems," in *2016 IEEE International Conference on Renewable Energy Research and Applications (ICRERA)*, 2016, pp. 325-329.

[20] F. Díaz-González, A. Sumper, O. Gomis-Bellmunt, and R. Villafáfila-Robles, "A review of energy storage technologies for wind power applications," *Renewable and Sustainable Energy Reviews,* vol. 16, pp. 2154-2171, 2012.

[21] A. S. Subburaj, B. N. Pushpakaran, and S. B. Bayne, "Overview of grid connected renewable energy based battery projects in USA," *Renewable and Sustainable Energy Reviews,* vol. 45, pp. 219-234, 2015.

[22] B. Ge, W. Wang, D. Bi, C. B. Rogers, F. Z. Peng, A. T. de Almeida, *et al.*, "Energy storage system-based power control for grid-connected wind power farm," *International Journal of Electrical Power & Energy Systems,* vol. 44, pp. 115-122, 2013.

[23] W. Buckles and W. V. Hassenzahl, "Superconducting magnetic energy storage," *IEEE Power Engineering Review,* vol. 20, pp. 16-20, 2000.

[24] J. X. Jin and X. Y. Chen, "Study on the SMES application solutions for smart grid," *Physics Procedia,* vol. 36, pp. 902-907, 2012.

[25] C. Abbey and G. Joos, "Supercapacitor energy storage for wind energy applications," *IEEE Transactions on Industry Applications,* vol. 43, pp. 769-776, 2007.

[26] L. Qu and W. Qiao, "Constant power control of DFIG wind turbines with supercapacitor energy storage," *IEEE Transactions on Industry Applications,* vol. 47, pp. 359-367, 2011.

[27] D. Pavković, M. Hoić, J. Deur, and J. Petrić, "Energy storage systems sizing study for a high-altitude wind energy application," *Energy,* vol. 76, pp. 91-103, 2014.

[28] H. Liu and J. Jiang, "Flywheel energy storage—An upswing technology for energy sustainability," *Energy and buildings,* vol. 39, pp. 599-604, 2007.

[29] H. Chen, X. Zhang, J. Liu, and C. Tan, "Compressed air energy storage," in *Energy Storage-Technologies and Applications*, ed: InTech, 2013.

[30] H. Ibrahim, R. Younès, A. Ilinca, M. Dimitrova, and J. Perron, "Study and design of a hybrid wind–diesel-compressed air energy storage system for remote areas," *Applied Energy,* vol. 87, pp. 1749-1762, 2010.

[31] M. Aneke and M. Wang, "Energy storage technologies and real life applications–A state of the art review," *Applied Energy,* vol. 179, pp. 350-377, 2016.

[32] M. Beaudin, H. Zareipour, A. Schellenberglabe, and W. Rosehart, "Energy storage for mitigating the variability of renewable electricity sources: An updated review," *Energy for Sustainable Development,* vol. 14, pp. 302-314, 2010.

[33] S. Rehman, L. M. Al-Hadhrami, and M. M. Alam, "Pumped hydro energy storage system: a technological review," *Renewable and Sustainable Energy Reviews,* vol. 44, pp. 586-598, 2015.

[34] J. I. Pérez-Díaz, M. Chazarra, J. García-González, G. Cavazzini, and A. Stoppato, "Trends and challenges in the operation of pumped-storage hydropower plants," *Renewable and Sustainable Energy Reviews,* vol. 44, pp. 767-784, 2015.

[35] M. Guittet, M. Capezzali, L. Gaudard, F. Romerio, F. Vuille, and F. Avellan, "Study of the drivers and asset management of pumped-storage power plants historical and geographical perspective," *Energy,* vol. 111, pp. 560-579, 2016.

[36] J. I. Pérez-Díaz and J. Jiménez, "Contribution of a pumped-storage hydropower plant to reduce the scheduling costs of an isolated power system with high wind power penetration," *Energy,* vol. 109, pp. 92-104, 2016.

[37] J. Kaldellis, D. Zafirakis, and K. Kavadias, "Techno-economic comparison of energy storage systems for island autonomous electrical networks," *Renewable and Sustainable Energy Reviews,* vol. 13, pp. 378-392, 2009.

[38] I. MWH Americas, P. Donalek, B. Trouille, P. Hartel, K. King, M. Bhattarai, *et al.*, *Technical Analysis of Pumped Storage and Integration with Wind Power in the Pacific Northwest*: MWH, 2009.

[39] C. Bueno and J. Carta, "Technical–economic analysis of wind-powered pumped hydrostorage systems. Part I: model development," *Solar Energy,* vol. 78, pp. 382-395, 2005.

[40] C. Bueno and J. Carta, "Technical–economic analysis of wind-powered pumped hydrostorage systems. Part II: model application to the island of El Hierro," *Solar energy,* vol. 78, pp. 396-405, 2005.

[41] R. Andrews. (2016). *El Hierro Renewable Energy Project – End 2015 Performance Review and Summary*. Available: http://euanmearns.com/el-hierro-renewable-energy-project-end-2015-performance-review-and-summary/. Accessed 23 Feb 2017.

[42] T. Fujihara, H. Imano, and K. Oshima, "Development of Pump Turbine for Seawater Pumped Storage Power Plant," *Hitachi Review,* vol. 47, pp. 199-201, 1998.

[43] P. Hearps, R. Dargaville, D. McConnell, M. Sandiford, T. Forcey, and P. Seligman, "Opportunities for Pumped Hydro Energy Storage in Australia," *Melbourne Energy Institute, Victoria,* vol. 3010, 2014.

[44] JCOLD. (2001). *Outline of the Plant*. Available: http://web.archive.org/web/20030430004611/http://www.jcold.or.jp/Eng/Seawater/Summary.htm. Accessed 23 Feb 2017.

[45] B. Veatch, "Cost and Performance Data for Power Generation Technologies," *Cost Report, ed. BVH Company,* 2012.

[46] D. A. Katsaprakakis, D. G. Christakis, I. Stefanakis, P. Spanos, and N. Stefanakis, "Technical details regarding the design, the construction and the operation of seawater pumped storage systems," *Energy,* vol. 55, pp. 619-630, 2013.

[47] G. Manfrida and R. Secchi, "Seawater pumping as an electricity storage solution for photovoltaic energy systems," *Energy,* vol. 69, pp. 470-484, 2014.

[48] D. A. Katsaprakakis and D. G. Christakis, "Seawater pumped storage systems and offshore wind parks in islands with low onshore wind potential. A fundamental case study," *Energy,* vol. 66, pp. 470-486, 2014.

[49] AER, "Authority of Electricity Regulation Annual Report 2015," 2016.

[50] RAEC. (2016). *Rural Areas Electricity Company website*. Available: http://reefiah.com/. Accessed 23 Feb 2017.

[51] RAEC, "RAEC Capability Statement 2014 - 2017," 2015.

[52] OPWP, "OPWP 7-Year Statement (2015-2021)," 2016.

[53] CarbonBrief. (2016). *Paris 2015: Tracking country climate pledges*. Available: https://www.carbonbrief.org/paris-2015-tracking-country-climate-pledges. Accessed 23 Feb 2017.

[54] UN, "Map of Oman, United Nations, Department of Peacekeeping Operations Cartographic Section," Rev. 4 ed, 2004, p. Map No. 3730

[55] SEZAD. (2016). *Special Economic Zone in Duqm Website* http://www.duqm.gov.om/. Accessed 23 Feb 2017.

[56] OPWP. (2016). *Oman Power and Water Procurement Company website*. Available: http://www.omanpwp.com/new/Default.aspx. Accessed 23 Feb 2017.

[57] OPWP, "OPWP 7-Year Statement (2014-2020)," 2015.

[58] RAEC, "RAEC 2015 Annual Report," 2016.

[59] Takamul. (2016). *Takamul Investment Company SAOC website,* . Available: http://www.takamul.com/AboutUs.aspx . Accessed 23 Feb 2017.

[60] OGC. (2016). *Oman Gas Company website*. Available: http://www.oman-gas.com.om/. Accessed 23 Feb 2017.

[61] AER, "Study on Renewable Energy Resources, Oman," COWI and Partners LLC MuscatMay 2008.

[62] A. Al-Badi, M. Albadi, A. Al-Lawati, and A. Malik, "Economic perspective of PV electricity in Oman," *Energy,* vol. 36, pp. 226-232, 2011.

[63] A.-Y. Sultan, Y. Charabi, A. Gastli, and S. Al-Alawi, "Assessment of wind energy potential locations in Oman using data from existing weather stations," *Renewable and Sustainable Energy Reviews,* vol. 14, pp. 1428-1436, 2010.

[64] A. Al-Badi, "Wind power potential in Oman," *International Journal of Sustainable Energy,* vol. 30, pp. 110-118, 2011.

[65] H. Al-Riyami, A. Al-Busaidi, A. Al-Nadabi, M. Al-Siyabi, M. Al-Abri, Z. Al-Rawahi*, et al.*, "Development of demand forecast model for the transmission system master plan of Oman (2014–2030)," in *GCC Conference and Exhibition (GCCCE), 2015 IEEE 8th*, 2015, pp. 1-6.

[66] AER, "Authority of Electricity Regulation Annual Report 2012," 2013.

[67] PAEW, "Public Authority for Electricity & Water 2015 Annual Report," 2016.

[68] IREA, "The Power to Change: Solar and Wind Cost Reduction Potential to 2025," 2016.

[69] U. S. D. o. Energy, "2014 Hydropower Market Report," Oak RidgeApril 2015 2015.

[70] U. S. D. o. Energy, "Pumped Storage Hydropower and Potential Hydropower from Conduits," February 2015 2015.

[71] NCSI, "Monthly Statistical Bulletin October 2016," National Center for Statistics and Information, Muscat2016.

[72] EIA. (2016). *Carbon Dioxide Emissions Coefficients*. Available: https://www.eia.gov/environment/emissions/co2_vol_mass.cfm. Accessed 23 Feb 2017.

[73] investing.com. (2016). *Carbon Emissions Historical Data*. Available: http://www.investing.com/commodities/carbon-emissions-historical-data. Accessed 23 Feb 2017.