Techno-Economic and Environmental Evaluation of Adding Renewable Energy Systems to a Reverse Osmosis Desalination Plant

Fathima Reaz and Bassam Abu-Hijleh

***Abstract*—** This research concentrates on a Reverse Osmosis (RO) desalination plant located in the emirate of Sharjah in the United Arab Emirates (UAE). Considering the location, this research assesses the technical and economic viability of introducing renewable energy systems (RE) into the existing RO desalination plant. The systems studied include solar photovoltaic (PV), wind turbines (WT) and hybrid PV-WT systems. Computer simulations software used in this study include HOMER Energy and IES VE. The simulations in HOMER Energy is done in a step by step series from 25%, 50%, 75%, 100% renewable fraction connected to the grid to a standalone system with 100% renewable fraction. Different RE configurations were considered in order to cover 25%, 50%, 75% and 100% of the plant's total electricity consumption. The results observed from the various configurations were that the hybrid PV-WT and PV systems are technically viable whereas the WT systems could not do the job. The economic analysis of these RE configurations showed that they were no economically viable compared to the cost of buying electricity from the grid.

***Index Terms*—**Reverse osmosis desalination, Photovoltaic and wind turbine energy systems, CO_2 emissions, simulation.

I. Introduction

The main drivers of desalination are physical water scarcity and population growth. According to statistical findings [1], UAE holds a 14 percent share when compared to the rest of the world on desalinated water capacity, which keeps growing considering the rate of domestic water consumption in the region. This increase in desalination plants will lead to a lot of energy usage, thus demanding a more sustainable solution to this energy water nexus. In principle, it is argued that the potential of renewable energy is such that it can provide and exceed more than what is utilized on earth, thus creating its significance in the world future energy portfolio [2]. The geographical location of UAE has bestowed upon it an abundance of solar irradiation and it is observed that in the northern regions there is average wind speeds of 3.5 -4.5 m/s, thus there is significant potential for its utilization [3].

Fathima Reaz is with the British University in Dubai, UAE (e-mail:2013317011@student.buid.ac.ae).

Bassam Abu-Hijleh works at the British University in Dubai, Dubai-UAE. (e-mail: bassam.abuhijleh@buid.ac.ae).

Although desalination can curb the shortage of fresh water, it should be noted that desalination is a very energy intensive process. The desalination process is mainly governed by two technologies, thermal desalination, and membrane desalination [4].The former technology derives fresh water by intensive heating whereas the latter uses high pressure pumps and membranes to separate fresh water from brackish water.

Desalination coupled with renewable energy can be considered a very sustainable way for the production of fresh potable water. The main renewable resources used for desalination purposes are solar thermal, solar photovoltaic, geothermal and wind energy [5]. In the comprehensive analysis concerning renewable technology and desalination technology selection; many factors come into play such as geographical location, feed water input quality (turbidity and salinity), locally available renewable resources, plant capacity, grid capacity and connection, O and M requirements, etc. Barriers in development of renewable desalination can come in technical, economic and organizational levels.

II. Research Methodology

For the study, simulation modeling is opted as the core methodology, which is complimented by a case study and a literature review. Firstly, a literature review was conducted for a comprehensive understanding of desalination systems, its operations and energy needs. Further study was done on renewable systems like solar and wind power generation systems that can be integrated to desalination units. Secondly, a case study was conducted on a presently operating reverse osmosis desalination plant in the UAE. The operations of the plant was studied in detail and the energy consumption of the plant was thoroughly analyzed for a period of two months. The energy need for the office use and for the desalination use was noted separately for more accuracy of simulation. The climatic conditions of the site as well as the dimensions and infrastructure of the plant were observed for simulation needs. Finally, simulation modeling was conducted with the information obtained from the case study and literature review. The simulation modeling was conducted in two parts as for such analysis there would be the need to use two simulation software. For the first part, a base model is created in the software IES VE

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to help locate the areas of maximum irradiation and minimal shading so as to help locate the PV arrays. By using IES VE, the wind rose was used in accordance to the site to understand where the wind turbine(s) can be placed. From this simulation, the total area that would be allocated for the PV cells as well as for the turbines can be understood. HOMER Energy is used in this study to simulate the different system configurations, combination of system components to be used, optimal number, and size of the components and the net present cost of each configuration. For the simulation process, the following parameters was first finalized;(a) Electrical load profile of the desalination unit, (b) PV panel selection, (c) Wind turbine selection, (d) Battery and converter selection and (e) simulation case configurations. The simulation case configurations scenarios are derived by considering each system (base case, solar PV, wind generation, hybrid system) at different output potential ratio (0%, 25%, 50%, 75%, 100% and surplus) with respect to the demand load profile of the desalination plant, when connected to the grid and when not connected to the grid. The net present cost for all scenarios would be taken into account for the economical evaluation. Firstly, the base case configuration was simulated and the model would be validated with the current energy readings. Secondly, the PV system configurations and the wind turbine system configurations was simulated individually and the results compared and validated in order to understand and justify if to go ahead with a hybrid case configuration system. In each set of results, the optimized result was selected for analysis and a sensitivity analysis is also conducted using HOMER on the specified range of variables. Finally, all the system configurations are compared with regard to its technical aspects and economical aspects.

The simulation software used in the study utilizes data from resources such as ASHRAE (for IES VE) and NASA SSE data base (for HOMER Energy). Both the resource inputs are verified so as to validate the data used and to avoid any errors in the climatic data used. The load profile is validated and calibrated as per the readings observed in the energy meter as well as validated with the electricity bills for the year.

III. Results and Analysis

A. *Technical and Economical Analysis*

The technical analysis was done by considering which would be the most feasible option concerning renewable energy and its balance systems. The analysis looked into the fact if the primary load supply is met, if there are any unmet loads, if there are any capacity shortage and maximum renewable capacity permissible. It should be noted that HOMER optimizes output considering the net present cost and would consider making more economically viable options than technical ones.

The economical analysis is done with the simulation results from HOMER. The factors that were considered are the initial capital cost, operating cost, net present cost, the levelized cost of energy (LCOE).It should also be taken into note that the HOMER software optimizes its results with regard to the net present cost and not the cost of energy due to the fact that the result is arbitrary and disputable in the case of the cost of energy. The economical inputs are derived from the market study and similar recent case studies and are given in US dollars.

The techno-economic assessment in each case configuration resulted in the selection of the most viable option both technically and economically for each case configuration. These optimal case configurations will be further discussed in this subsection to understand which system would be best opted for a certain renewable fraction. Thus, the renewable fraction would be the basis of each categorization. The production parameters, cost parameters and the components used will be discussed for each section.

Table I summarizes the 25% renewable fraction case configurations; it is observed that all the optimized systems do not have a battery and are connected to the grid. There is no excess energy, capacity shortage, or unmet electric load seen in either of the systems. When comparing the total net present cost, the PV system has the least NPC of $3,683,774.00 followed by the hybrid system with $3,964,293.00. It is seen that the wind turbine system has NPC $ 5,936,843.00 which makes it the least favorable in term so of economy. The LCOE values also favor PV system as a more economically favorable option considering that the LCOE for PV systems is 0.091$/kWh whereas for Wind turbine system it is 0.14$/kWh. This is due to the high cost of the wind turbine when compared to the PV panels. However, when a further comparison is done between the components used, the hybrid system seems to be the best technical and economical option considering the fact that; it can be installed with less area as land costs are quite high in the region of study. In this system, the primary loads are met with no capacity shortage, the renewable fraction obtained and the renewable production rate show that very negligible electricity is not used by the system.

In the 50% renewable fraction case configurations for PV system, WT system and hybrid PV -WT system. While analyzing the production parameters, it is observed that there is an excess electricity production of 15% in the hybrid system whereas the other systems have 0% excess electricity production. This electricity excess is due to the higher PV production in the system. The renewable fraction is met in each case with the optimal case being the PV system followed by the hybrid system and the wind turbine system. While considering the cost parameters, the NPC for PV system is at the lowest with $5,162,149.00 followed by the hybrid system with $5,225,491.00 and finally the wind turbine system with $10,672,210.00.The LCOE is also very high for the Wind system making it very uneconomical compared to the other two systems. By observing the components used in each system, it can be derived that the high NPC in the wind turbine system is due to the capital costs and the operation and maintenance cost for the wind turbines. While comparing the components in the hybrid system and the PV system, it can be seen that the PV system would fare better as the same amount of PV array is used in both systems. The PV system has a higher capacity converter of 1200kW whereas the hybrid system has a converter of 400kW and one wind turbine. Thus in the 50% renewable fraction case, the PV system would be the most technically and economically apt due to the components used, least net present cost and apt PV production rates.

TABLE I:
SUMMARY FOR 25% RENEWABLE FRACTION CASE CONFIGURATIONS CONNECTED TO THE GRID

Description	Photo Voltaic System	Wind Turbine System	Hybrid PV-WT system
Production			
Excess Electricity (%)	0.0	0.0	0.0
Unmet Electric Load (%)	0.0	0.0	0.0
Capacity Shortage (%)	0.0	0.0	0.0
Renewable Fraction (%)	25.9	25.4	25.1
Wind turbine Production (%)	-	25.39	13.42
PV Production (%)	28.03	-	12.68
Cost			
Total Net Present Cost ($)	3,683,774	5,936,843	3,964,293
Levelized Cost of Electricity ($/kWh)	.09104	.1448	.09884
Operating cost ($)	281566.40	320,002.90	298,185.10
Components			
PV Array (kW)	544	-	240
Wind turbine Vergnet GEV MP-C	-	2	1
Converter (kW)	400	400	400
Cell Cube Battery FB-200-1600 (Strings)	-	-	-
Grid (kW)	900	900	900

In the case configurations for 75% renewable fraction for the PV system, wind turbine system and the hybrid PV-WT system technical feasibility is most prominent in the PV system configuration with 0% unmet electric load and shortage of capacity where as the wind turbine system has 3.8% unmet electric load and 5.6% capacity shortage, and the hybrid system has 0.1% each for unmet electric load and capacity shortage. But as all the systems are connected to the grid, the hybrid system will fare well and will be a technically feasible option. However, there is a high excess electricity percentage of 19.3 in the hybrid system which shows that the system cannot use or store the electricity produced at some periods leading to loss and wastage. The cost parameters show that the hybrid system has the least net present cost of $8,918,045.00 and the least LCOE (0.14 $/kWh) which is due to the fact that this system uses only three batteries whereas the other systems have 4 strings. The wind turbine system shows a very high NPC and LCOE due to the high costs regarding the turbines and the low wind potential in the area. Through the comparison of all the systems, it can be seen that the optimized economical and technical option would be of the hybrid case with a PV array of 2752kW, 2 wind turbines, 3 batteries, 800kW converter and connected to a 300kW grid. If a system of net metering is introduced by the water and electricity authorities of the region , then more financial gains can be made using this system.

In the case configurations of all the systems in 100% renewable fraction and connected to the grid ; the systems are hypothetically technically feasible as they are able to provide for the required primary load but it can be seen that there is an excess electricity of 31.3% produced in the PV system and 28.2% produced in the hybrid system. This excess electricity produced is due to the fact that the grid and the battery are unable to absorb it . While considering the economics of the systems, the hybrid system has the least NPC of $17,715,200.00 followed by the PV system with $19,228,580.00.The NPC is of the wind turbine system is 6.3 times the NPC of the hybrid system . This high cost of the wind turbine system is due to the insufficient resource available thus leading to the use of high number of turbines and batteries to meet the load requirement. While considering the LCOE, it is seen that the hybrid system would be the best viable option with LCOE 0.16 $/kWh compared to 0.28$/kWh for PV systems. By observing the components involved in each system, the hybrid system has the least number of batteries with a PV array of 5760kW and 8 wind turbines. Thus in this case, the hybrid system is most technically and economically viable.

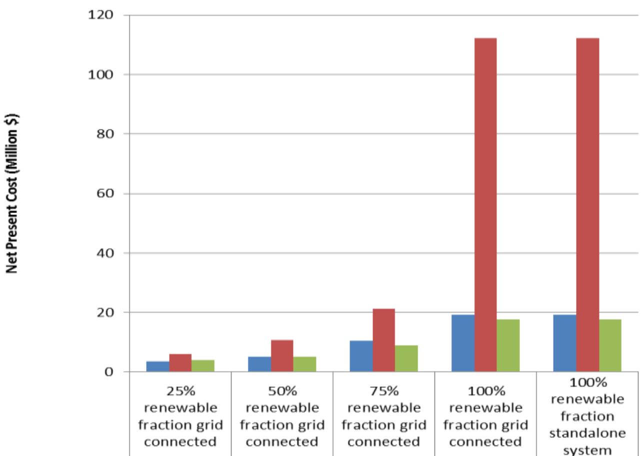
Finally, the standalone system configurations consider the same components as the 100% renewable fraction systems. There is a case of high excess electricity produced in the system. This is due to the fact that HOMER Software will first make the renewable energy meet the primary electric load, and then the batteries are charged before selling to the grid. In the standalone case the grid is not involved. If the cost of wear is too high for the batteries, then HOMER will choose not to discharge the batteries to meet the load. If more batteries are added to the system to store the excess power, this will prove to be economically unviable.

When considering all the case configurations, the hybrid case configurations are most viable technically and economically. The use of both the resources will help in higher space optimization with importance given for least shading effects in PV arrays and good positioning of wind turbines for least wake effects. Fig.1 illustrates the NPC values of each system. Considering the LCOE values of each system, it should be kept in mind that HOMER considers the COE formulation as arbitrary and disputable. Thus only the NPC will be considered to be the primary metric for choosing the best system in terms of economics.

Many factors like the price of land, feed in tariff, net metering systems, governmental support, financing, carbon taxing among many others would play a major role in implementing such systems in reality.

The major factor through which a system is deemed profitable in the desalination industry is through the cost of water produced. With the current system which is connected to the grid, the plant produces 0.21 m3 water with 1 kWh. But many other factors add to the cost of water such as the finance cost, administrative and management cost, chemical cost (anti scaling., ph balance, chlorination, etc.), consumables cost (cartridge changes every 15 days, membranes changes every three years), quality assurance and quality control, human resources and machinery depreciation costs.

When considering the 25% case configuration using hybrid PV –WT 1kWh of electricity costs $0.09 and the PV system 1kWh of electricity costs $0.1 this is quite low considering the cost from the grid at $0.12 for 1 kWh. But this calculation method by HOMER causes ambiguity thus making it an inappropriate and inaccurate measurement. This calculation also does not take into account on financing, feed in tariffs, net metering systems and other governmental supports. Thus with such provisions, introduction of renewable energy systems would be much more feasible to such industries.



	25% renewable fraction grid connected	50% renewable fraction grid connected	75% renewable fraction grid connected	100% renewable fraction grid connected	100% renewable fraction standalone system
PV system	3.68	5.16	10.63	19.23	19.23
WT system	5.94	10.67	21.36	112.29	112.29
Hybrid PV-WT system	3.96	5.23	8.92	17.72	17.72

Fig. 1. Economic Summary-NPC (Million $)

The environmental aspects will be looked upon by evaluating the CO2 emissions reduction by each configuration as that would be the only common aspect that can be compared with respect to each of the configurations simulated using HOMER Energy.

In the scenario where the grid is connected to the desalination plant, it is important to note that the grid derives it power from fossil fuel which is used in power plants to generate electricity. The emissions factors is derived from the greenhouse gas inventory report by the Environment Agency Abu Dhabi (2012).The results simulated for the 1200 kW peak power grid show that the local grid has high emissions of GHG considering 2,563,674.00 kg of CO2/year, 578.47 kg of CO/year, 152.23 kg of particulate matter /year, 15,527.00 kg of Sulphur dioxide/year and 4566.80 kg of nitrogen oxides /year.

In the scenario where the desalination unit is run by an independent power generator which is fuelled by diesel, the input parameters are as per the specifications by the manufacturer. The results show that the generator would emit 2,097,245.00 kg of CO2/year, 11,120.00kg carbon monoxide kg of CO /year, 599.99 kg of unburned hydrocarbons / year, 96.00 kg of particulate matter /year, 4325.60 kg of Sulphur dioxide /year and 2,128.00 kg Nitrogen Oxides/year.

When the emissions from both the sources are compared it is seen that the generator shows surprisingly lower emissions due to the fact that the generator selected varies its engine speed according to the system load allowing it to produce the needed power with significantly lower fuel quantity.

Through renewable integration, it is evident from the case studies that the emission levels would decrease considerably. It can be quickly analyzed for emissions by PV array case configurations that with increasing renewable fraction, the CO2 emissions are reduced. It should also be noted that in HOMER energy the emissions is calculated in a grid connected system by the simple formula; net grid purchases multiplied by the grid related emissions for each pollutant. Thus it can be analyzed that in the 75% and 100% renewable fraction system, the net grid purchases is in negative as the system is simulated such that it sells more power to the grid than it purchases from the grid .

While studying the emissions by wind turbine case configurations the optimal case configurations of wind turbines are taken and its emissions are analyzed. The most evident emission is the carbon dioxide emissions released for power production by the grid. The negative emission value for 75% and 100% renewable fraction when connected to grid is seen due to the negative net grid purchases. It is seen that the system sells more power to the grid than it buys from the grid over the year, the net grid purchases will be negative and so will the grid-related emissions of each pollutant. As in the previous case, the emissions have become less for every step of increment in the use of renewable energy, but it should be noted that the emissions are dependent on the grid usage rather than the percentage of the grid connectivity.

The hybrid system configurations have solar photovoltaic arrays and wind turbines working together to get the best of both resources in the area. Again the negative emission values are observed for the 75% and 100% grid connected system due to negative grid purchases as the system gives a lot of power to the grid. Similar to the previous observations regarding integration of renewable into a system, it is seen that the emissions are considerably reduced. It is also noted that the emissions are the least when using solar arrays and most while using a hybrid system. But it is also noted that these differences are not so drastic but very subtle. In conclusion, it can be seen that by the introduction of renewable systems into the desalination plant, the emissions are lowered at a very satisfactory rate thus improving the environment and helping to create a more sustainable future.

IV. Conclusion

The energy water nexus is a very indispensable niche in today’s scenario making desalination and renewable energy a very important topic of discussion. From the literature it is well understood that desalination of water requires a lot of energy which is predominantly produced by fossil fuels due to its economic benefits. In this study, a reverse osmosis desalination unit located United Arab Emirates which is a hot arid region where there is a physical scarcity of drinking water as well as abundant solar resources, is studied closely to understand the impact of renewable energy integration to the desalination plant.

The technical, economical, and environmental aspects in integrating the desalination unit is studied by conducting a comprehensive literature review followed by computer simulation studies.

The main aim of the research was to assess the performance of the sea water reverse osmosis plant when the renewable energy is introduced into its system using a step by step process. The main results have been obtained from the simulation modeling process using the software IES VE and HOMER Energy. Firstly, IES VE was used to understand the solar potential and wind potential in the actual site and the best locations to place the system unit. The maximum available area and other barriers and limitations were analyzed. Secondly, HOMER Energy was used to simulate case configurations containing the PV system, wind system and hybrid PV-WT system in a step by step manner starting from 25% renewable fraction and connected to the grid to a standalone system with 100% renewable fraction. Finally, the results were analyzed and inferences regarding the data were made.

The technical and economic analysis showed that hybrid PV-WT systems could be very proficient option to consider in this region where more emphasis is only made in the PV industry. Even though results show a very good outcome from the PV system, when restrictions regarding the space needed in considered and the higher technical feasibility of the hybrid system makes it a more superior option. The wind turbine configurations did not fare well in all the case scenarios except the 25% renewable fraction and attached to the grid. The low wind resource in the area plays a huge role in establishing these systems as many number of turbines and batteries are need to support the primary load which is not economically beneficial.

When comparing to the current price of electricity from the grid in this region, the renewable energy produced in many studies show high costs. The net present cost is used to identify the economic feasibility of the systems used in the study which show that the least cost incurring system is when the unit is connected to the grid with the NPC of $1,195,957.98. This is followed closely by configurations where 25% renewable fraction is integrated with PV systems and hybrid systems with NPC $3,683,774.00 and $3,964,293.00 and respectively. However, through many propositions which may not be always technical, a change to renewable energy can be introduced in this region such as; introduction of net metering, feed in tariffs, government incentives, improving the desalination process, more efficient and cheaper renewable system components through new noble technologies. Though these renewable case configurations may give a higher cost for electricity, it is seen clearly from the emissions reduced how this transition from fossil fuel to renewable will help save the world from a point of never coming back.

Thus from this study, it is understood that most of the configurations are technically achievable and the load demand can be fulfilled in the most optimal way in many cases. Some cases such as the 25% and 40% PV system and hybrid system cases can be considered economically viable than the rest when considering if carbon taxes are introduced in the region. It is clearly seen from the study that carbon emissions are reduced when the renewable system is connected to the grid. In the case of PV system which has just 25% renewable fraction and the rest connected to the grid shows a carbon dioxide reduction from 2563674 kg/year when only connected to the grid to 1879703 kg/year. The case where the renewable fraction is more, the carbon dioxide produced is also seen to be lesser. In the cases of 75% and 100% renewable fraction when connected to the grid , it is seen that negative emissions are obtained. . It is seen that the system sells more power to the grid than it buys from the grid over the year, the net grid purchases will be negative and so will the grid-related emissions of each pollutant. The emissions have become less for every step of increment in the use of renewable energy, but it should be noted that the emissions are dependent on the grid usage rather than the percentage of the grid connectivity. Thus from the simulation, it is understood that by the introduction of renewable systems into the desalination unit, a large amount of emissions can be reduced which will in turn make a very positive impact on the environment.

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Fathima Reaz a pro-active and research oriented architect who has a sustainable approach to creative design and is based in United Arab Emirates. Fathima has a bachelor of Architecture degree from the University of Calicut, India (2008-2013) and a Masters in Sustainable Design of Built Environment from The British University in Dubai-UAE (2014-2016). She is currently working for Alpha Utilities in UAE as an energy consultant. She has work experience in the field of architecture and Renewable Energy and have worked for companies such as DNV GL, SML Architects and Royal Stone Engineering Consultancy. She is software proficient and is inquisitive in the application of renewable energy systems in conventional building structures.

Bassam Abu-Hijleh Prof. Abu-Hijleh is currently the Dean of Faculty of Engineering & IT as well as the Atkins Chair of the MSc and PhD Sustainable programmes at the British University in Dubai (BUiD). He holds a PhD in Mechanical Engineering from the Ohio State University-USA. With 25+ years' post-PhD experience in energy related academia and research Prof. Abu-Hijleh has a strong technical background in Energy related topics with special focus on Renewable Energy and Energy Management & Conservation. His current research interests focuses on Experimental and simulation study of solar energy, Renewable/alternative energy sources, advanced energy production practices and Energy conservation & management.