CHEMICAL ENGINEERING TRANSACTIONS

VOL. 76, 2019

A publication of AIDIC

The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Petar S. Varbanov, Timothy G. Walmsley, Jiří J. Klemeš, Panos Seferlis

ISBN 978-88-95608-73-0; **ISSN** 2283-9216

DOI: 10.3303/CET1976189

Technoeconomics of Reverse Osmosis as Demand-Side Management for Philippine Off-Grid Islands

Michael T. Castro[a], Eugene A. Esparcia Jr.[a], Carl Michael F. Odulio[b], Joey D. Ocon[a,*]

[a]Laboratory of Electrochemical Engineering (LEE), Department of Chemical Engineering, University of the Philippines Diliman, Philippines
[b]Power Electronics Laboratory (PEL), Electrical and Electronics Engineering Institute, University of the Philippines, Diliman Philippines
jdocon@up.edu.ph

Providing water supply in off-grid islands is difficult due to remoteness and high logistics cost. Despite interest in providing energy sustainability in these areas, there is relatively lesser interest in coupling it with sustainable water access. One of the possible solutions is through the use of reverse osmosis (RO) technology for desalination since it has a low energy requirement and high throughput. In this work, the techno-economic viability of incorporating desalination units was elucidated as demand-side management in different dispatch algorithm, accounting water-energy nexus. Different water-energy system configurations were optimized and simulated using ISLA, an open-source microgrid optimizer. Results suggest the viability of installing desalination units with a minimum-level dispatch algorithm yielding the lowest levelized cost of water (LCOW) with only minimal increase in the levelized cost of electricity (LCOE).

1. Introduction

Off-grid islands have been the target of energy system studies due to the impracticality of grid extension. This has motivated the development of numerous tools that may be used to optimize the energy mix in these islands. Bajpai and Dash (2012) have shown that hybrid energy systems are optimal for stand-alone applications such as off-grid islands as backup generators and storage components can cover for the intermittency of renewable energy sources.

The access to freshwater for off-grid islands is an overlooked concern since transport of freshwater from the mainland may be impractical due to remoteness and high logistics cost. The production of freshwater through desalination systems (e.g. multi-effect distillation, mechanical vapour compression) have been investigated for techno-economic viability. Among different desalination technologies, reverse osmosis (RO) requires the least energy to produce freshwater (Rao et al., 2018). The feasibility of RO with a hybrid energy system for the small population is possible such as in the small community in Iraq (Khalifa, 2011). In addition, future forecasts suggest decreasing the cost of RO technology (Caldera and Breyer, 2017).

The water-energy nexus in off-grid islands have been the focus of desalination studies, in which the feasibility of a RO unit depends on how it interacts to the nexus. For instance, RO can be treated as an additional load to the hybrid energy systems (Gökçek, 2017) or as energy sink which can demand for more energy consumption necessary to meet water demands (Corsini and Tortora, 2018). A comparison between these algorithms was performed using HOMER Pro (Bognar et. al., 2012).

In this work, Island Systems $LCOE_{min}$ Algorithm (ISLA), an energy systems optimizer for an off-grid system, is used to optimize the water-energy system with Batuan, Ticao Island in the Philippines as a case study. The energy and water components were optimized to yield the lowest net present value (NPV) possible in three (3) different water-energy dispatch algorithms. The optimum component sizes, levelized cost of electricity (LCOE), levelized cost of water (LCOW), and power flows were compared and discussed.

Paper Received: 15/03/2019; Revised: 19/06/2019; Accepted: 24/06/2019
Please cite this article as: Castro M.T., Esparcia E.A., Odulio C.M.F., Ocon J.D., 2019, Technoeconomics of Reverse Osmosis as Demand-Side Management for Philippine Off-Grid Islands, Chemical Engineering Transactions, 76, 1129-1134 DOI:10.3303/CET1976189

2. Methodology

2.1 Framework

Figure 1 shows the overall framework used in this work, which is incorporated using ISLA (github.com/ISLA, 2019). The dispatch algorithm considers the energy and water demand and distributes energy accordingly among the energy and water components. The RO unit serves as a link between energy and water demand.

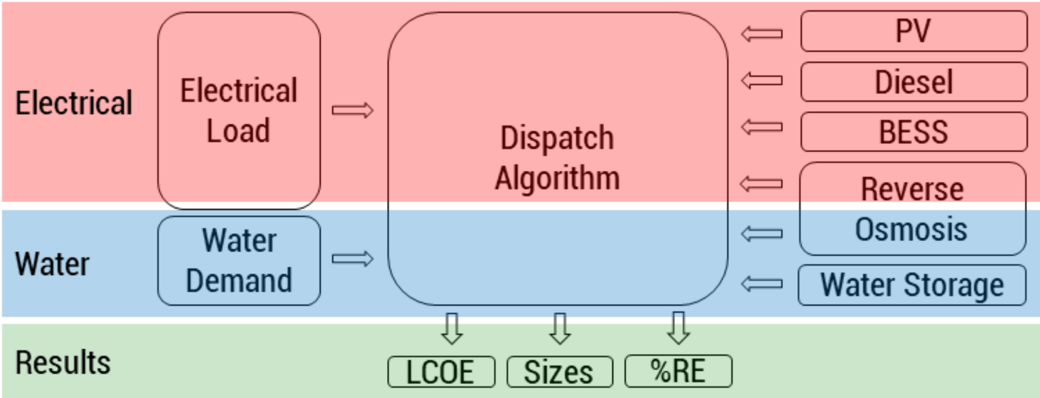

Figure 1. The overall framework of the water-energy model

2.2 Models

Electrical

Energy components such as solar photovoltaic (PV), diesel generators, and lithium (Li)-ion battery will be used in this work. Details on the equations used are available in the Github repository.

Water

The power requirement of RO is expressed using the following equation:

$$\dot{V}(t) = \frac{P_{de}(t)}{R} \tag{1}$$

where: $\dot{V}(t)$ = freshwater produced at time t [m^3/h]; $P_{de}(t)$ = RO power demand [kW]; and the R = ratio of energy required per volume of freshwater produced [4.38 kWh/m^3] (Gökçek, 2018). The excess freshwater produced by RO is sent to water storage (Gökçek and Gökçek, 2016). If water production from RO is insufficient to meet the water demand, water from storage will be used (Corsini and Tortora, 2018). The water storage equation is expressed using the following equation:

$$V_{st}(t+1) = V_{st}(t) + \left[\dot{V}(t) - \dot{V}_{ld}(t)\right]\Delta t \tag{2}$$

where: $V_{st}(t)$ = volume of stored water [m^3], $\dot{V}_{ld}(t)$ = water required at timestep t [m^3/h], and Δt = timestep [h]. For this work, the water storage size is assumed to be at least 80% of the peak daily water production.

2.3 Dispatch algorithm

Three (3) water-producing dispatch algorithms are investigated in this study: load-only, sink-only, and minimum level. A base case where energy system without RO is also simulated where it uses a load following algorithm (Blechinger, 2015) for comparison.

In load-only case, the water demand is treated as an additional energy demand (Gökçek, 2017). The water production from RO will be done to meet the water demand and water storage is not used. In sink-only case, water production from RO comes from the excess renewable energy generation. Water storage is used to meet water demand in a period where no excess energy generation is available. In the minimum level case, water production from RO also comes from excess renewable energy generation. However, if the water storage level reaches a specified minimum, the RO unit will act as additional energy demand (Corsini and Tortora, 2018). In this work, water storage minimum of 10 % is arbitrarily specified.

2.4 Cost calculations

The net present value (NPV) accounts the total annualized energy and water component costs in the system and is minimized by the dispatch algorithm. The levelized cost of electricity (LCOE) accounts the total cost of energy components per total load served in a given project lifespan. The following equations are used to calculate the levelized cost of water (LCOW) (Gökçek and Gökçek, 2016):

$$C_{\text{LCOW}} = \frac{f_{\text{CRF}} \sum_{\text{water}} C_i + C_{\text{LCOE}} \sum_{t=0}^{8760} P_{\text{de}}(t) \Delta t}{\sum_{t=0}^{8760} \dot{V}_{\text{ld}}(t) \Delta t} \tag{4}$$

$$f_{\text{CRF}} = \frac{i(1+i)^{t_{\text{s}}}}{(1+i)^{t_{\text{s}}} - 1} \tag{5}$$

wherein $\sum_{\text{water}} C_i$ is the sum of all annualized water component costs (RO and storage) [$]; C_{LCOE} is the LCOE [$/kWh]; i is the inflation rate; and t_s is the project lifetime [y].

2.5 Case study: Batuan, Ticao Island, Masbate (12°25′N 123°46′E)

An off-grid area in Batuan, Ticao Island, Philippines is arbitrarily selected for the case study. Different water-energy systems configurations were optimized and simulated using ISLA. For comparison, systems without water components were evaluated to determine the techno-economic implications of adding desalination units.

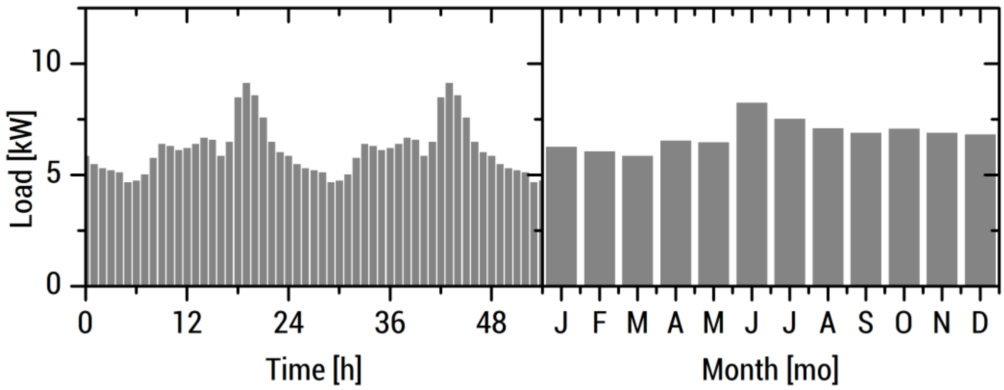

Figure 2: Hourly load profile for one week (left) and monthly average load (right).

Figure 2 shows the normalized load profile of all National Power Corporation – Small Power Utilities Group (NPC-SPUG) areas are used (Navarro, 2016) and adjusted based on the energy peak demand.

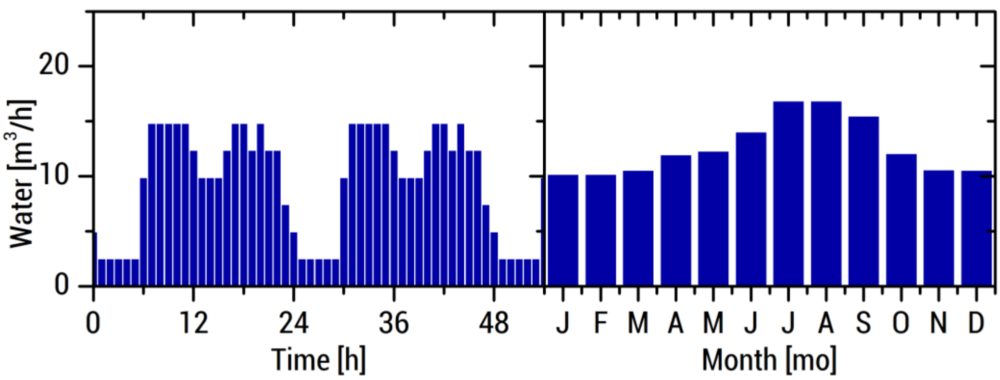

Figure 3: Water demand profile for one week (left) and monthly average demand (right).

Figure 3 shows the estimated water demand profile of the off-grid area. The water demand is estimated using the population data and the per-capita freshwater demand. The World Health Organization estimates a water requirement of 20 L of freshwater per capita per day (Gökçek and Gökçek, 2016). Therefore, the estimated annual freshwater demand in Batuan, Ticao Island is 110,127 m^3 for a population of 15,086. The water demand profile is obtained by fitting the annual demand to an hourly water consumption profile of low-income single-family households (California Public Utilities Commission, 2011) corrected for seasonality (Griffin & Chang, 1991).
The techno-economic parameters used in the simulations are presented in Table 1.

Table 1: Techno-economic assumptions used in this work.

Comp.	Parameter	Unit	Value	Ref.
Load	Total	GWh	162.8	
	Peak	MW	25.9	
Water	Total	m^3	11,0127	
	Peak	m^3/h	402.7	
PV	CapEx	$/kW	1,200	[1]
	OpEx (fix)	$/kW y	25	
	Lifetime	y	20	[2]
Li-Ion	CapEx	$/kW	2,000	[3]
	CapEx	$/kWh	300	
	OpEx (fix)	$/kWh y	3	
	Lifetime	y	10	[4]
	RT. Eff.	1	0.90	

Comp.	Parameter	Unit	Value	Ref.
Diesel	CapEx	$/kW	500	
	OpEx (var)	$/kW h	0.03	
	Fuel Cost	$/L	0.9	
	Fuel infl. rate	1	0	
	Lifetime	h	15,000	
Desal.	CapEx	$/($m^3$/d)	2400	[5]
	OpEx (var)	$/$m^3$	0.08	[5]
	Lifetime	y	6	
Water	CapEx	$/$m^3$	1,000	[5]
Storage	OpEx (var)	$/$m^3$ y	10	
	Lifetime	y	20	
Project	CapEx	$	0	
	OpEx (fix)	$/y	0	
	Lifetime	y	20	
	Inflation	1	0.1	

References: [1] Fu, et. al (2017); [2] Blechinger, 2015; [3] DiOrio et. al. (2015); [4] Moseley and Garche (2015); [5] Gökçek (2017)

3. Results and discussion

3.1 Optimum sizes

Table 2 shows the optimum sizes of each energy and water component at different dispatch algorithms. These metrics are compared to yield insights into the economics of RO implementation.

Table 2. Optimum component sizes in different scenarios

Dispatch Algorithm	System	PV [kW]	BESS [kWh]	Diesel [kW]	Storage [m^3]	RO [m^3/d]	LCOE [$/kWh]	LCOW [$/$m^3$]	RE [%]
No	Diesel	-	-	13.1	-	-	0.370	-	0.0
Desal.	PV-DS	28.2	-	13.1	-	-	0.344	-	36.3
	PV-Li	102.1	280.7	-	-	-	0.528	-	100.0
	Hybrid	30.8	18.4	13.1	-	-	0.331	-	43.5
Load	Diesel	-	-	129.3	322.2	402.7	0.393	4.302	0.0
Only	PV-DS	264.9	-	129.3	322.2	402.7	0.365	4.178	39.5
	PV-Li	1,113.6	2,412.8	-	322.2	402.7	0.572	5.084	100.0
	Hybrid	342.6	219.7	129.3	322.2	402.7	0.356	4.138	51.9
Sink	Diesel	-	-	-	-	-	-	-	-
Only	PV-DS	1,062.5	-	15.6	406.3	414.1	0.349	2.820	47.4
	PV-Li	1,093.8	252.2	-	531.3	406.3	0.359	2.914	100.0
	Hybrid	1,093.8	37.1	12.5	406.3	414.1	0.355	2.821	61.9
Min.	Diesel	-	-	131.3	325.0	406.3	0.396	4.331	0.00
Level	PV-DS	1,031.3	-	25.8	344.1	421.9	0.347	2.818	48.7
	PV-Li	1,125.0	287.5	-	330.3	421.9	0.372	2.821	100.0
	Hybrid	1,031.3	1.4	25.8	344.1	421.9	0.347	2.818	49.4

Table 2 shows the optimum sizes of each energy and water component at different dispatch algorithms. In load-only case, the LCOW values follow with the LCOE with hybrid energy system yields the lowest LCOW and lowest LCOE. The relation between LCOW and LCOE is due to the dispatch algorithm used where the cost of water production highly depends on the cost of energy production. In sink-only case, the LCOW is at a minimum using solar PV-diesel energy systems, which also yields the lowest LCOE. In the minimum level case, the LCOW is the lowest among different dispatch scenarios. For comparison, the LCOE of solar PV-diesel energy system is 0.87 % higher than the solar PV-diesel energy system without desalination units, therefore implying that installation of RO will not significantly increase energy price.

3.2 Power Flows

Chapter 2 Figure 4 shows the comparison of the power flow diagram of different water-energy dispatch algorithm. In load-only case, there is an increase in energy generation capacity to accommodate RO as an additional load. In sink-only and minimum-level case, the water storage level depends on the solar PV generation. The power flow of the minimum-level case does not explicitly reveal how the system will interact if the water level reaches 10 % due to the assumption that water level is high at the initial time.

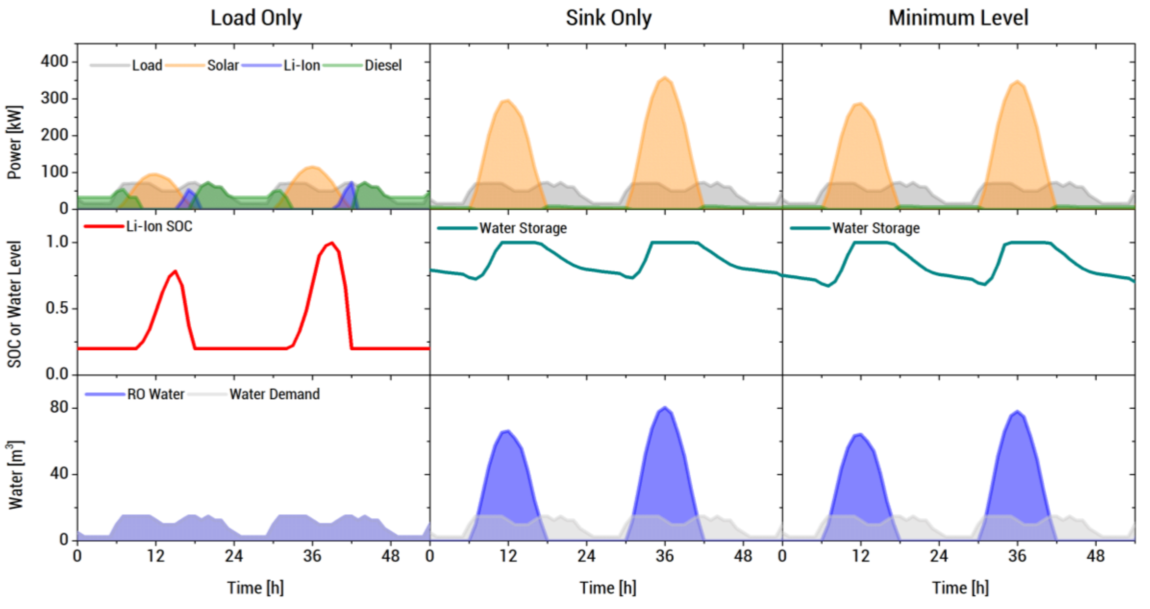

Figure 4: Power flow of the load-only case (upper right), sink-only case (lower left), and minimum-level case (lower right)

4. Conclusions

Putting up RO desalination units for off-grid islands provides a promising alternative for water access. In this work, the techno-economic optimization and simulation results show that a PV-diesel hybrid system with a minimum-level dispatch algorithm provides the lowest LCOW of 2.818 $/m^3 among tested configurations. In addition, the additional energy cost is only 0.87% even if RO units were added in the system. This work hopefully provides a framework for water-energy nexus analysis. Future works would include other desalination technologies with more detailed models and a national-scale water-energy analysis with more robust techno-economic analysis.

Acknowledgements

M.T. Castro would like to thank the DOST-SEI Undergraduate Scholarship for financial support. J. D. Ocon would like to thank the Federico Puno Professorial Chair Award and the ASEAN Science & Technology Fellowship. C. M. Odulio would like to thank the ERDT Faculty Dissemination Grant.

References

Bajpai, P., Dash, V., 2012, Hybrid renewable energy systems for power generation in stand-alone applications: A review, Renewable and Sustainable Energy Reviews, 16(5), 2926–2939.

Bognar, K., Blechinger, P., Behrendt, F., 2012, Seawater desalination in micro grids: an integrated planning approach. Energy, Sustainability and Society, 2(1), 14.

Caldera, U., Breyer, C., 2017, Learning Curve for Seawater Reverse Osmosis Desalination Plants: Capital Cost Trend of the Past, Present, and Future, Water Resources Research, 53(12), 10523–10538.

California Public Utilities Commission, 2011, Embedded Energy in Water Studies Study 3: End Use Water Demand Profiles. California, USA.

Corsini, A., Tortora, E., 2018, Sea-Water Desalination for Load Levelling of Gen-Sets in Small Off-Grid Islands, Energies, 11(8), 2068

DiOrio N., Dobos A., and Janzou S., 2015 Economic Analysis Case Studies of Battery Energy Storage with SAM, National Renewable Energy Laboratory, Golden, Colorado, USA.

Fu R., Feldman D., Margolis R., Woodhouse M., Ardani K., 2017, U.S. Solar Photovoltaic System Cost Benchmark: Q1 2017, National Renewable Energy Laboratory, Golden, Colorado, USA.

Griffin, R., Chang, C., 1991, Seasonality in Community Water Demand, Western Journal of Agricultural Economics, 16(2), 207-217

Gökçek, M., Gökçek, Ö. B., 2016, Technical and economic evaluation of freshwater production from a wind-powered small-scale seawater reverse osmosis system (WP-SWRO), Desalination, 381, 47–57.

Gökçek, M., 2018, Integration of hybrid power (wind-photovoltaic-diesel-battery) and seawater reverse osmosis systems for small-scale desalination applications, Desalination, 435, 210–220.

Khalifa, A. J. N., 2011, Evaluation of different hybrid power scenarios to Reverse Osmosis (RO) desalination units in isolated areas in Iraq, Energy for Sustainable Development, 15(1), 49–54.

Moseley P., Garche J., 2015, Electrochemical Energy Storage for Renewable Sources and Grid Balancing, Elsevier, Amsterdam, Netherlands

Navarro S., 2016, Hybrid Opportunities in SPUG Areas using HOMER, Asian Clean Energy Forum, <d2oc0ihd6a5bt.cloudfront.net/wp-content/uploads/sites/837/2016/03/Silver-Navarro-Hybrid-Opportunities-in-SPUG-Areas-using-HOMER-final.pdf> accessed 13.03.2019

Rao, P., Morrow, W. R., Aghajanzadeh, A., Sheaffer, P., Dollinger, C., Brueske, S., Cresko, J., 2018, Energy considerations associated with increased adoption of seawater desalination in the United States., Desalination, 445, 213–224. doi:10.1016/j.desal.2018.08.014