CHEMICAL ENGINEERING TRANSACTIONS
VOL. 88, 2021

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Yee Van Fan, Jiří J. Klemeš

ISBN 978-88-95608-86-0; **ISSN** 2283-9216

DOI: 10.3303/CET2188044

Techno-Economic Potential of Reverse Osmosis in Desalination Coupled-Hybrid Renewable Energy Systems in Off-Grid Islands

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The archipelagic geography of the Philippines has resulted in thousands of inhabited off-grid islands wherein energy and water access are hindered. Electricity in these islands is provided by diesel generators, while water is obtained from rainwater, groundwater, or imports from the mainland. As an alternative to these costly and unsustainable sources, hybrid renewable energy systems (HRES) coupled with reverse osmosis (RO) desalination has been investigated for the cogeneration of electricity and water. In this work, the techno-economic potential of coupled RO-HRES in selected off-grid areas in the Philippines was evaluated. Solar photovoltaics, wind turbines, lithium-ion batteries, and diesel generators were considered as HRES components. Dumaran Island and Bantayan Island were chosen as case studies because both islands have faced electricity and water supply concerns. Moreover, these islands present different use cases as Dumaran Island is mainly residential while Bantayan Island has a growing resort industry. Three scenarios were considered in this work to analyze the transition from the status quo to the energy-water system: diesel-only, HRES, and RO-HRES. The islands and scenarios were modeled using the Island Systems $\mathrm{LCOE_{min}}$ Algorithm, an in-house energy systems modeling tool written in Python 3. Transition from the diesel-only system to HRES decreased the system costs by an average of 15.1 % in both islands. However, the installation of RO was primarily beneficial for the resort island wherein electricity costs increased by only 0.8 % from the HRES scenario and water costs were 80 % lower than current rates in surrounding islands. In contrast, RO deployment in the residential island raised electricity prices by 10.8 %.

1. Introduction

The Philippines is an archipelagic country with thousands of remote off-gid islands whose distance from the mainland has been a barrier to both energy and water access. These islands are typically powered by diesel generators, which contribute to greenhouse gas emissions and operate for only a few hours each day due to the difficulty of transporting diesel fuel (Ocon and Bertheau, 2019). In addition, freshwater in these islands is obtained from rainwater, which is unreliable and unpredictable, or from groundwater, which is vulnerable to increased demand (Holding et al., 2016). There is also an option to import freshwater from the mainland, however, this incurs sizeable transport costs, as reported by the Department of Science and Technology (DOST, 2021).

The energy aspect of this problem has received notable attention. Hybrid renewable energy systems (HRES), which consist of renewable energy (RE) technologies, energy storage systems, and diesel generators, have been investigated as an alternative to the diesel-only systems in off-grid islands (Manoj Kumar et al., 2020). RE technologies, such as solar photovoltaics (PV) and wind, displace reliance on diesel-based generation while energy storage systems, such as lithium-ion (Li-ion) batteries, stabilize the intermittent generation of RE. The techno-economic potential of HRES in the Philippines has been evaluated in previous studies. A study by Ocon and Bertheau (2019) showed that HRES with solar PV, Li-ion, and diesel can provide a 20 % lower levelized cost of electricity (LCOE) compared to diesel-only systems.

Paper Received: 26 April 2021; Revised: 29 July 2021; Accepted: 31 August 2021
Please cite this article as: Castro M.T., Ocon J.D., 2021, Techno-Economic Potential of Reverse Osmosis in Desalination Coupled-Hybrid Renewable Energy Systems in Off-Grid Islands, Chemical Engineering Transactions, 88, 265-270 DOI:10.3303/CET2188044

As for water access, reverse osmosis (RO) desalination has been considered for the conversion of surrounding saltwater into freshwater due to its low cost and energy consumption. This requires electricity for pumping saltwater into a semipermeable membrane, so RO coupled with HRES is studied for the simultaneous generation of energy and water. This interdependence, known as the energy-water nexus, must be analyzed as a whole (Namany et al., 2019) because independently optimizing the water and energy systems may result in non-optimal solutions. Previous works on coupled RO and energy systems have focused on comparing energy dispatch strategies (Bognar et al., 2012) and desalination technologies (Castro et al. 2020), however, the techno-economic potential of RO-HRES systems has yet to be evaluated in detail.

In this work, we evaluated the techno-economic potential of RO-HRES systems in Dumaran Island in the province of Palawan and Bantayan Island in the province of Cebu, which are residential and resort islands, respectively. These islands were selected as they are off-grid and have problems regarding their water supply. Dumaran Island relies on freshwater imports (DOST, 2021), while Bantayan Island sources freshwater from both groundwater and imports (Oxfam, 2021).

2. Methodology

The methodology is divided into five parts. First, the islands and modeling scenarios were introduced. Second, the energy and water consumption of each island was estimated. Third, the techno-economic data used in the simulations were presented. Fourth, the modeling of the scenarios was described. Lastly, performance metrics were calculated to assess the techno-economic potential of RO-HRES systems in off-grid islands.

2.1 Case studies

This study considered two types of off-grid islands for a comprehensive case study. Dumaran Island (10.54 ˚N, 119.86 ˚E) in the province of Palawan is a residential island, whereas Bantayan Island (11.21 ˚N, 123.74 ˚E) in the province of Cebu has an active resort industry but is still partly residential. The techno-economic potential of RO-HRES systems in these islands was assessed based on three scenarios. In the first scenario, the electrical load was supplied only by diesel generators. This represents the status quo in many Philippine off-grid islands, wherein diesel generators are the typical source of electricity. In the second scenario, an HRES consisting of solar PV, wind turbines, Li-ion batteries, and diesel generators is utilized to supply the electrical demand. Comparing this scenario with the previous one illustrates the techno-economic potential of transitioning from a diesel-only system to HRES. In the final scenario, a RO-HRES system is considered for the simultaneous generation of electricity and water. This scenario evaluates the techno-economic potential of integrating RO units into HRES.

All scenarios were modeled using the Island Systems LCOE_{min} Algorithm (ISLA), an in-house energy systems modeling software (Castro et al., 2020). ISLA simulated the hourly supply and demand of electricity and water for one representative year to determine the component sizes (i.e., power, energy, volume, and volumetric flowrate ratings) that minimized the net present cost (NPC) of the system. This required estimates of the electricity and water demand, as well as techno-economic parameters describing each component. We then computed performance metrics from which the techno-economic potentials were assessed.

2.2 Energy and water consumption

The energy and water demand profiles in both islands were estimated from three parts: the normalized hourly profile, the normalized monthly profile, and the peak demand. The normalized hourly and monthly profiles are combined to form a year-long demand profile with an hourly resolution. This year-long profile is then scaled to meet the peak demand.

For the residential Dumaran Island, the peak electrical demand and normalized monthly electrical profile were obtained from the National Power Corporation – Small Power Utilities Group (NPC-SPUG), which operates diesel generators in several off-grid islands, while the normalized hourly electrical demand profile was obtained from (Bertheau and Blechinger, 2018). As for the water demand, the peak water consumption was 20 L/capita·day as recommended by the World Health Organization (Cipollina et al., 2012). This should be sufficient for drinking and other activities requiring freshwater. The normalized hourly profile was based on the low-income single-family indoor profile reported by the California Public Utilities Commission (2011) due to the absence of a local water demand profile, while the normalized monthly load profile was taken from (Griffin and Chang, 1991). The peak electrical and water demand were 286 kW and 428 m^3/d.

As for Bantayan Island, the peak electrical demand and the normalized hourly electrical demand profile were taken from a report by the Energy Regulatory Commission (2017), while the normalized monthly electrical profile was obtained from (Bertheau and Blechinger, 2018). Just like with Dumaran Island, the peak water demand was also calculated from the 20 L/capita·day recommendation and the normalized monthly load profile was taken from (Griffin and Chang, 1991), but the normalized hourly profile was taken from the standard income single-family indoor profile from (California Public Utilities Commission, 2011). The peak electrical and water demand were 6,817 kW and 1,661 m^3/d, respectively.

2.3 Techno-economic data

Aside from the electrical and water demand, the simulations will also require the global horizontal irradiance (GHI) and wind speeds in both locations, as well as techno-economic data describing the components. The GHI and wind speeds at 10 m were obtained from the Phil-LIDAR 2 (Blanco et al., 2015). The techno-economic data used in this work is presented in Table 1. The wind turbine has a 10 m height, so no wind speed corrections were applied. Two operating costs were imposed on the diesel generators: a fixed cost proportional to the power rating (i.e., USD/kW·y) and a variable cost that depends on the generated electricity (i.e., USD/kWh).

Table 1: Techno-economic modeling parameters.

Component	Parameter	Value	Ref.	Component	Parameter	Value	Ref.
Solar PV	CapEx [USD/kW]	1,500	[a]	Diesel	Lifetime [y]	10	[c]
	OpEx [USD/kW·y]	15	[a]		Fuel Cost [USD/L]	0.9	[c]
	Lifetime [y]	20	[a]		CO_2 emissions [kg/L]	2.67	[c]
Wind	CapEx [USD/kW]	2,500	[a]	RO	CapEx [USD/(m^3/d)]	1,250	[d,e]
	OpEx [USD/kW·y]	600	[a]		OpEx [USD/m^3]	0.232	[d]
	Lifetime [y]	20	[a]		Lifetime [y]	6	[f]
Li-ion	CapEx [USD/kWh]	700	[a]	Reservoir	CapEx [USD/m^3]	1,000	[g]
	OpEx [USD/kWh·y]	5	[a]		OpEx [USD/m^3·y]	10	
	Lifetime [y]	10	[a]		Lifetime [y]	20	
Diesel	CapEx [USD/kW]	500	[b]	Project	CapEx [USD]	0	[a]
	OpEx [USD/kW·y]	20	[b]		Discount rate d [%]	8	[a]
	OpEx [USD/kWh]	0.02	[b]		Lifetime N [y]	20	[a]

[a] (Bertheau, 2020), [b] (Bertheau and Cader, 2019), [c] (Ocon and Bertheau, 2019), [d] (Reddy and Ghaffour, 2007), [e] (Ghaffour et al., 2013), [f] (Coutinho de Paula et al., 2017), [g] (Gökçek, 2018).

2.4 Scenario modeling

The system architectures of the three scenarios are shown in Figure 1. In the diesel-only and HRES scenarios, only the electrical demand was served. The HRES operated under a load-following algorithm. If RE exceeds the electrical load, then the Li-ion batteries are charged. Otherwise, Li-ion batteries and diesel generators are dispatched by just enough to meet the load. As for the RO-HRES scenario, water generated by the desalination unit was sent to a reservoir from which the water demand was drawn. Details regarding the modeling and optimization in ISLA can be found in a previous work (Castro et al., 2020).

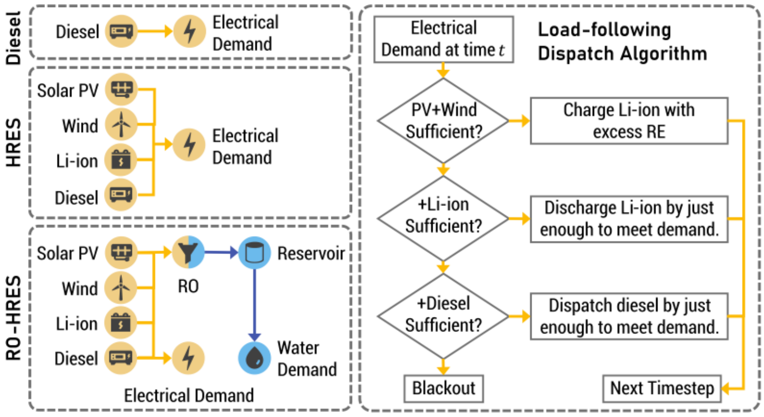

Figure 1: System architectures of the diesel-only, HRES, and RO-HRES scenarios (left) and the load-following dispatch algorithm describing the operation of the HRES (right)

The RO unit was parameterized by the energy intensity (EI) and turndown ratio (TDR). The EI is the electricity required to produce a unit of freshwater and was assumed to be 4.35 kWh/m^3 for RO (Abdelkareem et al., 2018). The TDR is the ratio between the minimum allowable throughput and the design throughput, which is 0.33 for RO (Kim and Garcia, 2015). This prevents damage caused by very low operating points.

The electrical demand of the RO unit depends on the water level in the reservoir. A minimum water level of 20 % is imposed as a safety net against the unpredictable nature of RE generation. If the water level is above 20 %, then the RO unit generates water solely from excess RE generation after the Li-ion batteries are charged. However, if the excess RE generation is below the operating point set by the TDR, then no water is generated. If the water level is below 20 %, then electricity is actively supplied by the HRES to the RO unit (i.e., RO is treated as an additional electrical load rather than a sink for excess RE) either to keep the water level at 20 % or to satisfy the minimum operating point given by the TDR, whichever is greater.

2.5 Techno-economic metrics

The techno-economic potential of the RO-HRES systems were assessed based on the LCOE and levelized cost of water (LCOW), as shown in Eq(1) and Eq(2), respectively (Gökçek and Gökçek, 2016). Both depend on the capital recovery factor (CRF) given by Eq(3). The discounted cost of electricity C_{el} and water C_{wt} components, energy demand of the islands E_{el} and desalination unit E_{de}, and water production of the desalination unit V_{de} are calculated by ISLA. The optimum sizes, NPC, and CO_2 emissions are also considered in this study.

$$\mathrm{LCOE} = \frac{\mathrm{CRF} \cdot C_{\mathrm{el}}}{E_{\mathrm{el}}} \tag{1}$$

$$\mathrm{LCOW} = \frac{\mathrm{CRF} \cdot C_{\mathrm{wt}} + \mathrm{LCOE} \cdot E_{\mathrm{de}}}{V_{\mathrm{de}}} \tag{2}$$

$$\mathrm{CRF} = \frac{d(1+d)^N}{(1+d)^N - 1} \tag{3}$$

3. Results and discussion

In this section, the techno-economic metrics pertaining to the optimized systems are presented. The power flows of the RO-HRES scenarios are then shown to analyze the interactions between the energy and water systems.

3.1 Techno-economic metrics

The techno-economic metrics describing each island and scenario are presented in Table 2. In both islands, the transition from the diesel-only system to HRES resulted in the addition of solar PV to reduce reliance on the diesel generators. Li-ion batteries were also installed to capture excess solar PV generation. The electricity generation costs decreased by 14.7 % and 15.4 % while the CO_2 emissions dropped by 38.6 % and 34.5 % in the residential and resort islands, respectively. Wind capacity, however, was small in the HRES because the excess RE generation would require more Li-ion batteries, which would incur additional costs.

Table 2: Techno-economic metrics describing each island and scenario.

Island	Scenario	PV [kW]	Wind [kW]	Li-ion [kW]	Diesel [kW]	LCOE [USD/kWh]	NPC [10^6 USD]	CO_2 [10^3 t/y]
Dumaran	Diesel				375.9	0.279	4.49	1.15
(Residential)	HRES	375.9	94.0	62.6	375.9	0.238	3.83	0.71
	RO-HRES	580.7	217.8	0.0	435.5	0.264	6.28	0.64
Bantayan	Diesel				8,947	0.273	121.9	31.6
(Resort)	HRES	11,930	0	746	8,947	0.231	103.1	20.7
	RO-HRES	11,733	1173	0	8,448	0.233	119.3	20.5
Island	Scenario	RO [m^3/d]	Reservoir [10^3 m^3]	LCOW [USD/m^3]				
Dumaran	RO-HRES	640.7	15.1	4.21				
Bantayan	RO-HRES	5,179	128	6.90				

The transition from HRES to RO-HRES, on the other hand, required additional wind power as this generated excess RE to power the RO units. The Li-ion installations were removed as these competed with RO for excess RE. The residential and resort islands saw a 63.8 % and 15.8 % increase in overall costs, as indicated by the NPC, however the trends in the LCOE and LCOW were different. The residential island experienced a 10.8 % increase in electricity generation costs due to the higher solar PV and Li-ion installation sizes. In contrast, the resort island showed a negligible 0.8 % increase in LCOE, although it had a much higher LCOW. Nevertheless, the LCOW in both islands were a notable improvement from the current 75 USD/m^3 and 35 USD/m^3 in the residential island (DOST, 2021) and islands surrounding the resort island (Oxfam, 2021), respectively.

3.2 Power flows

The daily, weekly, and annual power flows (i.e., power generation vs. time) and water level are shown in Figure 2. The daily and weekly power flows showed the importance of wind power in slowing the decrease of the water level. The annual power flows explained the differences in the LCOE and LCOW trends upon transition from HRES to RO-HRES in the two islands. In the residential island, the water level was frequently close to the 20 % minimum, hence an additional electrical capacity was required for water generation. The cost of desalination consequently had a greater impact on the LCOE. The resort island, on the other hand, had an annual electricity demand 28 times that of the residential island, but its water demand was only three times that. As a result, the HRES system produced a larger proportion of excess RE generation, as evidenced by the deviation of the water level from the 20 % minimum. The cost of desalination therefore weighed more on the LCOW.

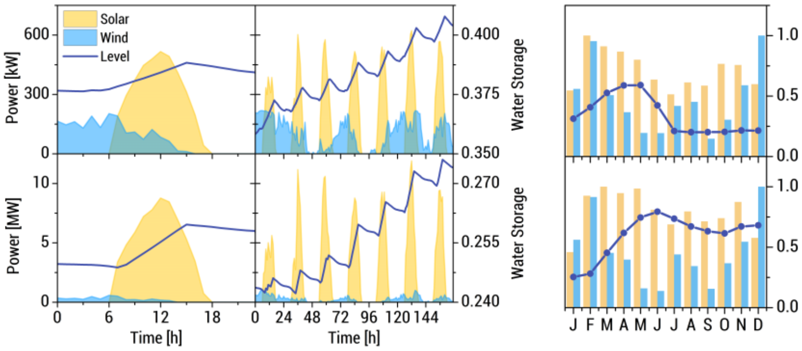

Figure 2: Representative daily (left), weekly (middle), and average annual (right) solar PV generation (yellow), wind generation (light blue), and water level (dark blue) in the residential Dumaran Island (top) and resort Bantayan Island (bottom). The solar PV and wind generation in the annual power flow are normalized

4. Conclusions

In this work, we assessed the techno-economic potential of RO-HRES systems in Philippine off-grid islands. The study involved the residential Dumaran Island and the resort Bantayan Island to account for various use cases. The transition from a diesel-only system to HRES was favorable in both islands as this contributed to lower generation costs and did not require additional diesel generator capacities. In contrast, further transition into RO-HRES was marked by increased system costs. The residential island, which generated less excess RE, saw an increase in electricity generation costs. Meanwhile, the resort island, which generated more excess RE, had a higher water generation cost than the residential island but had minimal changes in electricity costs.

From the results of this case study, it can be argued that a transition from diesel-based generation to HRES is generally advantageous for off-grid islands. However, the installation of RO is much more beneficial for islands with a larger electrical demand. Larger islands naturally generate larger amounts of excess RE, which results in a smaller disturbance in electricity generation costs upon installation of RO. Moreover, larger wind turbines have a lower per-kW cost than smaller ones, which make them an affordable source of electricity for RO. This study provides a framework for analyzing the techno-economic potential of coupled RO-HRES systems, which can be extended to other islands worldwide. Future work on RO-HRES should evaluate the techno-economic potential of RO-HRES systems in islands all over the archipelago. This would determine if the technologies prioritized in HRES deployment should also be prioritized during the integration of RO. It is also worthwhile to collect water consumption profiles of off-grid communities in the Philippines.

Nomenclature

C_{el} – discounted cost of energy components, USD
CRF – capital recovery factor, -
C_{wt} – discounted cost of water components, USD
d – discount rate, -
E_{el} – annual electrical demand, kWh
E_{de} – annual electrical demand of the desalination unit, kWh
EI – energy intensity, kWh/m^3
GHI – global horizontal irradiance, kW/m^2
LCOE – levelized cost of electricity, USD/kWh
LCOW – levelized cost of water, USD/m^3
N – project lifetime, y
NPC – net present cost, USD
TDR – turndown ratio, -
V_{de} – annual water demand, m^3

Acknowledgements

M.T.C. would like to acknowledge the Engineering Research and Development for Technology (ERDT) Graduate Scholarship. J.D.O. would like to acknowledge the NEXUS Project funded by the Department of Science and Technology's Grants-in-Aid program (DOST-GIA) through the National Academy of Science and Technology (NAST).

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