Sustainable Water Supplies for the Caribbean

Water Resources Management beyond 2020
Adam Simmonds, Project Manager, Necker Island
Chris Hough, PE President - Design by Initiative LLC
Dean Bedford, PE Gemini Seawater Systems LLC

Sustainable development, is typically defined as development that meets the needs of the present without compromising the prospects of future generations. This definition can be expanded to mean the needs of present users without compromising the ability of future generations to meet their own needs, particularly with regards to use and waste of natural resources.

One of the greatest challenges facing the Caribbean is the development of sustainable water resources. Naturally occurring supplies are becoming less predictable due to climate change or are being exceeded by demand, due to growth. This results in the implementation of desalination to make up the ever-increasing shortages. Although there have been numerous improvements to reduce the amount of energy required to desalinate seawater, it still requires substantial energy that has for the most part, been supplied through carbon-based fuels. Continuing the approach into the future will only serve to worsen climate change. The purpose of this paper is to show there are means of augmenting water supplies and the distribution of potable water without increasing the carbon footprint.

Desalination

In order to understand how this can be achieved, one must first understand the capital and operational costs of desalination. For this paper, the term desalination refers to the treatment of seawater to potable water standards utilizing membrane-based methodology. There are other means of desalinating seawater that may be amenable to renewable energy, but they will not be addressed herein.

Water treatment using membrane technologies (e.g. microfiltration, ultrafiltration, nanofiltration, brackish and seawater) has been used extensively throughout the world as a means of treating non-potable water, primarily for the following reasons:

1. The process attains very high levels of contaminant removal making it the treatment of choice for many projects;
2. As for desalination plants, there is an endless supply of feedwater (seawater);
3. Treatment plants are modular in nature, allowing capacity and the associated capital costs to be matched to immediate demands with expansion capabilities for future increases in demand;
4. Multiple, smaller distributed treatment plants can be used rather than a large single plant with an extensive distribution system; and
5. Major improvements in membrane technology and the mechanical equipment used in the treatment process have been made in the past 15 to 20 years making the treatment process very reliable and cost effective to operate.

The two major perceived problems with seawater desalination are high capital and production costs. Compared to naturally occurring options, desalination is significantly higher in respect to implementation and operation. However, the issue facing the world with respect to water is that most low capital and production cost sources have been developed and pushing these supplies beyond their safe yield is not, by definition, sustainable. Accordingly, the unit capital and production costs for these once inexpensive options is increasing to the point that the cost to implement desalination become feasible. In order to understand where this crossover point occurs, one must first understand the capital and production costs for a desalination option.

The treatment process for a typical desalination plant is the Caribbean consists of a seawater supply (wells in the upper regions of the Caribbean and intakes in the windward and leeward islands), seawater pumping, pretreatment consisting of filtration, scale control and cartridge filtration, desalination with energy recovery, post treatment, storage and finished water pumping to distribution. The residuals for the plant (membrane concentrate and backwash streams) are either disposed via injection wells or through open discharge. The plant site would include buildings to house the equipment and the power supply, generally from the local power authority. As with most treatment processes, the cost to construct, and to a lesser degree, operate a plant is lower, on a unit basis for larger plants compared to smaller facilities. For this paper, two plants are examined to show this relationship; a 100,000 US gallon per day

(GPD) plant, typical of resorts and private develops or islands and a 1,500,000 US GPD plant, more in line with modules used by utilities.

Table 1 presents a breakdown of the unit treatment capital costs for each plant size based on two projects. The costs in Table 1 do not include site, building or civil costs as these are very site dependent and would be applicable to other methods of treatment being considered.

Table 1

Desalination Treatment Capital Costs

	Plant 1		*Plant 2*	
No. of Production Trains	2		6	
Train Capacity, USGPD	60,000		250,000	
Plant Capacity, USGPD	120,000		1,500,000	
		Unit Capital Cost, $/GPD		Unit Capital Cost, $/GPD
Seawater Supply[1]	$116,200	19.2%	$517,200	11.6%
Pretreatment[2]	$80,200	13.3%	$842,000	19.0%
Desalination Process[3]	$270,000	44.7%	$2,100,200	47.3%
Electrical Systems	$71,000	11.8%	$456,000	10.3%
Post Treatment[4]	$28,000	4.6%	$89,200	2.0%
Project Management	$38,540	6.4%	$437,000	9.8%
Total Process Equipment	**$603,940**	**100.0%**	**$4,441,600**	**100.0%**
Unit Capital Cost, $/USGPD	**$5.03**			**$2.96**

As shown, the unit cost of capacity for a large capacity plant approaches $3.00 per install gallon while the subsystem process costs for smaller plants drive the unit cost of production to approximately $5.00 per installed gallon of capacity.

[1] Seawater supply consists of open seawater intake located approximately 600 feet offshore, HDPE conduit anchored using ballast blocks and Manta type anchors. Feedwater pump station located on shore and equipped with priming system, cleanable basket strainers, end suction centrifugal pumps operated with VFDs.
[2] Pretreatment consists of multimedia filtration, filter aid, cartridge filtration and chemical scale control.
[3] Desalination process consists of axial piston high pressure pumps, isobaric energy recovery units with boost pumps controlled using PID loops, Zeron100 high-pressure piping, and membrane arrays designed for an average flux ranging from 8.3 to 8.9 GFD.
[4] Post treatment consists of up flow calcite beds for alkalinity and hardness and two liquid chemical feed systems for chlorination and corrosion inhibition. Post treatment instrumentation includes storage level, finished water conductivity, chlorine residual, and pH and discharge pH, temperature and pH.

Table 2 presents the production costs for these two plants, excluding operating, maintenance and management labour. In this table, the plant and equipment maintenance allowance is the cost for all maintenance of plant components (e.g. pump seals and rebuild kits, etc.) as well as replacement of components once their useful life has been reached. It can be thought of as a contribution to a sinking fund that would provide funding for all future plant maintenance. Using this approach, plant life is, in theory, infinite. It also allows the treatment process to be upgrades in the future in the event on improvements in components.

The slightly lower unit operational cost for larger plants reflect the ability to use of larger, more efficient pumping systems that result in lower maintenance and replacement, and the ability to purchase consumables at a more attractive price based on higher consumption. As is shown in Table 2, energy consumption makes up over 65 percent of the cost of production based on a unit cost of energy of $0.38 per kilowatt. In many locations throughout the Caribbean, the cost of energy is substantially higher than this, shifting the energy percentage

Table 2

Desalination Treatment Production Costs

Plant	*Case 1*		*Case 2*	
Consumable[5]	$/Kgal	Percentage	$/Kgal	Percentage
Chemical Addition[6]	$0.46	6.8%	$0.26	4.5%
C/F and Membrane Replacement[7]	$0.28	4.2%	$0.25	4.4%
Plant and Equipment Maintenance[8]	$1.58	23.6%	$1.01	17.6%
Energy[9]	$4.37	65.4%	$4.23	73.6%
Total (Excluding Labor)	**$6.68**	**100.0%**	**$5.74**	**100.0%**

[5] Consumable costs are calculated without any importation duties.

[6] Chemical addition consists of 2.0 mg/l of scale inhibitor, 1.0 mg/l sodium hypochlorite, 40 mg/l Calcium carbonate and 6.0 mg/l corrosion inhibitor.

[7] Cartridge filter replacement is based on once per month and membrane replacement based on a service life of three years.

[8] Plant and process equipment maintenance is based on preventative maintenance plan following manufacturer requirements and experience in the Caribbean. Costs assume no importation duty.

[9] Energy costs are based on $0.38 per kilowatt, 800 psi membrane operating pressure, 15 psid membrane differential, and finished water pumping to 65 psi. energy consumption is determined based on manufacturer published efficiencies.

Table 3 presents a breakdown of the energy usage for the two case plants and includes the total running load, expressed in kilowatts along with the total connected load for the facility, also expressed in kilowatts.

A few comments with respect to Table 3.

1. The feedwater supply is the second greatest load in any desalination plant as this pumping system must supply approximately 2.2 to 2.5 times the rated plant capacity in seawater to account for the plant operating at a recovery rate[10] of 40 to 45 percent.

Table 3

Energy Consumption within a Desalination Plant

	Case 1	*Case 2*
Total Capacity, USGPD	120,000	1,500,000
Feedwater Supply	2.07	2.41
Membrane Feed Pump	7.51	6.91
Energy Recovery Boost Pump	0.79	0.81
Cleaning/ Flush Pump	0.01	0.01
Finished Water	0.86	0.75
Controls & Building HVAC	0.25	0.23
Total Unit Consumption, kWh/1,000 Gallons	**11.49**	**11.12**
Total Running Load, KW	**64.8**	**725.6**
Total Connected Load, KW	**95.6**	**945.0**

Knowing this, it is imperative, from an energy conservation standpoint, to locate the desalination plant at the lowest practical elevation possible.

2. The lower membrane feed pump energy usage reflects the improvement in mechanical efficient for larger pumps. This value will increase as membrane fouling occurs. Monitoring and taking steps to control membrane fouling

[10] The recovery rate is the volumetric efficiency of the system as defined as the volume of water produced as a percentage of the feedwater. A 40 percent recovery system produces 40 gallons of permeate for every 100 gallons of seawater pumped into the membrane array.

through pretreatment adjustments and periodic cleaning/membrane replacement is critical.

3. The finished water pump power consumption is based on pump operations at a constant duty point. Unless the finished water pumping system is supplying water to an elevated storage facility, the high-service pumps operate in response to water demand, most of time, well below their best efficiency point. In this case, the value shown in Table 3 is typically very low.

4. In terms of the power supply to operate the two plants, the 100,000 GPD plant would require a firm power supply of 100 kW to operate while the 1.5 MGD plant would require a firm power supply of 1.0 MW to operate. These requirements are based on staggering the starting of the various loads and trains to minimize the inrush.

Water supplies are sized based on maximum daily demand over time. Membrane based treatment plants produce water at a fixed rate. With multiple treatment trains, the plant output can be adjusted in equal steps, based on the number of trains available. Most plants are designed for an on-line factor of 90 to 95 percent at full production. In other words, to meet a projected daily demand of 1.0 million gallons, a desalination plant designed to produce 1.1 MGD would be required.

With a basic understanding of the capital and operating costs of a desalination plant, we will examine how renewables be integrated into the power supply to make this a more sustainable source of potable water.

Constant vs Deferrable Load

With respect to the power supply design, desalination plants have been treated as a constant running load that require 24-hour per day power supply. When considering renewable energy supplies, they can also be treated as a deferrable load that runs when surplus energy is available. This approach stores water produced using renewable energy rather than first storing energy provided by renewables for later use to produce water. This approach could require the desalination plant capacity be adjusted to offset the reduced operating hours per day if battery storage is to be minimized. The optimum plant capacity is determined by balancing the capital and

operating cost for the additional capacity verses the capital and maintenance costs for renewable energy options (wind or solar) as well as the required battery storage cost. To understand this approach, one needs to look at the long-term energy costs of the treatment process. For this study, a 20-year planning horizon has been assumed. The higher the cost of energy for a location, the shorter the payback period for the renewable system along with the desired reduction in carbon footprint for the water supply.

Figure 1 presents the present value of energy for the 100,000 GPD plant as a function of the cost of energy. Only the energy associated with the treatment of seawater has been included in the present worth calculation. The energy associated with the finished water pumping has been excluded as this would be applicable to other forms of water treatment.

Figure 1
Present Worth of Energy as a Function of Power Cost for a 100,000 GPD SWRO Plant

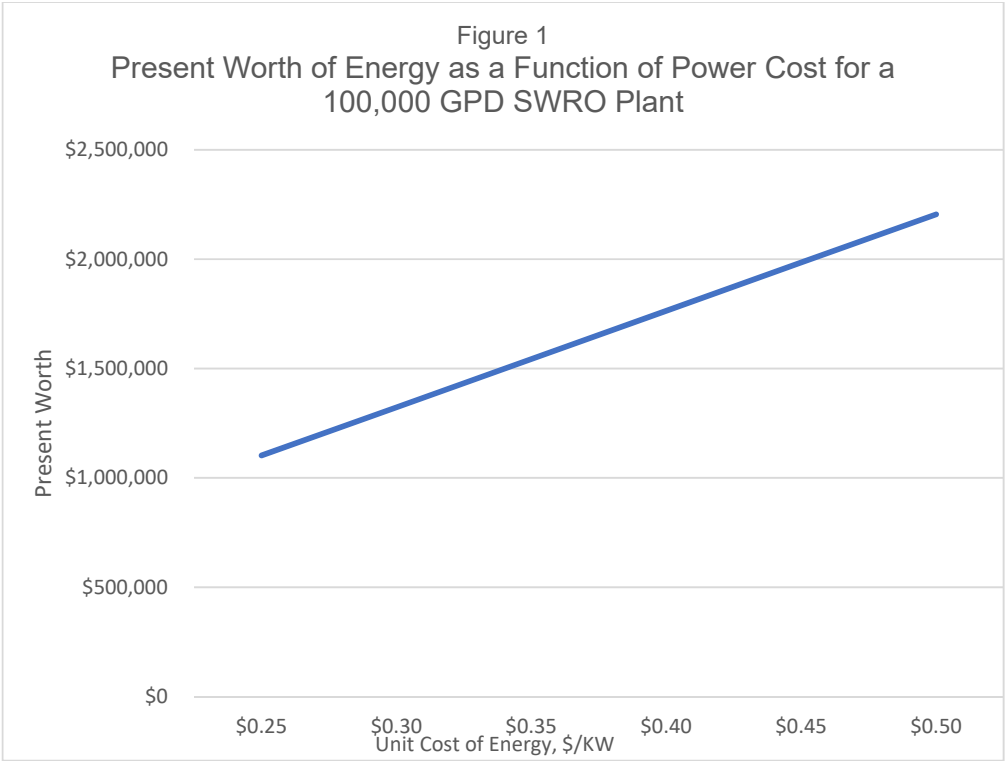
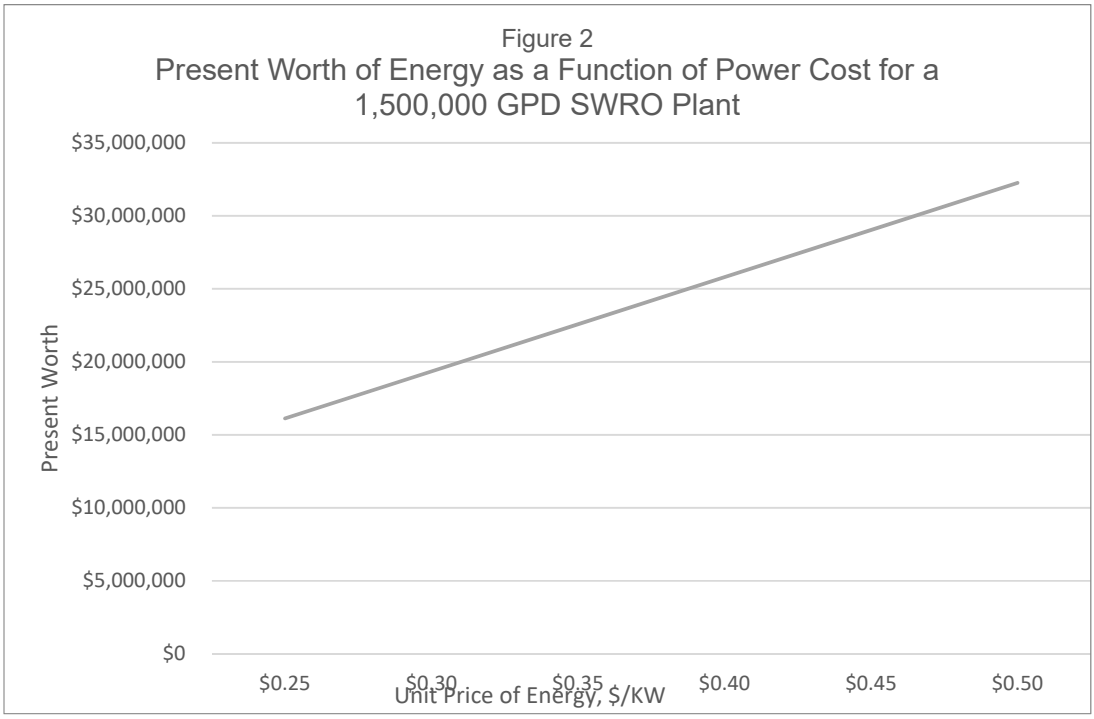


Figure 2 presents the present value of energy for the 1,500,000 GPD plant as a function of the cost of energy. These two figures provide an idea of the amount of money spent on energy over the typical life of a desal plant using conventional carbon based grid power. Depending on the cost of energy, there exists a vast amount of capital which can be used to either offset the cost to invest in renewable energy or reduce the total dependency on grid power.



If renewables are to be used and the treatment plant is treated as a constant load, the microgrid would consists of a renewable energy source, power management including battery storage for system stability (absorbing production peaks or high instantaneous load events) and typically are upplemented by diesel powered generators. . If the goal is minimizing fuel consumption, the battery system needs to be sized for power stabilization and supplying energy to the desalination plant during non-power production periods from the renewable source.

Once the water supply has been designed and the loads known, an analysis is performed to find the optimum balance of each component.

Configuration 1 – Operating as a constant load

Using the Homer Energy model, two scenarios were investigated, one using photovoltaics,the second using wind turbines and the third a combination of both to determine the required amount of battery storage needed to operate the desalination plant as a constant load. This was calculated whilst maintaining a pre-determined level of renewable penetration and keeping energy costs as low as possible The results of this analysis will be presented at the CWWA conference.

Configuration 2 – Operating as a deferrable load

The previous three scenarios were reexamined but this time treating the desalination plant as a deferrable load, in order to study the impact on battery sizing and therefore capital system cost and energy costs. The results of this analysis will also be presented at the CWWA conference.

Case Study on Renewable Energy and Water Production

In February 2014, Sir Richard Branson committed as part of a green initiative, to develop and implement a microgrid on Necker Island with the objective of achieving a renewable energy production level, (often referred to as percent penetration of renewable energy) of 80 percent of power consumed. During the planning phase, it was determined that water production would be used as a deferrable load.

This approach required the existing desalination plant to be redesigned. In 2017, the project was started only to be suspended by Hurricane Irma. As a result of the impact of Irma, the project was redesigned to make the island and the water supply more hurricane tolerant.

Although at the time of this writing the desalination system has been operational for ten months, completion of the renewable energy system has been on-going to include the installation and commissioning of the three wind turbines as well as the power management control system. This project was not without its share of challenges, all of which to date have been successfully overcome. A number of these have been included at the conclusion of this paper to assist others contemplating implementation of renewables.

Power Generation

The Necker Island microgrid is designed to produce 480-volt AC power at 60 Hertz and comprises of the following:

- Four each, 320 kWe diesels driven generators. Two are required to meet the island peak load without any renewables while the remaining two are in standby mode or being serviced. The island has enjoyed very impressive power uptime in excess of 99.5 percent and survived Hurricanes Maria and Irma;

- 480 VAC paralleling switchboard with fully automated load following control with renewables interface facilities;

- Three each, 273 KWH, 1000-volt lithium ion battery modules with space for a fourth (refer to following photos);

Switch-gear module (foreground) and battery module

Internal view of battery module

- Three each, 250kWe DC to AC invertors
- 350 kWe DC solar field;

Photovoltaic Panels

- Three each, 100kWe wind turbines;

100 KW Wind Turbines

- 480 VAC renewable energy switchboard and interface with generator paralleling board.

- Comprehensive PC based controls system upon a fiberoptic / modbus communication platform.

Desalination System

At the outset of this project, the existing desalination system serving the island consisted of a single reverse osmosis train designed to treat seawater extracted from two beach wells and produce 60,000 US GPD. The system pretreatment consisted of media filtration and scale control using sulfuric acid. The membrane feed pumping system consisted of a positive displacement reciprocating pump coupled to an energy recovery Pelton Wheel. The discharge from the Pelton Wheel drained by gravity into a collection sump from which it was repumped to discharge. Finished water was transferred to storage using residual pressure from the RO unit. The overall unit energy consumption of the treatment process was approximately 14.5 kWH per 1,000 gallons produced.

Although this system was very reliable and energy efficient, the following drawbacks were noted:

1. Using a single RO unit did not provide redundancy;

2. The membrane feed pump was driven by a 60-horsepower motor that was started using a reduced voltage starter;

3. Since the time of construction, isobaric energy recovery had been commercialized which could provide greater operational flexibility, lower energy usage and did not require repumping after discharge;

Original Membrane Feed Pump, Calder Turbine and Drive Motor

4. The high-pressure pump utilized lubrication oil;

5. The cost and lead time for high pressure pump parts had increased substantially since the time of installation; and

6. In order to consider treating the desalination plant as deferrable load, the plant capacity would need to be increased to permit the island water demand to be achieved at a reduced running time.

The proposed upgrades to the plant consisted of the following:

1. Utilization of an open seawater intake to meet the feedwater needs of a larger plant;

2. Installation of two each, 50,000 GPD unit that would utilize axial piston positive displacement pump and isobaric energy recovery; and

3. A new PLC based control system that would be provided to permit interfacing with the power management system to permit load shedding if required.

The upgrades would utilize as much of the existing plant as possible to control project costs.

In September 2017, Hurricane Irma passed over the island as a very strong Category 5 hurricane. Although the RO plant is located 10 feet above normal sea level, storm surge resulted in building flooding. Seawater reached a depth of 16 inches inside the process and electrical rooms, damaging motors and electrical switchgear. The reinforced concrete building was still intact along with the building roof. Motors were rinsed with fresh water and the windings allowed to dry. Critical electrical parts were flown into the island to permit the motor starters to be replaced. The plant was returned to service, supplying critical potable water to not only Necker Island but also Virgin Gorda. It was clear that the overall system design needed to be revisited to determine how to sure up the water system to be better suited to withstand another major hurricane.

Desalination Plant Redesign

The proposed improvements to the plant included:

1. Testing the wells to determine if the yield could be increased to meet the feedwater requirements. This decision was made of concern the location of the proposed intake would have resulted in catastrophic damage by the storm;

2. With exception to the feedwater supply pump, raising all pumps and motors 30-inches off the floor on reinforced concrete plinths;

3. Replacing all field pipelines (feedwater supply, potable water, irrigation water and concentrate disposal) with HDPE for flexibility and durability;

Axial Piston High Pressure Pump and Companion Isobaric Energy Recovery System

4. Replacing the motor control center with a central power distribution panel to feed variable frequency drives. All electrical equipment would be mounted at least 30-inches off the floor;

Wall Mounted Three-Phase Power System

5. All electrical cabling would be routed using overhead fiberglass cable trays instead of the existing buried power conduits;

6. The use of VFDs would permit PID loop control for the seawater supply, energy recovery boost and post operational flushing pumps.

The upgrades to the desalination plant were completed in November 2018 (see following photos). The estimated unit power consumption for the revised design was 11.8 kWH per 1,000 gallons of permeate produced. At the time of commissioning, the reconfigured plant had a unit power consumption of 10.3 kWH per 1,000 gallons of permeate produced or 12.7 percent below the design value and 29 percent below the old plant value.

Revised Building Design

FUTURE CONSIDERATIONS

Involvement with the development and implementation of the Necker Island microgrid project whose principle driver was carbon footprint reduction has allowed the authors to contemplate that much more can be done to lower carbon footprint beyond the traditional approach. It cannot be overstated that, in keeping with system engineering concepts, that challenges were of course encountered, and successfully overcome, when the inevitable 'unthought of', 'hindsight' issues associated with multi-disciplined entities arose - "the importance of a committed team comprising all specialist stakeholders is paramount – *this equipment will not all come together seamlessly without such an approach"*

Some brief points to consider

- Optimization of Carbon-Based Power System

  Any existing diesels driven generators that will be providing power must be optimized, especially parasitic loads. Fuel consumption can be reduced by up to 11 percent while reducing NOX emission.

- Finished Water Storage Design

  Another factor that needs to be considered is the volume of finished water storage available. This includes local storage that receives the plant output without high service pump and remote storage that is supplied by the high service pumping system. As most of the Caribbean islands are mountainous, ideally remote storage would be sufficient to provide at least 24-hours of demand o the service region. When examining renewable energy, this is important for two reasons. First, the high service pumps can be sized for a constant output which allows the pump efficiency to be maximized. Pumps that follow demand typically operate most of the time either below or above the best efficient point. Over a 24-hour period, the average energy usage is significantly higher than would be attained if the pump operated at the BEP. Secondly, depending on the volume of remote storage, water transfer from the plant can be done solely with renewable energy during the day converting this to a deferrable load.

- Proper Transformer Sizing for Inrush

- Understanding how to properly control load sharing and synchronization between renewable power supplies with and without generators.

- Optimal solar installations orientation

- In regions with a reliable wind resource, wind turbines have an excellent footprint to power density and remain operational after sunset, helping to reduce battery storage capacity, or during cloud cover. Noise emissions are not as bad as one may think but again needs detailed appraisal. For this project location, the daily energy production from wind is without doubt greater than solar for like systems sizes

- Use of air conditioning.

  Absolutely needed, we just have to define 'where' absolutely needed. By example: Calculations arrived at a scenario that to air condition remote renewable energy system areas, a practice that has become custom and practice, for batteries and switchgear installations, that in the case of this example related to 65000 gallons of fuel over 10 years, a significant fuel cost and parasitic loss on the renewable energy production system and a consequent increase in the carbon footprint.

  Warehousing, does it need to be air conditioned or will evaporative cooling be sufficient. Evaporative cooling is generally considered more suitable for lower relative humidity regions. Our work revealed that evaporative cooling in 85^0F / 75% relative humidity environments will result in an air off evaporator cooler temperature of 73^0F which is very adequate for warehousing, workshop or laundry areas.