

Article

Stand-Alone Direct Current Power Network Based on Photovoltaics and Lithium-Ion Batteries for Reverse Osmosis Desalination Plant

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Abstract: Plummeting reserves and increasing demand of freshwater resources have culminated into a global water crisis. Desalination is a potential solution to mitigate the freshwater shortage. However, the process of desalination is expensive and energy-intensive. Due to the water-energy-climate nexus, there is an urgent need to provide sustainable low-cost electrical power for desalination that has the lowest impact on climate and related ecosystem challenges. For a large-scale reverse osmosis desalination plant, we have proposed the design and analysis of a photovoltaics and battery-based stand-alone direct current power network. The design methodology focusses on appropriate sizing, optimum tilt and temperature compensation techniques based on 10 years of irradiation data for the Carlsbad Desalination Plant in California, USA. A decision-tree approach is employed for ensuring hourly load-generation balance. The power flow analysis evaluates self-sufficient generation even during cloud cover contingencies. The primary goal of the proposed system is to maximize the utilization of generated photovoltaic power and battery energy storage with minimal conversions and transmission losses. The direct current based topology includes high-voltage transmission, on-the-spot local inversion, situational awareness and cyber security features. Lastly, economic feasibility of the proposed system is carried out for a plant lifetime of 30 years. The variable effect of utility-scale battery storage costs for 16–18 h of operation is studied. Our results show that the proposed design will provide low electricity costs ranging from 3.79 to 6.43 ¢/kWh depending on the debt rate. Without employing the concept of baseload electric power, photovoltaics and battery-based direct current power networks for large-scale desalination plants can achieve tremendous energy savings and cost reduction with negligible carbon footprint, thereby providing affordable water for all.



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Keywords: high voltage direct current transmission; photovoltaics; lithium batteries

1. Introduction

According to a study by NASA [1], freshwater shortage is one of the biggest challenges of the 21st century. With limited supply from streams, lakes and rivers, groundwater and rain harvesting, desalinated water is the only possibility to meet the need of water for all human beings. Desalination plants operate in more than 120 countries [2] and consume a lot of electric power. Typically, an average of 10–13 kWh of electric power is consumed per thousand gallons of water forced through pressure treatments in the desalination process [3]. Based on recent data of global greenhouse gas emission, 73.2% of emissions are due to energy production and the use of energy in various sectors [4]. Zoonotic diseases are passed from animals to humans and are a serious health risk, as the COVID-19 pandemic has made very clear [5]. With the possibility of a second pandemic, worse than the current one, there is an urgency to solve climate and related ecosystem challenges before the highly advocated 2050 time-frame. Thus, future desalination plants must use green sustainable

electric power. The purpose of this paper is to show that for reverse osmosis desalination plants, stand-alone direct current (DC) power networks based on photovoltaics and lithium-ion batteries can provide sustainable green electric power at low-cost.

There are numerous studies that delve into different desalination techniques and integrate renewable energy with desalination. The choice of desalination technique depends on a plethora of factors like geographic location, raw water type (seawater, brackish or groundwater) and quality (total dissolved solids), intake and outfall types, energy recovery systems, cost of electrical power, post-treatment of brine, distribution costs and environmental regulations. A comprehensive review of different desalination techniques is presented in [6,7]. As outlined in [6], solar energy can be utilized for either thermal (distillation/vapor compensation) or mechanical energy (pressure-based membranes) needs of desalination plants. As of 2021, seawater reverse osmosis (SWRO) is an energy efficient and commercially viable large-scale desalination method.

A thorough review of plausible renewable energy integration with desalination is outlined in [8–11]. Direct and indirect solar desalination techniques are discussed in [10,11]. Direct methods like solar stills use thermal energy from solar irradiation while indirect methods use either concentrating solar thermal collectors or photovoltaic panels to convert solar irradiation into heat or electricity; based on desired desalination process. The concentrating collectors need additional system costs and accurate engineering design and control techniques resulting in lower deployed projects over the years. Globally, solar concentrating projects have not performed as was originally expected. In the United States, failure of Kepco Solar of Alamosa LLC and Xcel Energy project in 2021 is a recent example [12]. Photovoltaics (PV) based reverse osmosis (RO) desalination stands out as the most viable and commonly deployed desalination plant design. Various other renewable energy sources like wind [13] and tidal waves [14] are also integrated with desalination. However, the cost of additional infrastructure required for harnessing wind and sea-waves makes these technologies less lucrative as compared to PV systems. Reference [15] illustrates a complete PV-RO system for small scale desalination at the Masdar Institute. Although the authors provide a detailed RO plant design the energy infrastructure lacks battery storage citing inefficient technology and higher storage costs. The lithium-ion battery storage technology has tremendous advancements since the paper was published and is absolutely necessary for 24 h a day \times 7 days a week and 365 days a year operation of large-scale desalination plants. A stand-alone hybrid renewable energy system is demonstrated in [16], where authors elaborate the use of a diesel generator as a back-up to PV and battery storage. Although convenient for smaller and islanded communities, the use of diesel generators worsens greenhouse gas emissions and defeats the purpose of a sustainable energy powered stand-alone desalination plant. Another study focusses on a grid-tied large-scale desalination plant design with PV and local storage options [17]. The authors of reference [17] extensively cover both cases for battery and pumped hydro storage while ensuring a grid-tied desalination system. As explained in Section 4, the grid-tied architecture has several drawbacks and thus we have proposed a stand-alone system. A similar system is explained in reference [18], where the authors outright illicit battery storage to be coupled with desalination systems owing to higher costs. The battery storage cost numbers used in reference [18] are highly inaccurate. It is assumed that the batteries are replaced after every five years with 60% depth of discharge operations. Utility-scale lithium-ion batteries are capable of at least 15 years of lifetime with 80% depth of discharge and thus the higher costs of battery storage in reference [18] are flawed. Our proposed paper is centered around the design of PV and battery storage-based energy infrastructure needed for stand-alone operation of a large-scale RO desalination plant. Furthermore, we have studied the effect of duration of operation on capital cost of battery storage and showed that longer duration of 16–18 h storage has significantly lower costs than short-duration battery usage. We utilize standardized pressure membrane design concepts and parameters. The flow rate control, pumping pressure balance and other desalination plant specific optimizations are therefore beyond the scope of this paper. The primary goal of the paper is to ensure reliable PV and

battery storage generation to meet the load demands for a round-the-clock operational desalination plant. The novelty of the proposed design is that it is an end-to-end direct current (DC) based stand-alone network.

The remainder of the paper is organized as follows: In Section 2, we have discussed the importance of the water-energy-climate nexus for a sustainable world. This is followed by sustainable green electric power generation and storage in Section 3. Fundamental issues of existing power grids are discussed in a critical analysis in Section 4. This section highlights the need for desalination plants to be grid independent. For desalination, the key features of an end-to-end DC power network are discussed in Section 5. The methodology and design of a DC power network for reverse osmosis desalination plant is described in Section 6. Various design parameters, decision-tree based algorithm for power balance and results of successful stand-alone operation during cloud cover contingency are also covered in this section. Financial analysis for a 30-year projected lifetime is carried out in Section 7. Finally, the paper is concluded in Section 8.

2. Water-Energy-Climate Nexus for Sustainability

2.1. Water for Energy

The relationship between water and energy is critical for sustainable living. Water plays a pivotal role in traditional fossil fuel and nuclear-based power generation. The lifecycle of fossil-fuel-based power generation requires water for extraction, purification, washing and treatment of raw materials. Water is also extensively used as a coolant in coal and nuclear power plants. Globally, the agricultural sector accounts for the majority of freshwater withdrawals. However, the scenario is quite different in the United States. Thermoelectric power generation accounts for 41% of water withdrawal in the U.S, the largest by any sector, followed by irrigation and public usage [19]. Figure 1 highlights the withdrawals by sector, highlighting the fact that thermoelectric power generation has accounted for the most water withdrawals in the U.S. since 1965–2015 [19]. Relying heavily on coal and nuclear power generation has caused tremendous strain on availability of surface and groundwater resources in the U.S. It is estimated that within the next 30–50 years, nearly half of the country's 204 water basins may fall short of meeting monthly water demand [20].

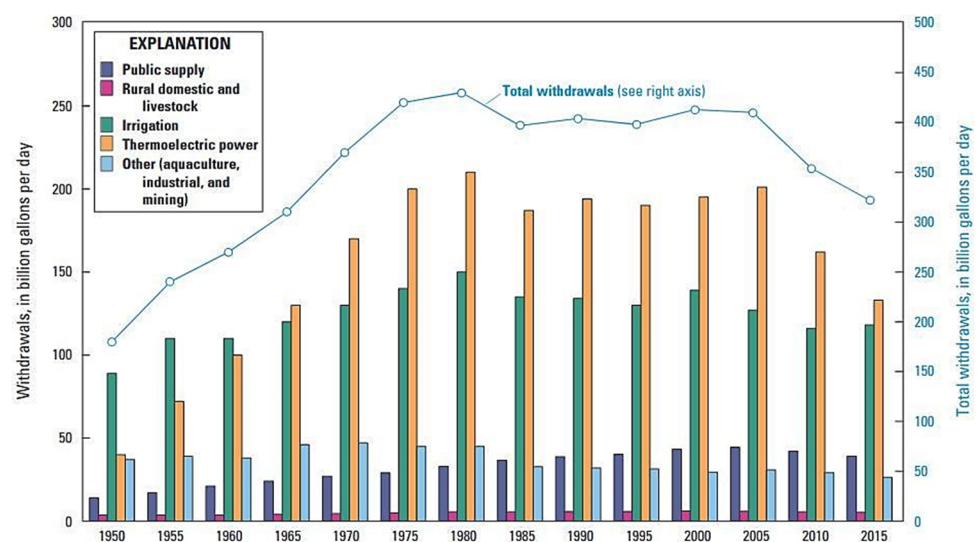


Figure 1. Trends in total water withdrawals by water-use category, 1950–2015 [19].

The International Energy Agency predicts the world's energy consumption will increase by 35% by the end of 2035 [21]. This will in turn increase water usage by 15%, creating extreme strain on the already scarce water resources [21]. Therefore, diversification of the energy-mix towards free fuel sources, namely, solar and wind energy, is essential

for water conservation. Figure 2 identifies the water requirements for electricity generation by different sources of energy [22]. As compared to traditional power generation, photovoltaics (PV) and wind turbines consume the least amount of water, while also providing cheaper and cleaner electricity. Utilizing PV power for electricity generation has negligible impacts on the global water usage. It is evident that reduced water needs can mitigate the imminent threat of water shortage. Hence, integration of PV and wind power in electricity generation will achieve a sustainable water-energy nexus.

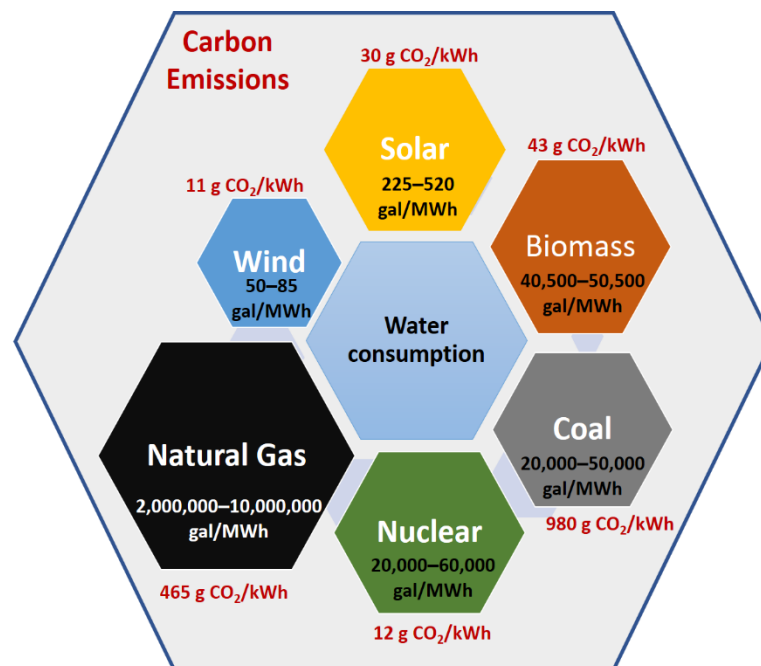


Figure 2. Water usage and carbon footprint of electricity generation sources [22].

2.2. Energy for Water

Rising water costs and plummeting freshwater resources are the two major roadblocks for sustainable living. Energy plays a vital role in making water resources available for human activities like agriculture (irrigation), industrial use, potable consumption, et cetera. Energy is utilized for pumping, distribution and treatment of water resources. Storage and transportation of water over long distances needs heavy-duty pumps that consume tremendous amounts of energy. Water discharged after cooling from nuclear and fossil fuel-based power plants also consume energy for proper treatment before mixing it with freshwater sources. Wastage of energy has direct cost implications on water networks. Conversely, energy costs have a hidden cost of water consumption associated with the total \$/kWh price [23]. Conservation of energy is thus essential for reducing potable water costs. The average water rates in the U.S. over the 8-year timespan between 2008 and 2016 increased by nearly 40% [24]. Energy consumption by drinking water and wastewater utilities can comprise 30–40% of the total water bill [25]. Integration of nearly-free fuel PV with the water networks can significantly curb rising water costs.

The advantage of local PV and wind networks for water utilities and wastewater treatment plants is resiliency during extreme events. The recent power grid failure in Texas, had a crippling effect on the water network as well as leaving thousands of homes without availability of potable drinking water. The water grid should achieve self-sufficiency in power requirements by operating stand-alone renewable power farms. This will ensure reliability of water sources when the central power grid fails and also reduce electricity costs incurred by water utilities. Integration of renewable energy with water treatment and distribution is thus essential for communities where high cost of energy is a barrier for freshwater availability [22].

2.3. Role of Carbon Emissions towards Sustainability Nexus

Along-with the issue of water scarcity, climate-change is another threat looming over the existence of mankind. According to the United Nations, global temperatures may rise by 1.5–2 °C by 2030–2050 [26]. Rising temperatures increase the occurrence of extreme weather events like tsunamis, floods and droughts. Along with loss of life, such natural disasters also have a crippling effect on the availability of water and power grids. Curbing carbon emissions is thus crucial for the sustainability of mankind. Movement of water and fossil-fuel-based electricity generation have severe carbon emissions that need to be addressed. The shift to stand-alone PV-water infrastructure can assist in a reduced carbon footprint bolstering the water-energy-carbon nexus. This sustainability nexus for the United States is shown in Figure 3 [22]. Water treatment, transport and waste-water management together consume about 2500–12,700 kWh/million gallons (Mgal) of energy [25,27] and generate 290 million metric tons equivalent (MMT eq.) of CO₂ emissions [27]. Electricity generation accounts for 26.9% of 2018 greenhouse gas (GHG) emissions, accounting for 1802 MMT eq. of CO₂ and withdraws about 16,000 gallons of water per kWh (gal/kWh) generation [25]. As seen earlier in Figure 2, electric power generation by PV and wind turbines have minimum carbon footprints along-with water requirements.

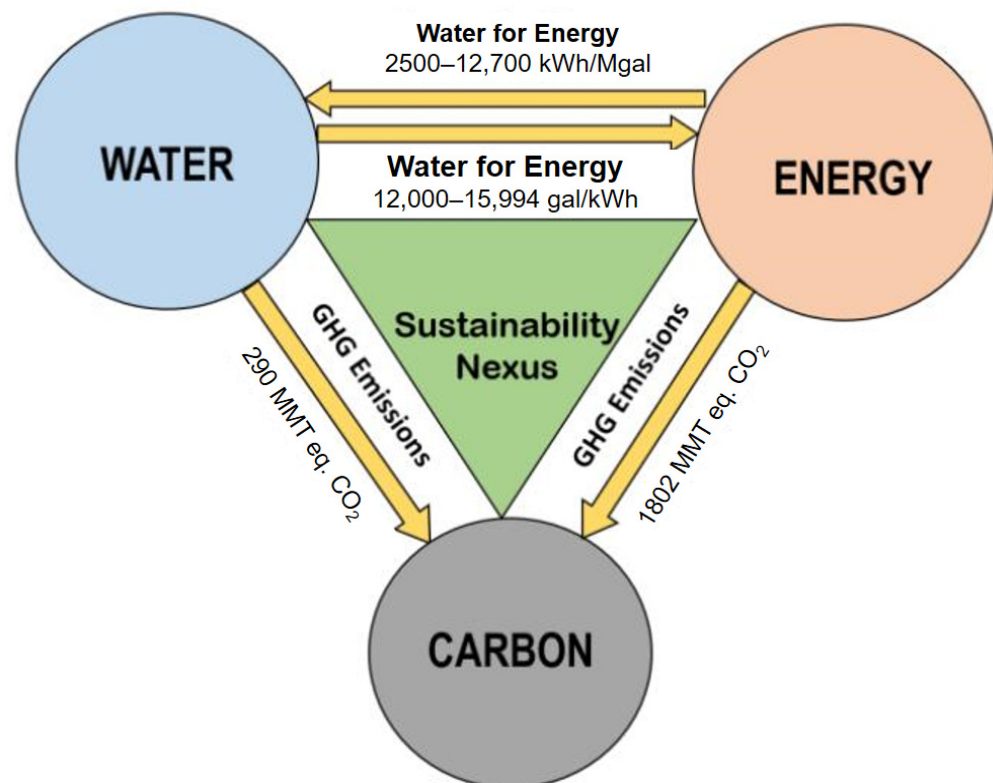


Figure 3. Water-energy-carbon nexus for the United States, 2019 [22]. In this figure, gal, Mgal and MMT represent U.S. Gallons, U.S. Million Gallons and Million Metric Tons respectively.

Understanding the interdependencies within this nexus and undertaking appropriate measures to curb emissions will enable a sustainable environment for mankind. Use of nearly-free PV power is a solution to provide affordable water for all at cheaper prices while reducing carbon emissions significantly.

3. Green Sustainable Electric Power Generation and Storage

Nature's inexhaustible free sources of energy, namely, solar, wind and tides, are the only sustainable sources of energy. Currently, electric power generation by tides is not commercially viable. With global incident solar power of 23,000 TWy/y and intensity of

4–6 kWh/d in most of the places, abundant solar power is the ideal source of energy [28]. In places where we have lower incident solar intensity, there is an abundance of wind energy for electric power generation and solar energy can be a complimentary source [28]. Solar energy followed by wind energy are the safest and cleanest sources of energy [29]. As discussed previously, power generation by photovoltaics and wind turbines require the lowest use of water when compared to other renewable sources such as biomass and geothermal. Figure 4 [29] shows that photovoltaics has emerged as the technology for the lowest cost of electric power generation. As predicted in 2014 [28], no major energy source has grown faster than solar power in the past decade. According to reference [30], installed solar photovoltaics (PV) capacity has grown at an average annual rate of over 42% over the past 10 years, translating into a doubling of global capacity every 1.7 years on average. The lowest cost of PV generated electric power is €0.0112/kWh (\$0.0132) [31].

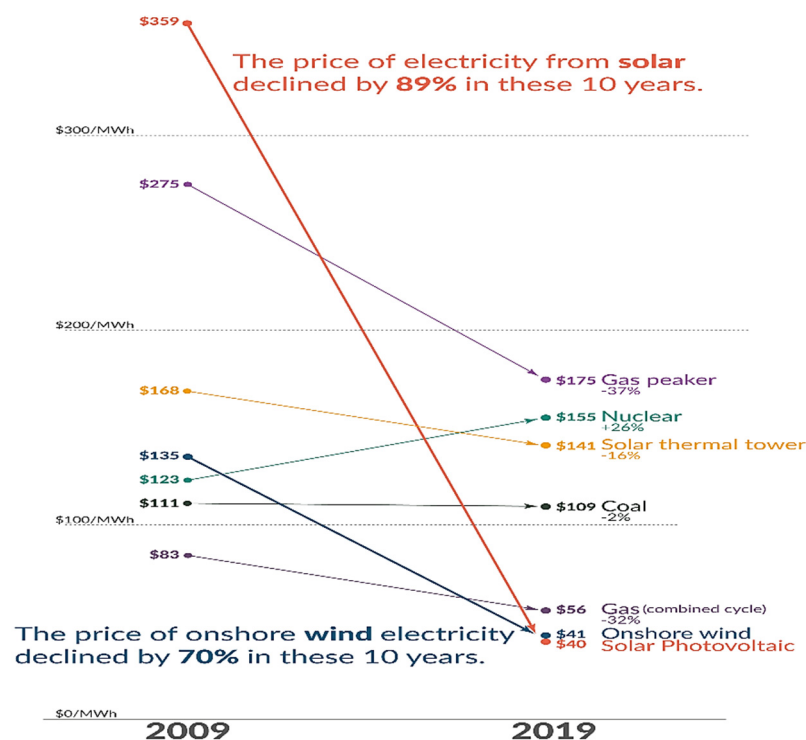


Figure 4. The price of electricity from new power plants [29].

Driven by the advancements in technology (particularly higher energy density), volume manufacturing and the growth of battery electric vehicles, storage of electric power by lithium-ion batteries is emerging as a practical low-cost solution [32]. The price of battery packs for electric buses in China has been reported as less than \$100 per kWh [33]. At utility scale, the cost of storing electric power by lithium-ion batteries for four hours is between 0.8 and 1.4 cents/kWh and is expected to reach 0.4–0.9 cents by 2022 [34]. Recent reports of higher energy density of solid-state batteries will further reduce the cost of lithium-ion batteries [35].

4. Fundamental Issues of Existing Power Grid

The existing electric power grid is a complex interconnected network based on alternating-current (AC) infrastructure. Except for a few inductive loads, virtually all our loads need direct current (DC) as input power. More than 30% power and capital can be saved by using a DC power network [36]. A recent blackout in Texas lasting several days confirmed the fundamental weaknesses of the AC power grid [37]. Due to the use of AC power in place of DC power, utilities employ various complex practices such as energy arbitrage, peak shaving, load leveling, spinning reserves, black start capability

and other grid ancillary services [38–40]. PV systems generate DC power and batteries store DC power. PV-battery systems are often used as back-ups or during peak-load hours that result in tremendous DC power wastage. Furthermore, the system components and design for harnessing renewable energy into the grid, are often based on active (P) and reactive (Q) power flows and frequency, voltage and phase balance for grid stability. Since, renewable energy sources generate variable voltage and current profiles, they have to first be synchronized to the specific operable levels, standardized by the utility power grid. This requires additional components and unnecessary inverter stages for grid synchronization. All grid synchronization issues can be avoided with localized DC power infrastructure and load-specific spot-conversion (DC to AC) where necessary. The future grid infrastructure should be flexible to realize the maximum potential of PV generation coupled with advanced sensing, real-time decision making and contingency planning. Some features that should be incorporated into the future grid infrastructure are outlined below.

4.1. Modifying the Baseload Power Design

Traditionally, reliable power was supplied only through fossil fuel and nuclear plants for fixed baseloads. This scenario is changing rapidly with renewable energy integrations and dynamic loads. The myth that solar and wind power cannot be dispatched on-demand and hence are unreliable is debunked by appropriate plant sizing and use of a battery energy storage system (BESS) that can store and regulate power to the load as and when needed. The term “baseload power” indicates relatively low-cost electricity available at every instance of time to meet minimum load levels. However, as discussed previously, today, the cost of electricity from solar and wind power is cheaper, compared with baseload plants. When coupled with BESS, solar and wind power generation can effectively serve the bulk of the load [41].

On the contrary, the baseload coal and nuclear plants have high inertia and cannot be ramped down quickly when bulk load can be supplied with PV and wind generation [42]. Although perceived as reliable, slow baseload plants limit the maximum utilization of PV and wind energy. Moreover, the generation, transmission and distribution planning, security constrained power flows and contingency analysis, are all entirely calculated and designed for baseload operation. With the dynamic nature of loads, smart algorithms for demand-response management and increased renewable penetration, it is necessary to upgrade all the power flow analysis to real-time generation-load balancing techniques. This can only be possible when we detour from baseload system design and incorporate grid flexibility. PV and wind with storage can ensure grid robustness, resilience and reliability while reducing electricity prices and carbon emissions [43]. The idea of baseload power has severe flaws. As we move towards local energy generation in micro-grids and nano-grids, it is important to design newer power-flow techniques rather than accepting baseload power design as an energy dogma.

4.2. Eliminate Conversion Losses with PV-DC System Design

The concept of grid tied PV systems incorporates multiple DC to AC conversion stages as shown in Figure 5 [44]. The majority of grid-tied PV systems are solely designed with the objective to minimize electricity costs by consuming PV power and discharging batteries when the time-of-usage rates from the grid are higher. During peak-load hours “prosumers” are incentivized to reduce the dependency on grid by relying on PV generation and battery storage. The PV power produced during non-peak hours is either sold directly to the grid or used for local battery charging. The prosumer receives renewable energy credits or minor reductions in their electricity bills in exchange for the PV power sold to the grid. This design is highly flawed. The fact that a producer of electricity only gets minimum benefits as outlined by the utility and cannot directly harness the full capacity of the locally generated power is not in the best interest of consumers.

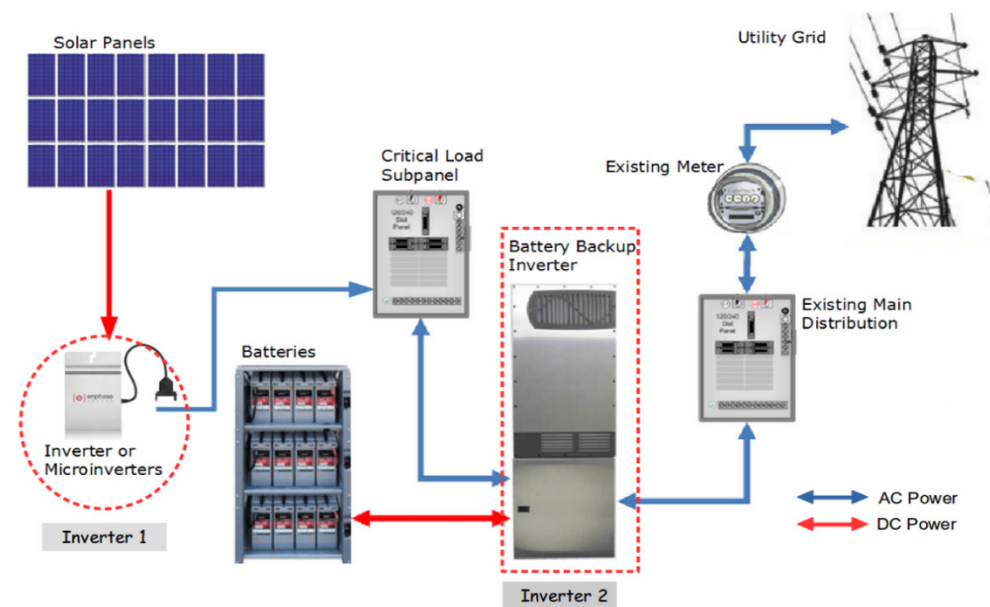


Figure 5. Existing practice for grid-tied PV-battery systems with unnecessary inverter stages [44].

The PV-battery charging infrastructure is also routed via additional hybrid inverters. Hybrid inverters are special inverters placed at the output of PV panels that convert DC power generated from PV panels into AC power and then back into DC power for battery charging. Hybrid inverters are designed to work in grid-outage scenarios. Such practices are highly inefficient. The losses in AC to DC conversion stages, along-with transmission losses, account for tremendous energy wastage at utility scale power plants.

5. End-to-End Direct Current Power Network for Desalination Plant

Based on the limitations of existing grids discussed previously, we propose an end-to-end stand-alone DC power network for desalination plants. As shown in Figure 6, if the solar farm can be located in the vicinity of the desalination plant, a low voltage DC (LVDC) network can be used to convert typical 1500 V DC output of the solar farm to 480 V DC which is required by desalination plants. In principle, it is also possible to design 480 V PV modules to construct solar farms. Thus, only current conversion will take place in DC-to-DC power conversion. In cases where it is not possible to co-locate the solar farm and the desalination plant, high voltage DC (HVDC) can be used to provide the desired power for operating the desalination plant. In cases where the solar farm cannot provide total power required to run the desalination plant, it is possible to get part of the power both from LVDC and the rest from HVDC power networks. It is important to mention here that unlike the current practice of HVDC (AC/DC and DC/AC conversion takes place on both ends of HVDC), no such conversion is required in our case. Due to the absence of these conversions, the cost of our HVDC will be much lower compared to the current practice of HVDC.

The proposed power network will have key features of situational intelligence and cyber security as discussed in the following sub-sections:

5.1. Situational Intelligence in End-to-End DC Power Network

Internet-of-Things (IoT) sensors have made it possible to collect real-time data from various components in a power network. Increased data flows from connected devices enable better monitoring, analytics and visualizations that increase the asset health and improve system performance. In the proposed desalination power network, IoT sensing devices will continuously monitor each stage of the desalination process. The intake and outfall systems will be equipped with salinity and water quality sensors to ensure longevity of screening films and pre-filtration pumps. The RO membrane stages (the most critical

desalination stage) require constant monitoring to check for membrane health under high pressure water inflows. The sensors in the RO stage will monitor physical parameters like temperature, pressure and vibrations to estimate the operating conditions of the plant. We also propose predictive analysis using deep learning methods to determine the optimal speed of the high-pressure desalination pumps. During the availability of excess sunlight, these pumps with variable speed control can ramp up the potable water generation by increasing the flow through membranes. Intelligent controllers can set thresholds for acceptable speed change while controlling the vibrations to maintain longevity of the pumps and mechanical parts. According to ABB's Ability smart sensor technology for pumps, motor lifetime can be extended by up to 30%, and energy consumption reduced by up to 10% [45]. These are tremendous savings considering MWh energy consumption of desalination plants. According to [46], by monitoring membrane fouling and predicting optimal membrane cleaning frequency, the RO desalination plant can achieve up to 15% savings in replacement costs and increased operational efficiency of the plant by 30%.

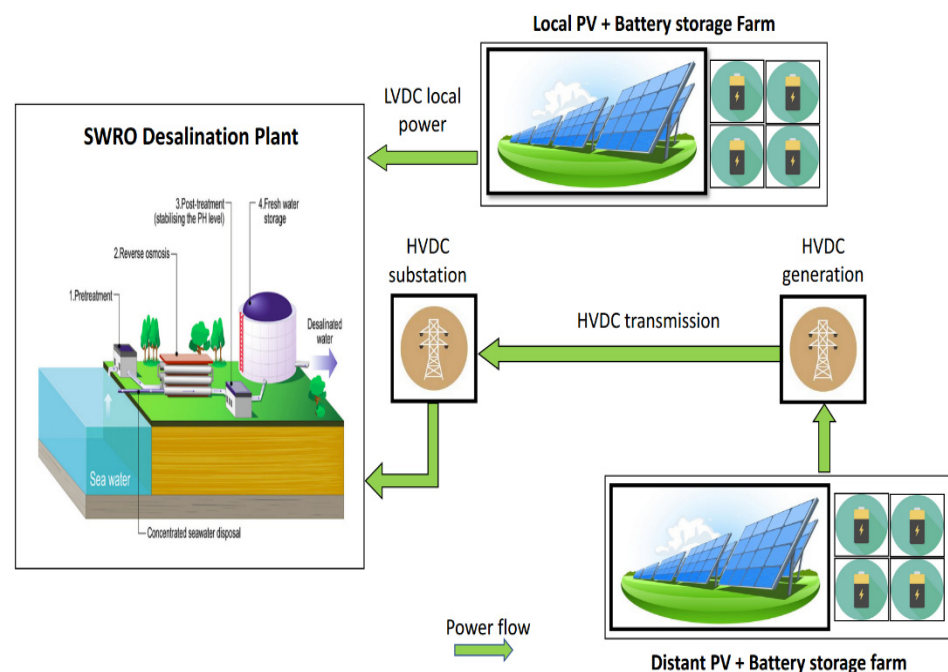


Figure 6. End-to-end DC power network for desalination plant. In this figure, PV, SWRO, HVDC and LVDC represent Photovoltaics, Seawater Reverse Osmosis, High voltage Direct Current and Low voltage Direct Current (LVDC) respectively.

IoT sensors can also be used to monitor temperature and state of charge of lithium-ion battery storage. This will surely increase the battery lifetime and aid in maintenance or replacement of system components. The PV-battery charging infrastructure and HVDC transmission systems can also incorporate intelligent sensing and decision making. According to [47], more than 70% of PV farms by 2025 will incorporate artificial intelligence (AI) techniques for proactive decision-making abilities to boost PV farm efficiency. Real-time monitoring increases situational awareness. Predictive and prescriptive analytics using AI and IoT techniques can lead to increased situational intelligence that optimize the performance of the proposed stand-alone desalination network.

5.2. Cyber-Security in Decentralized DC Grid

With increased interactions between information technology (IT) and operational technology (OT) within the smart grid, the threat of a cyber-attack crippling the entire centralized power grid infrastructure is alarming. Due to the water-energy nexus, an intrusion into the power grid can have adverse effects on the water networks too. Centralized power

distribution systems are more susceptible to cyber-attacks due to multiple intrusion data-points and increasing similarities in network architecture. This is a legitimate concern in mono-cultures where many systems run identical software and access to some components makes the entire system vulnerable [48]. Once a vulnerability is found, the whole grid is immediately compromised. However, the proposed stand-alone desalination PV grids are smaller in size with fewer distributing nodes and limited entry-points.

Sandworm APT's attack on Ukraine [49] would not have been possible in a local network of DC power. The localized industrial control systems (ICS) within a local DC grid, will not be integrated on the same network as the control center operations, thereby adding an extra layer of security against intrusions. Decentralizing control of the grid, would force attackers to compromise many control centers that are independently maintained [48]. According to [50], a major vulnerability during the Ukraine attack was a wider area of responsibility for control center operators leading to unparalleled access to distribution system resources at three different locations. Local decentralized grids on the other hand will effectively limit the area of responsibility of control centers and minimize intrusion depth with restricted access.

Another advantage of a local DC network is that it should be able to stop cascading failures. The reach of a cyber-attack will be limited and isolated. Furthermore, an attack on the individual DC power network is also less attractive since disabling isolated neighborhoods is less useful than disabling a whole country [48]. Individually installed, configured and maintained components in a decentralized network are highly susceptible as well, but can be quickly replaced with minimal damage to a single house, or neighborhood. Alternatively, hacking a central transformer can disable the power distribution operations, requiring maintenance or full replacements that may go on for 18 months depending on the nature of the attack [51].

6. Stand-Alone DC System for RO Desalination

6.1. Power Networks

The reverse osmosis (RO) desalination plant design is based on PV farm generation with lithium-ion batteries for storing electric power. Roof mounted PVs can be used to get some power for the desalination plant. In place of roof mounted PVs, it is possible to use solar tiles in the construction of new buildings and there is no need of conventional roofing on the buildings of desalination plants [52]. To keep calculations simple, we have not considered PV power generation from rooftop PV or solar tiles. Hence, all the load requirements will be met by the PV farm and batteries located near to the plant. The complete architecture for generation, transmission and distribution is based on DC power with certain loads having local inverters for DC to AC conversion. Sea-water RO (SWRO) desalination plants use tremendous energy for pumping operations in feed-water intake, pre-filtration stages, the RO stage, post-treatment, brine discharge, potable water storage and distribution stages. Figure 7 shows the complete desalination plant design with power, data and water flows.

With reference to Figures 6 and 7, we have considered the higher cost case where power is obtained only from the HVDC power network. The other two cases where 100% or part of the total power is obtained from the LVDC network will be cheaper than this case. In essence, the proposed system incorporates a distant PV farm that is sized to meet the fixed hourly load demand of the desalination plant. Co-located battery storage with lithium-ion batteries are discharged during the night time to subsidize the load in the absence of sunlight. The numerous design considerations, sizing profiles and equipment specifications are explained in the following subsections.

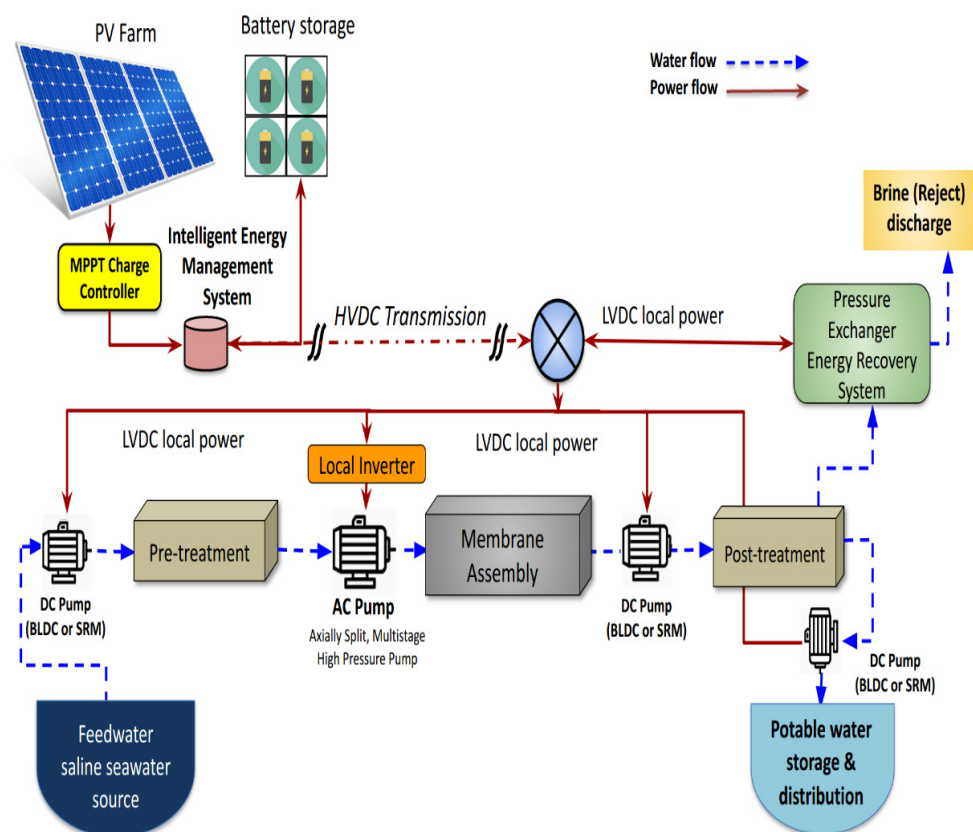


Figure 7. Proposed stand-alone desalination plant system design based on DC architecture. In this figure MPPT, BLDC and SRM represent Maximum Power Point Tracking, Brushless DC, Synchronous Reluctance Motor respectively.

6.2. Geographical Considerations

Variability in desalination projects arise from factors like geographic site location, feed-water type and salinity, intake and outfall types, energy recovery systems, cost of electrical power, post-treatment of brine, water distribution costs and environmental regulations. The location for our case study is the Claude Bud Lewis Carlsbad Desalination Plant in San Diego County, CA, USA. The SWRO desalination plant at Carlsbad, California is the largest RO plant in the U.S. designed to generate approximately 50 million gallons per day (MGD) of potable water (about 56,000 acre-feet per year (AFY)) [53]. The potable water generated from this plant serves approximately 400,000 people in the county. Initially co-located with the Encina Power station, the Carlsbad Desalination Plant is equipped with energy recovery devices that recapture energy from high-pressure brine discharge to improve overall plant efficiency. Table 1 [54] highlights some features about the Carlsbad Desalination Plant.

The primary goal of the paper is to ensure 100% utilization of PV + battery power for the desalination plant operation along with additional improved energy savings with DC architecture. For this purpose, we have based our design and sizing calculations assuming daily plant capacity of 50–55 MGD potable water generation with 32 MW of total hourly average power required for complete plant operations.

6.3. PV Irradiation Profile

The very first step for designing a PV farm is to calculate the irradiation profile for the desired farm location. We gathered the data for hourly irradiation profile based on National Renewable Energy Laboratory's (NREL's) National Solar Radiation Database (NSRDB) considering the previous 10 years of hourly irradiation values [55]. This was done to eliminate any erroneous readings picked up by the pyrometer (a device used to measure

irradiance on a planar surface) that resulted in near zero values for direct normal irradiation during cloud cover. The solar farm was oversized to meet the maximum load demand for the minimum irradiation day. Thus, we ensured reliability of meeting the yearly load by appropriately oversizing for a worst-case (cloudy) day scenario. The PV panel output profile was temperature compensated. An optimum tilt of solar panels was also calculated every four months (spring, summer and winter) which ensured better irradiance as compared to one tilt for the entire year. Single-axis or double-axis trackers were not used since the desired location produced sufficient tilted and temperature compensated irradiance.

Table 1. Claude Bud Lewis Carlsbad Desalination Plant information [54].

Claude Bud Lewis Carlsbad Desalination Plant	Detailed Specifications	
Location and co-ordinates	33.14° N, 117.33° W	
Plant capacity	50–60 MGD/d	
Daily energy requirement	675–768 MWh/d	
Hourly fixed load	30–35 MWh/h (average: 32 MWh/h)	
Brine disposal	50–60 MGD/d	
Reverse osmosis (RO)	2000 + pressure vessels with 16,000 RO membranes	
Energy recovery system	144 + pressure exchangers recover 33% of power	
Energy consumption at every stage of desalination (with high efficiency motors)	Intake	=4.168 MW
	Pre-filtration	=1.097 MW
	Reverse osmosis	=22.45 MW
	Energy recovery	=−7.61 MW
	Storage and distribution	=6.975 MW
	Miscellaneous (HVAC, lighting, chemical feed)	=1 MW
	Total hourly power	= 28.085 MW

MATLAB code was used to calculate the optimum tilt and temperature compensated PV panel output for the desired solar farm location. Figure 8 shows the hourly irradiation profile for best, median and worst day of the year. Figure 9 shows the daily irradiance values for one year that account for both tilt and temperature compensation.

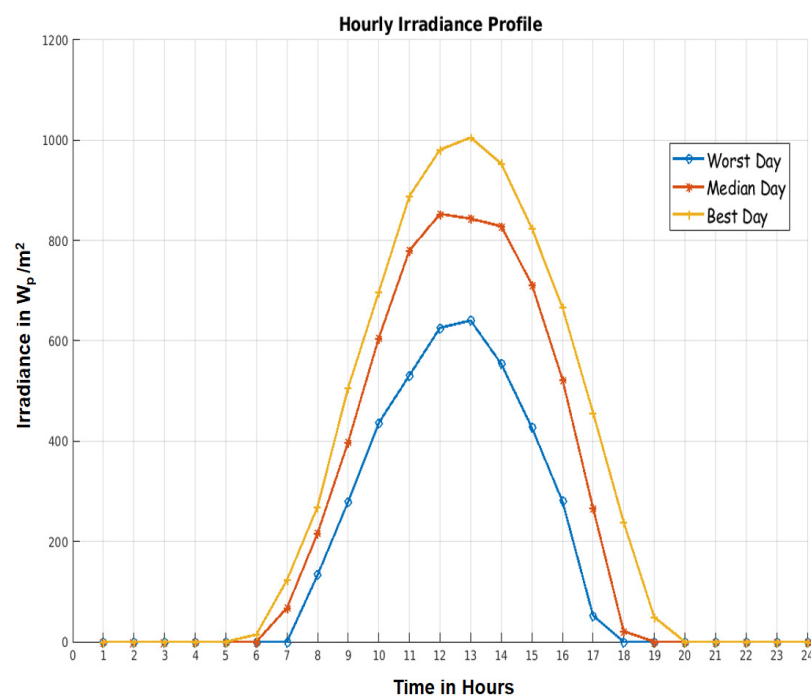


Figure 8. Hourly irradiation profile for best, median and worst day scenario for PV farm. In this figure, W_p/m^2 represents Watt-peak per sq. meter.

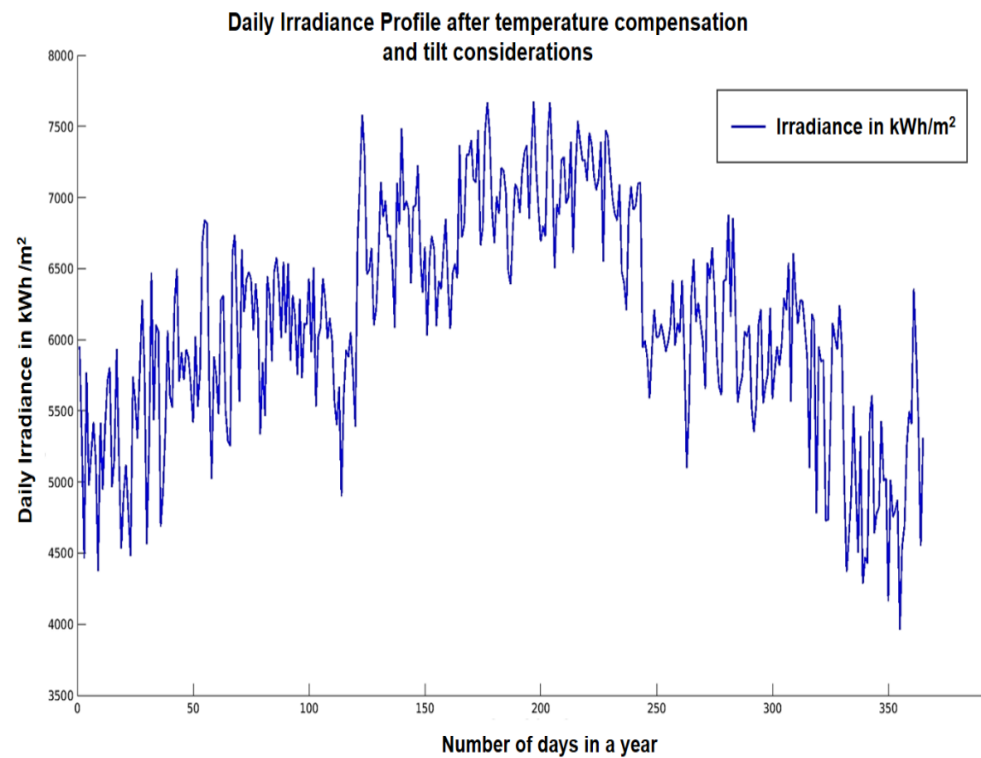


Figure 9. Daily irradiation profile of PV Farm with optimum tilt and temperature compensation.

6.3.1. Temperature Compensation Calculations

The temperature of solar panels is compensated using the formula:

$$\text{Compensated Panel Eff} = \text{Panel Eff} + T_{\text{test}} - T_{\text{ambient}} \times T_{\text{power derate factor}} \quad (1)$$

where:

Panel Eff is assumed to be 22.2% for SunPower's X-Series: X22-360-COM [56],

$T_{\text{test}} = 25 \text{ }^\circ\text{C}$; assuming standard testing conditions (STC),

T_{ambient} = Ambient temperature for location from NSRDB,

$T_{\text{power derate factor}} = -0.29\%$ per $^\circ\text{C}$ rise from T_{test} .

An interesting observation from temperature compensation is that at lower temperatures during winter, the power derate factor significantly decreases which leads to higher panel efficiency during colder winter sunlight hours. During summer, as the power derate factor drops the panel efficiency due to soaring temperatures, the PV panel efficiency is not optimal. Thus, the PV panel exhibits improved power efficiency during lower temperature days.

6.3.2. Optimum Tilt Calculations

The model to estimate global horizontal irradiance (GHI) with optimum tilt for PV panels is based on hourly direct normal (DNI) and diffused horizontal (DHI) irradiance values. The reflected radiation will be ignored for optimum tilt calculations. The equations below describe the process for determining the tilt of PV panels.

$$\text{GHI (on tilted PV surface)} = \text{DHI} + \text{DNI} \times \cos \theta \quad (2)$$

where $\cos \theta$ is estimated using Equations (3)–(8) as below:

$$\cos \theta = \sin \delta \times \sin \phi \times \cos \beta - \sin \delta \times \cos \phi \times \sin \beta \times \cos \psi + \cos \delta \times \cos \phi \times \cos \beta \times \cos \eta + \cos \delta \times \sin \phi \times \sin \beta \times \cos \psi \times \cos \eta + \cos \delta \times \sin \psi \times \sin \eta \times \sin \beta \quad (3)$$

where: δ = >declination angle; evaluated from (4)

$$\delta = 23.45^\circ \times \sin \left(\left(\frac{360}{365} \right) \times (day - 81) \right) \quad (4)$$

Φ = >latitude of desired farm location; in this case $\phi = 33.14^\circ$

Ψ = >panel azimuth angle = 0° ; since in the Northern Hemisphere, PV panels are orientated true south assumed to be 0° facing directly towards the equator

β = >panel tilt daily values evaluated from (5)

$$\beta = 90 - \alpha \text{ where elevation angle } \alpha = 90 - \phi + \delta \quad (5)$$

\mathbb{T} = >hour angle; evaluated from (6)–(8)

$$\text{Equation of time (EoT)} = 9.87 \times \sin \left\{ 2 \times \left(\frac{360}{365} \right) \times (day - 81) \right\} - 7.53 \times \cos \left\{ \left(\frac{360}{365} \right) \times (day - 81) \right\} - 1.5 \times \sin \left\{ \left(\frac{360}{365} \right) \times (day - 81) \right\} \quad (6)$$

$$\text{Time Correction Factor (TC)} = 4 \times (\text{Longitude} - \text{Local Standard Time Meridian}) + \text{EoT} \quad (7)$$

$$\text{Hour Angle (h)} = 15^\circ \times (\text{Time Local} + (\text{TC}/60) - 12) \quad (8)$$

Based on the above calculations, the tilt for the solar panels was divided into three seasons each spanning four months to accommodate seasonal variations in irradiation. The average tilt of every season was used to plot the initial tilted GHI profile.

Tilt in spring, summer and winter are 40° , 14° and 45° , respectively.

However, it was observed that the worst cloud cover days usually occur in the months of January and December (based on the past 10 years' historical data from NREL) and hence the tilt values were adjusted to be closer to the average of January and December during spring and winter seasons, respectively. Hence, updated optimum tilt values to maximize PV irradiance during worst cloud cover scenarios are:

Optimum tilt in spring, summer and winter are 55° , 14° and 55° , respectively.

MATLAB code was used to calculate the optimum tilt and temperature compensated PV panel output for the desired solar farm location.

6.3.3. Sizing Considerations

The PV farm is sized to eliminate all deficit days and generate enough surplus to charge the batteries that meet the load demand during non-sun hours. The MATLAB flowchart logic implementing the complete power-flow is presented below in Figure 10. The PV farm is oversized to meet the fixed load of 32 MW during the worst day (extremely cloudy day) with daily GHI of 3.95 kWh/m^2 . The size of the PV farm is also determined by adequate power for charging the co-located battery storage systems. The area of the farm is calculated by accounting for transmission losses, DC–DC conversion losses, battery round trip efficiency losses and finally inverter losses. The assumptions for these losses are stated in Appendix A. The total farm capacity to generate enough power to always meet load requirements is 230 MW. The optimum tilted and temperature compensated irradiance values are multiplied by the farm area of $1,040,724 \text{ m}^2$ to generate hourly PV farm output. The 230 MW farm adequately meets the 768 MWh daily demand with load-generation balance at every hour and generates excess power each day during summer months. The excess power generated by the PV farm can be sold to the existing grid. During hot summer months, the San Diego county needs additional power and is sometimes forced to schedule rolling blackouts. The PV farm can offset this additional load profile during summer months. The additional excess power generated by the solar farm can provide nearly-free electric vehicle charging stations as well.

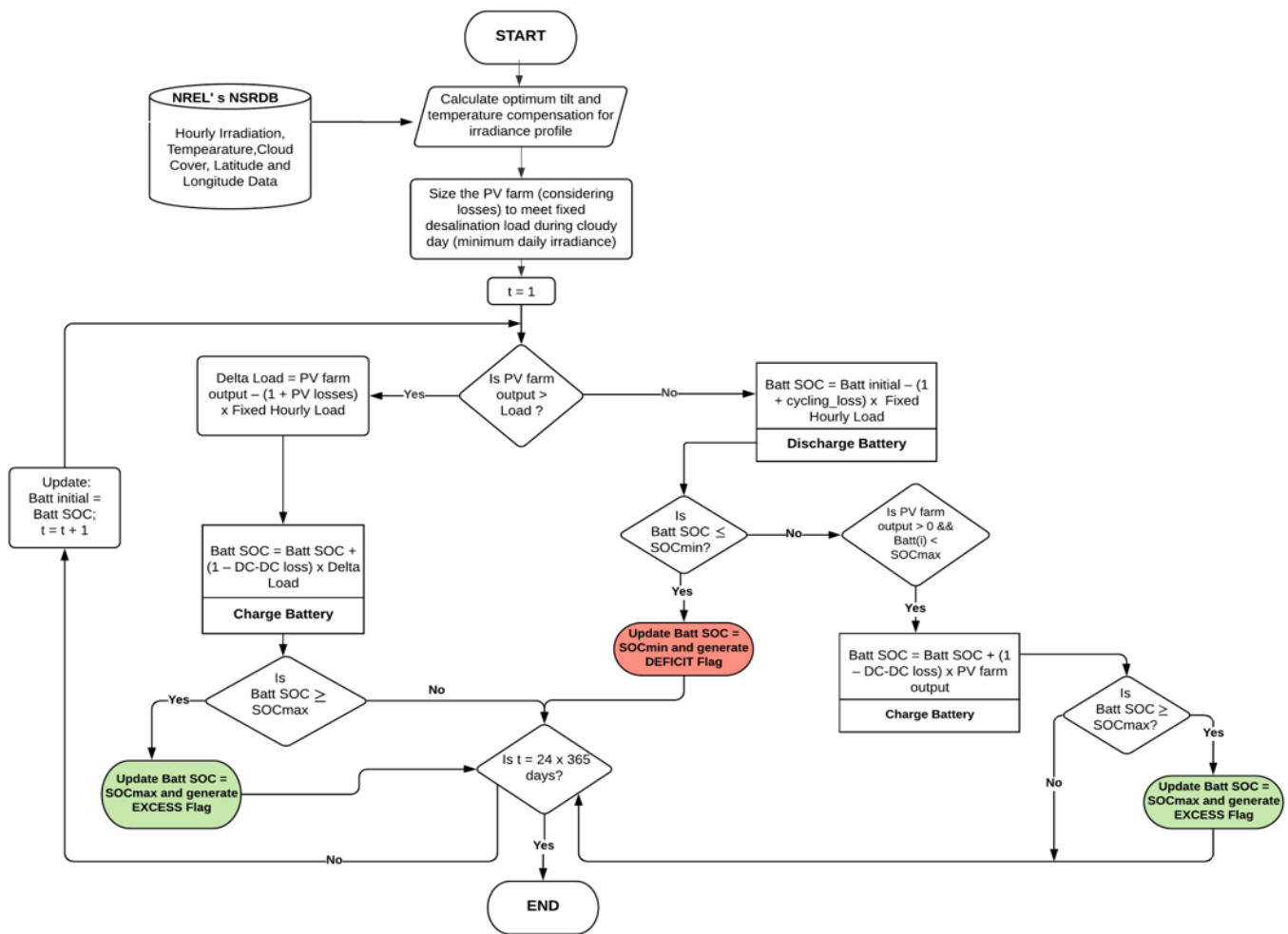


Figure 10. Flowchart for desalination system operation. In this figure, NREL and NSRDB represent National Renewable Energy Laboratory and National Solar Radiation Database respectively.

6.3.4. Battery Storage Profile and System Results

Battery storage is essential for resiliency of the stand-alone desalination plant. To ensure load balance the hourly battery profile was evaluated. The battery charging and discharging conditions were implemented as outlined in the flowchart (Figure 10). Initially, the battery is discharged to meet the hourly load until sunrise. As PV power generated from the solar farm is available immediately after sunrise, battery charging is preferred over supplying PV directly to the load. This is done to reduce transmission losses and incur a minimal DC to DC conversion loss for battery charging. During the early sun hours, when the irradiance is not sufficient to meet the load demand, the battery continues to be discharged. When the PV output exceeds the load, the power generated by PVs is directly supplied to the battery. At this stage, the battery enters charging mode and is charged by remaining PV generation until it reaches the maximum state of charge (SOC). Various battery parameters, like SOC, depth of discharge (DoD), battery cycle efficiency et cetera, are taken from Samsung's SDI lithium-ion storage datasheet [57]. The battery is sized to ensure that no power deficit occurs during its 15–18 h of operation every day.

The battery size is fixed at 810 MWh considering charging/discharging losses as outlined in Appendix A. The battery is sized to undergo one charge-discharge cycle per day. The complete system profile indicates no deficiency even for an extreme cloud cover day for battery and PV farm is shown in Figure 11. It can be seen from Figure 11 that on the worst PV generation day (extreme cloudy weather), the battery is charged and discharged

within operable limits while maintaining load balance without any deficit. This bolsters the stand-alone operation of our system with minimal losses.

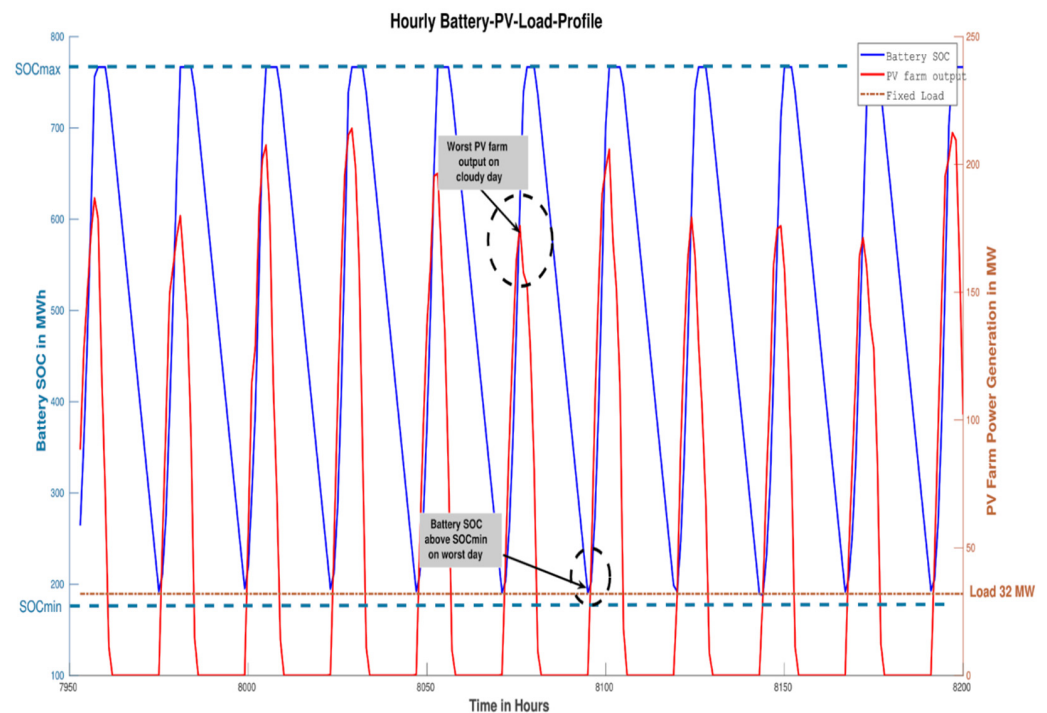


Figure 11. Hourly plant operation with PV-battery-load profiles for worst case scenario. In this figure, SOC represents State of Charge.

7. Financial Analysis

Power accounts for up to 44% of operating costs of a medium-capacity sea-water RO desalination plant as illustrated in [22]. The cost of desalinated water (\$/gallon) can be lowered by reducing electricity cost and transportation of power costs. Significant reduction in cost of electricity will have direct impacts on cost of potable water as well. However, calculating reductions in cost of desalinated potable water is not the primary focus of the paper. Thus, our financial calculations will be focused on providing cheaper and cleaner energy infrastructure that provides the lowest electricity cost for SWRO desalination.

For power cost analysis, we will not be using the levelized cost of electricity (LCOE) model in our calculations. The LCOE model is based on various assumptions instead of field data. Some assumptions about the initial capacity of power plants and operable specific lifetime are flawed. The major flaws of LCOE models are highlighted in the economic and feasibility section in [32]. Our financial calculations are based on actual field data obtained from several completed or in-process projects in this domain. This makes the financial analysis current to reflect the latest costs and market trends in this sector.

As we stated in Section 6, the worst case (highest cost) will be obtained when all the power is obtained by an HVDC power network. In this section, we have analyzed only this case. In the other two cases, the cost will be lower than this case. Currently, in the United States, subsidies are available for the use of PV and batteries. For electric power generation, municipal city owned utilities have provided lower cost than for profit utilities [58]. For this reason, we have considered the case without any subsidies and selected the ownership of the power network to be by the municipal government. It is also possible to have public and private partnership and the private company can take advantage of the subsidies. In this scenario, the cost will be lower than the case we have considered in this paper. The following assumptions are used:

1. According to a December 2019 article [59], the cost of a DC power PV system has dropped to as low as USD 0.7 per watt. In future, the cost will be lower. To be conservative, we have used a PV system cost of \$0.7 per watt.
2. In conventional HVDC, the conversion cost of AC to DC and DC to AC stations is quite high. In our case, there is no such conversion cost and HVDC cost will be much lower than for existing AC infrastructures. However, we have used the \$250,000/km cost of HVDC for AC infrastructure [60] in our calculations. In practice, the distance will be lower than 10 km. For HVDC, the cost of \$2.5 million is used in our calculations.
3. At utility scale, battery cost is given for 4 h. However, in our case 16–18 h of battery storage will be used. Due to higher volume, the cost will be much lower than the 4 h case. We have used Department of Energy data to extrapolate the cost for our case. These details are given in Appendix B and the cost in 2021 is \$226/kWh. Based on the accelerated growth of electrification of transportation, and the progress of solid-state batteries [61], it is obvious that the cost will be lower than \$226/kWh. We have studied the impact of battery cost variation from \$100–\$246/kWh.
4. The typical life of lithium batteries is 15 years. After 15 years, older batteries will be replaced by new batteries. Lithium batteries are following the cost reduction trend of PV [62]. We expect after 15 years the cost to be \$50/kWh.
5. We have assumed equity of 25% and the debt of 75% and studied the rate variation from 3–8% for 10 years.
6. We have used reference [63] to calculate interest on debt and Appendix C illustrates the detailed calculation formulas.

For 24×7 operation of the desalination plant on green electric power, the estimated electric power cost of 5.3 cents/kWh is lower than reported by anyone. It is worth mentioning here that by virtue of our system design, we have surplus power of 204,875 MWh per year, mostly in summer months. If this power can be sold to the existing grid, the cost will be further reduced.

In Table 2, we have studied the cost of electric power generation as a function of battery cost with debt rate as the variable. These simple calculations also show that for emerging economies (generally pay high debt rate) it is very important to provide low-interest rate debt to provide a solution to the water-energy-climate nexus. Ultimately, like the use of cell phones in emerging economies, the lower cost of batteries will benefit all economies, but it may be too late to fight climate related challenges.

Table 2. Calculated net system cost with varying battery storage costs and rate of interest.

Amortized Annual Rate of Interest	Battery Storage Costs (\$/kWh) (15–18 h)	Total System Costs (\$/kWh) for 30-Year Lifetime
Rate = 3%	100	0.03792
	150	0.04331
	200	0.0487
	226	0.05251
	246	0.05366
Rate = 5%	100	0.04082
	150	0.04662
	200	0.05243
	226	0.05544
	246	0.05776
Rate = 8%	100	0.04548
	150	0.05194
	200	0.0584
	226	0.06176
	246	0.06435

8. Conclusions

In this paper we have shown the urgent need to provide a solution to the water-energy-climate nexus. The existing power grid has fundamental weaknesses and there is a need for alternate sustainable solutions to provide ultra-low-cost electric power for the desalination process. Based on photovoltaics and batteries, we have proposed a stand-alone direct current power network for a reverse osmosis desalination plant. Unlike the conventional grid, the concept of baseload is not employed in the design of DC power networks. For inductive loads, a local inverter is used to provide AC power. Our proposed power network utilizes an hourly decision tree approach to ensure load-generation balance for complete autonomy from the grid. A future scope for the proposed system is to utilize a dynamic programming approach for DC power flows, minimizing losses and optimizing the plant load (increase pumping speeds during sun hours) by using artificial intelligence prediction techniques. The features of situation intelligence and cyber secured energy exchange between other desalination plants and the grid can also be considered. Financial analysis of our proposed system has shown that with today's cost, the power network will provide lower cost than any other technique. Due to constant reduction in the cost of PV and batteries, we expect even lower cost in the future. We can hence recommend that future desalination plants operate on stand-alone PV and battery-based DC power networks to maximize profits and provide clean and affordable water for all mankind at ultra-low cost.

Author Contributions: Conceptualization, R.S.; methodology, V.P.; software, V.P.; validation, R.S. and V.P.; investigation, V.P.; resources, R.S. and V.P.; writing—review and editing, R.S. and V.P.; supervision, R.S.; project administration, R.S. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

The MATLAB code assumptions are as stated below:

- The PV farm is appropriately sized to meet the power requirements on worst cloudy days. The minimum daily irradiance is calculated from the past 10 years' irradiance data as 3.95 kWh/m². The mean and maximum value of irradiance at the site location are 6.15 kWh/m² and 7.67 kWh/m², respectively. It is important to note that these irradiation values are calculated from optimum tilt and temperature correction.
- The PV farm area is calculated to be 1,040,724 m². Additional area for co-located battery storage is assumed to be 25,000 m² resulting in the total land area of 1,065,724 m² for the complete PV farm.
- The PV farm is sized at 230 MW and the lithium-ion battery storage is sized at 810 MWh.
- The PV farm is assumed to incorporate silicon PV panels of 22.2% efficiency. The optimum panel fixed tilt is set for every four months as 55°, 14°, and 55°, respectively.
- The lithium-ion battery is operated between SOC_{max} = 95% and SOC_{min} = 20% of battery capacity to ensure longer lifetime. The battery is adequately sized to ensure one charge-discharge cycle every day. This reduces battery sitting loss and charge degradation due to idle hours of operation. The SOC at every hour is maintained well above depth of discharge (DoD) of 20% of battery capacity. An assumed 6000 lifetime cycles will ensure approximately 15 years of operation before replacement.

Following are the power flow losses after researching the most recent and state-of-the-art systems:

Battery cycling loss = 10% for 1 complete charge-discharge cycle [64],

DC-DC conversion loss = 2% (for battery charging) [65],

HVDC transmission loss = 3% [66],

Inverter loss = 7% (for specific AC loads/pumps) [67].

Appendix B

The battery storage cost calculations are highlighted below. The equation used to calculate battery storage (BESS) cost from [68] is:

$$\text{Storage Costs (\$/kWh)} = \text{Battery Pack Cost (\$/kWh)} + (\text{EOS} + \text{BOS} + \text{Labor} + \text{Other cost}) / (\text{Storage System Size} \times \text{Duration of Hours}) \quad (\text{A1})$$

The cost of battery pack in the year 2021 is reported as low as \$100/kWh [69]. However, we have used the market average of \$137/kWh [69].

- Due to DC architecture the cost of a central inverter has been neglected. For certain high-pressure pumps local inverter cost of 0.06 \$/kWh can be used.
- The structural balance of system (BOS), electrical balance of system (EOS), labor and installation costs, Engineering and Procurement Cost (EPC), sales tax and developer costs are all assumed unchanged from the NREL 2018 data [68]. It is highly likely that these costs have reduced further in 2021 due to advances in battery technology. However, we have assumed these unchanged costs to consider the worst-case scenario. Actual BESS cost will be even lower than these values.
- A power curve fit expression is used to extrapolate the data points from 0.5–4-h costs (Figure A1) to 8 and 16 h of storage operation (Figure A2).
- As seen for 16-h storage, the cost is \$226/kWh for a 60 MW system. Since our system is sized for 32 MW this cost can further be decreased.

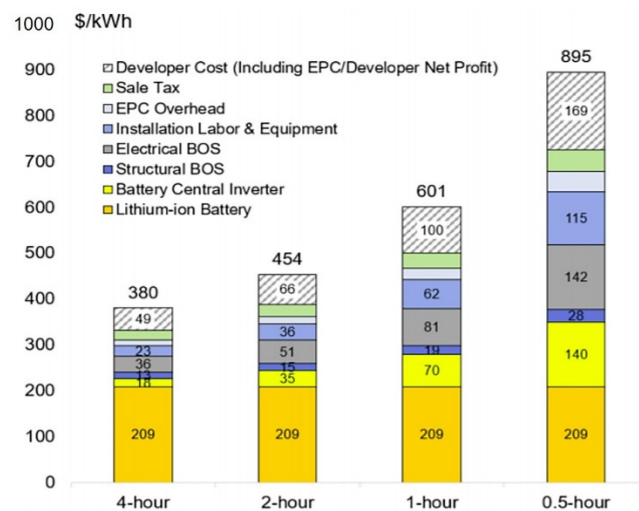


Figure A1. U.S. utility-scale Li-ion battery stand-alone storage costs for durations of 0.5–4 h (60 MW) 2018 [68]. In this figure, EPC and BOS represent Engineering and Procurement Cost and Balance of System respectively.

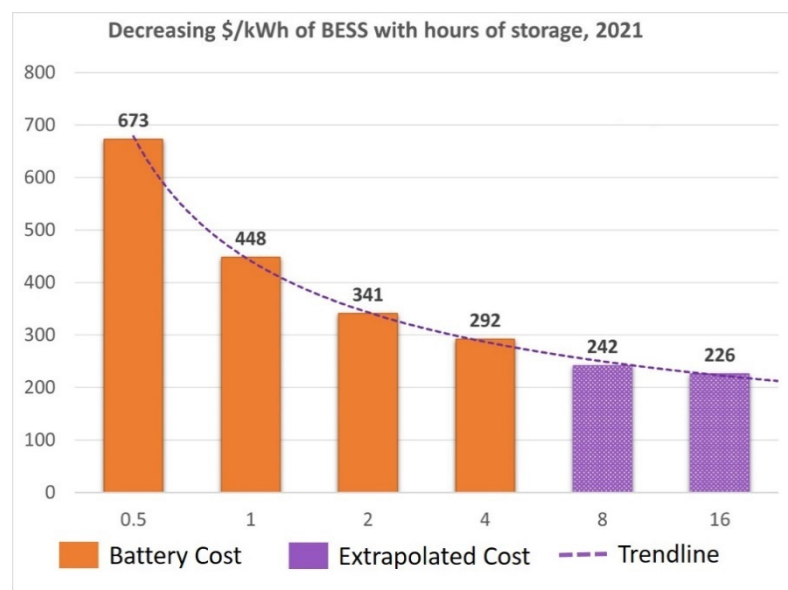


Figure A2. Battery storage costs from NREL and extrapolated costs for 8 and 16 h operation of the battery energy storage system (BESS) [68].

Appendix C

The amortized amount payable for every installment is taken from reference [70]:

$$\text{Amortized amount of each monthly payment (A)} = P \times \{(I \times (1 + I)^n) / (1 + I)^n - 1\} \quad (\text{A2})$$

where:

P : amount of principal; first balance

I : periodic rate of interest

n : total number of payments

The first payment is calculated on the principal loan amount. For each payment, the interest portion is calculated as the period rate (r) times the previous balance and is usually rounded to the nearest cent. The principal portion of the payment is calculated as:

$$\text{Principal (P)} = \text{Amortized Amount (A)} - \text{Interest (I)} \quad (\text{A3})$$

The new balance is calculated by subtracting the principal from the previous balance as given in Reference [70].

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