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Brackish water RO plant as a variable load for renewables based hybrid power system for increased power output

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ABSTRACT

Water and energy are the two needs that control human lives and propagate civilization. The scarcity of water can be addressed easily if energy is abundant. But we can see that most of the places that are water-stressed are also energy-stressed. Making the normal electricity grid supply available may not be a cost-effective option. Rural/remote locations such as hills and islands often have the problem of both water and energy. Hence there is a need to identify energy sources such solar, wind and biomass that are available locally to cater to water and energy needs. These sources are of intermittent nature and hence there is a need to store the energy when available. Also, combination of two or more of these renewable sources is also required to meet the demands. These are known as hybrid power system. This paper carries out an analysis of various sizing combinations of systems with solar photovoltaic, wind energy and stored energy in batteries for production of drinking water from a brackish water source. When the power produced is less than that required by the load, the generated power has to be stored in a battery and again discharged when required. We propose a BWRO plant that can take reduced power input also and reduced water output under such conditions and thus reduce the need of higher capacity of storage batteries. The system can operate the RO plant whenever the power is available, produce drinking water and store in a tank. This paper analyses the model of the entire hybrid power system in MATLAB to simulate the performance of the hybrid power system for different combinations of capacities. The analysis under various input conditions and analyzed the results.

Keywords: Renewable energy; Hybrid power system; Desalination; RO; Solar; Wind; Battery; Storage

1. Introduction

Water and energy are basic needs for the development of a civilized society [1]. But the fresh water availability is a point of major concern in most of the developing economies and in many parts of the world. There are established methods of desalination to solve the above problem. But, the desalination process itself is inherently energy-intensive. We can observe that remote locations such as islands, hills etc. lack both energy and water thus complicating the issue further. The cost of extending the conventional electrical grid to these places is also very high. The locally available renewable sources are the next resort and desalination plants have to be coupled with them [2]. They also put less stress on the environment [3]. Selection of plant and technologies are largely determined by site-specific factors [4].

Researchers have discussed the various aspects of fresh water production using renewable energy sources and hybrid systems [5–9]. But there are certain problems associated with renewables driven desalination plant. Due to the intermittency nature of renewable sources, there is a need for storage batteries. The power generated has to be stored in batteries when the generated power is sufficient enough to feed the available load. Also the batteries will discharge to feed the load during low generation periods. The addition of large capacity of storage batteries not only increases the initial cost but also reduced power output due to its charging and discharging efficiencies.

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1.1. Energy Storage systems:

The power system is expected to perform well in terms of its reliability and availability leading to better energy security. But the very basic nature of renewable energy sources contradicts this objective. Hence various energy storage systems (ESS) like the pumped energy storage, battery storage and fuel cells are to be employed to meet the objective [10–12]. The energy storage finds a multi-faceted application in the power system. Load management is the primary application of ESS. There is always a need to balance between the load end requirements and the generation instantaneously [13–15]. When the demand exceeds the supply, ESS supplies the additional power required. Another important application is the meeting up of peak demand. Very short time spike load requirements can be met out by the ESS [16,17]. Also energy storage systems help in reducing the capacity of DG sets and can cater power back up requirements for emergency loads. Future energy storage systems are expected to contribute for easier transition to smart grid networks [18,19]. All the above storage systems already considered takes away a portion of generated energy for energy conversion purposes during the process of storage and again during usage. Hence, it is necessary to analyze the situation where we are able to utilize the energy instantaneously to make a final product that can be stored. A suitably sized reverse osmosis plant finds its application under such circumstances. This eliminates the energy wastage in terms of roundabout efficiency in storage/reuse and thus increases the net overall energy available for the load. This paper proposes to use a brackish water desalination plant as a variable load coupled with hybrid power system and attempts to analyze the effect in power output from the system.

2. Modelling the renewable energy systems

The availability of renewable energy sources differs from site to site and hence a detailed study is necessary with respect to various available resources is a prerequisite. We have chosen solar photovoltaic and wind energy as sources for our work based on solar irradiance and wind speed data. The selected systems are required to be modelled for further analysis.

2.1. Solar photovoltaic

Solar PV cells work on the basis of photovoltaic effect that converts energy in the sunlight to electrical energy directly. A PV cell is made up of thin layers of semiconductor materials and the most common material used in silicon. When light impinges on the silicon layers, the energy is transferred to the electrons generating electrical charges. When these charges are conducted using metal external contacts, we obtain electrical energy in the form of direct current.

Modelling the solar PV system is essentially finding the relationship between the solar irradiance and the corresponding power output from the PV cell. The same is given by Luque and Hegedus model of PV cell [20]. Table 1 gives the description of symbols used.

Table 1
Symbols used in solar PV model equations

Symbol	Description
I_{sc}	is the short circuit current
V_{oc}	is the open circuit voltage
V_t	is the thermal voltage
R_s	is the series resistance
STC	is standard test conditions
I^*_{sc}	is the short circuit current of module at STC
V^*_{oc}	is the open circuit voltage of module at STC
G^*	is the irradiance at STC
T_a	is the ambient temperature
T_c	is the operating temperature of module above ambient
T^*_c	is the temperature of module at STC
NOCT	is normal operating cell temperature
$\frac{dI_{SC}}{dT_c}$ and $\frac{dV_{oc}}{dT_c}$	are temperature coefficient of current and voltage
σ_{oc}	is the empirically adjusted parameter equal to −0.04
G_{oc}	is the empirically adjusted parameter taken as equal to the value of
V^*_M	is the maximum voltage of module at STC
I_M	is the maximum current of module at STC.

$$I \ = \ I_{SC}\left[1-\exp\left(\frac{V-V_{\propto}+IR_s}{V_t}\right)\right] \tag{1}$$

$$I_s c = I^*_{SC}\frac{G}{G^*}[1+\frac{dI_s c}{dT_c}(Tc-Tc^*)] \tag{2}$$

$$Tc = Ta + C_t Geff \tag{3}$$

$$C_t = \frac{NOCT(^o c)-20}{800W\ /\ m^2} \tag{4}$$

$$V_{\propto} = \left[V^*_{\propto}+\frac{dV_{\propto}}{dT_c}\left(T_c-T^*_c\right)\right]\left[1+\sigma_{\propto}1n\left(\frac{Geff}{G_{\propto}}\right)1n\left(\frac{Geff}{G^*}\right)\right] \tag{5}$$

$$Rs = \frac{V^*_{\propto}-V^*_M+V_t 1n\left(1-\frac{I^*_M}{I^*_{sc}}\right)}{I^*_M} \tag{6}$$

$$P_v\left(t\right) = NpvVm\left(t\right)\mathrm{Im}\left(t\right) \tag{7}$$

Eq. (7) gives the estimated power output from the solar PV cell.

PV equipment is basically a static equipment without any moving parts. Hence the requirement for maintenance is very minimum. Also it has a long life of around 15–20 years. There is no emission of greenhouse gases and no noise during operation.

2.2. Wind energy

Wind energy is also an indirect form of solar energy. The difference of pressure in atmosphere is the basic source of wind energy. The high wind speed regions of the world has been more or less commercially exploited. Recently, small scale wind turbines are an essential part of standalone power systems that are distributed in nature rather than the conventionally centralized system. The power production of both solar PV and wind energy system can be largely improved by employing controls with maximum power point tracking and more efficient and effective energy storage systems.

The wind energy is modeled using the below relation. Table 2 gives the description of symbols used.

$$P_w(t) = \begin{cases} 0(v < v_{in}) \\ a_1v^2 + b_1v + c_1(v_{in} \le v < v_1) \\ a_2v^2 + b_2v + c_2(v_1 \le v < v_2) \\ a_3v^2 + b_3v + c_3\left(v_2 \le v < v_{out}\right) \\ 0(v > v_{out}) \end{cases} \tag{8}$$

2.3. Energy storage battery

The modelling of battery storage system is required to track the amount of energy stored in the system at a given point of time during the simulation. For estimating the state of charge of the battery, we need to know the power generation from the renewable sources during the hour, the load requirements and the state of charge at the start of the hour. The state of charge at a given hour $E_b(t)$ is given by the equation

$$E_b(t) = E_b(t-1) + [E_{ch}(t) * \eta_{ch}] - [E_{dis}(t) * \eta_{dis}] \tag{9}$$

where $E_b(t-1)$ denotes the state of charge in the preceding hour, $E_{ch}(t)$ and $E_{dis}(t)$ are the charge and discharge quantities of energy storage, η_{ch} and η_{dis} are the charging and discharging efficiencies respectively. We have chosen both the charging and discharging efficiencies of 90% for the lead-acid storage battery.

2.4. Reverse osmosis (RO) desalination using solar PV and wind energy

Many systems have been developed with reverse osmosis plants driven by solar PV [21,22]. Brackish water RO has minimum energy needs compared to other desalination process. Wind powered desalination plants are also being considered in many parts of the world [23–25]. The intermittent nature of solar PV and wind sources demand development of hybrid power sources with combination of these energy systems [26]. The RO plant can serve as an indirect energy storage system because the plant can be operated when power generation is more, producing and storing water in tanks. This can reduce the need for larger energy storage system like batteries, and hence increase efficiency [27,28].

Table 2
Symbols used in wind model equations

Symbol	Description
$P_W(t)$	is the hourly output power of wind generator at wind speed v
v	is wind speed at projected height
V_{in} and V_{out}	are cut-in and cut-off wind speed of the wind generator respectively

3. Hybrid solar PV-wind power scheme

Fig. 1 shows the schematic diagram of the hybrid system with the desalination plant as load. A brackish water RO desalination plant is connected as a load to the hybrid power system. This plant produces drinking water when the power available (both generated and stored put together) is sufficient to operate the plant. The water produced will increase up to its rated capacity, if the power produced is also more. Hence the load can handle variation in the power generation due to the renewable sources. The RO plant indirectly stores power produced in the form of product water thereby eliminating the need for having higher capacities of expensive batteries.

3.1. Analysis of hybrid power system with RO plant

We have modeled the entire hybrid power system in MATLAB using Eqs. (1)–(8). The main objective of the model is to analyze the various combinations of solar PV, wind generator and battery capacities with a variable desalination load to obtain the total power generation.

3.2. Data

The hybrid power system design options are analyzed for the selected site, Kalpakkam. Kalpakkam is situated in South India and has the following latitude and longitude:

Latitude: 12°34′ North
Longitude: 80° 10′ East

The solar irradiation data is measured by using the ‘Online Solar Radiation Meter’ installed at the site and the

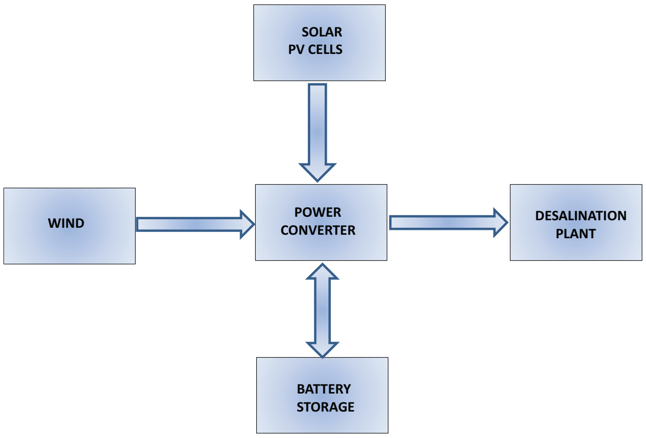

Fig. 1. Schematic diagram of a typical small hybrid powered desalination plant.

wind data is extracted from the meteorological data available at IGCAR, Kalpakkam.

3.3. Simulation methodology

We have used the hourly solar irradiance data measured in kWh/m^2/d and wind speed data in m/s as inputs for simulation. The above data is used to calculate the power output available from PV and wind sources using the models as described in Section 2. The simulation is performed for two cases:

3.3.1. Case 1: with constant load

A constant load of 2 kW is chosen. The power generated by renewables is calculated for every hour of the year. When the power generated by the renewables is more than 2 kW, load will be fed and excess power will be used to charge the battery. When the power generated is less than 2 kW, load will be fed by both renewables and battery source, if available. Else, only batteries will keep charging and load will be disconnected.

3.3.2. Case 2: with desalination load

A brackish water reverse osmosis (BWRO) plant with a capacity of 24 m^3/d is chosen as the load to be the system. This plant can operate at full load with 2 kW of power input and with reduced output up to a power input of 0.5 kW. Again, the power generated by renewables is calculated for every hour of the year. The power generated is utilized as per the following logic. When the power generated by the renewables is more than 2 kW, the plant will operate at full load producing rated output and excess power will be used to charge the battery. When the power generated is less than 2 kW and more than 0.5 kW, the plant will operate at lesser capacity. If the power generated is less than 0.5 kW, only batteries will keep charging and the plant will operate at lesser load using batteries until the battery is discharged to it maximum level beyond which the plant will shut down and only batteries will keep charging. The logic used for the simulation is given in Fig. 2.

The above simulation is carried out for various combinations of solar PV capacities (1–10 kW), wind generator capacities (1–10 kW) and battery capacities (0.5–2 kW).

4. Results and discussion

The output of the simulation gives data on total KWHr generation throughout the year for 400 combinations of Solar PV, Wind generator and Battery capacity for the ranges mentioned in Section 3.3. Table 3 lists the partial results of different configurations of hybrid power systems with constant load and with BWRO plant load.

From the results, we can see that there is a clear increase in the total kWh produced throughout the year. The increase is mainly due to direct utilization of renewables power generation to the maximum extent particularly when the power generated in low. In other case, this has to be used for charging the battery or will be wasted if the battery charge is already full. Hence the BWRO plant indirectly acts as a storage device tapping the generated energy to the maximum possible extent.

For example, in combination number 100, a solar PV of 5 kW, wind of 2 kW and battery of 1 kW capacities produces 5142 kWh/y with a constant load and 7520 kWh/y with BWRO plant as load. The average increase in kWh/y is around 25%.

Fig. 3 shows the plot of kWh/y produced for various combinations of solar PV, wind and battery capacities. We can observe that there is a clear increase in the power produced with BWRO plant. Also we can see that the increase in power production is more predominant when the capacities of solar PV, wind and batteries are in lower ranges. This is because of effective utilization of power during low power periods. At higher ranges, the increase becomes more or less steady.

The production capacity of water at various combinations also can be found out using the above results. We have taken a specific energy consumption of 1.5 kW/m^3 of desalinated water production for the chosen BWRO plant. The daily water production for a particular combination of renewables (solar PV – 10 KW, wind generator – 5 KW) is shown in Fig. 4. The total desalinated water production for the whole year for the above combination works out to 7768 m^3 and the average production per day is around 21.28 m^3. This shows that with a suitably sized storage tank, we can deploy to proposed configuration easily to cater to desalinated water requirement of around 20 m^3/d.

5. Cost of water for various combinations of PV and wind capacities

We have made an attempt to analyze the performance of the system for various combinations of solar PV and wind generator capacities. The obvious and most important factor for analysis is the cost of water per m^3 of water produced. Also we need to ensure that the total amount of water produced during a year should be able to cater to the requirements as desired. Apart from this, we also considered the availability of the power for running of the BWRO plant (i.e.) % of plant operating hours in a year.

The cost model of the various energy sources is developed considering the capital cost per kW capacity. The annualized capital costs are calculated by using the capital recovery factor which is calculated by taking the life span of systems and the interest rate into account. Also the operation and maintenance costs are included in the model. The annual total cost of the hybrid power system for a particular set of capacities of solar PV, wind and battery is finally calculated by summation of the individual costs.

The formulae used for the cost model is as given below. Table 4 lists the description of symbols used.

$$ACC = CC \; x \; CRF \tag{9}$$

$$\begin{aligned} ATC &= C(PV)x\left[ACC(PV) + AMC(PV)\right] \\ &+ C(W)x\left[ACC(W) + AMC(W)\right] \\ &+ C(B)x\left[ACC(B) + AMC(B)\right] \end{aligned} \tag{10}$$

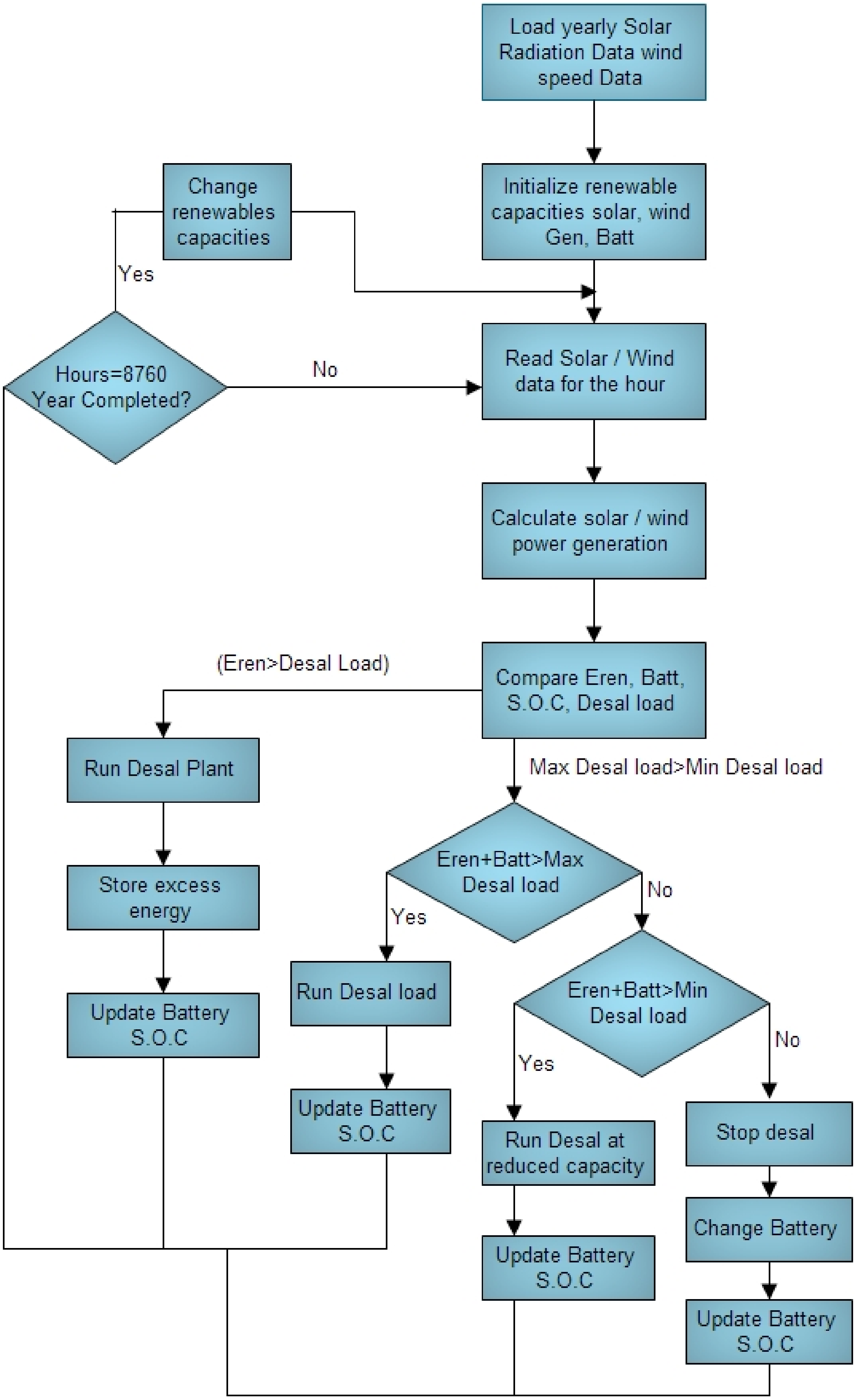

Fig. 2. Proposed methodology of simulation.

Table 3
Partial list of different configurations of hybrid power systems and kWh/y generated with constant load and BWRO plant load

Combination no. of each configuration of PV, wind and battery capacities	PV	Wind	Battery	kWh/y produced with constant load	kWh/y produced with desal load
1	1	1	2	58	2557
5	1	2	0.5	778	3901
10	2	1	1.5	1226	4773
12	2	1	0.5	1368	5667
13	1	3	0.5	1712	4928
50	1	7	1	3732	7673
75	4	2	1	4480	7167
80	1	9	2	4600	8652
81	3	4	0.5	4816	7862
92	2	7	2	4940	8716
100	5	2	1	5142	7520
101	4	3	0.5	5174	7774
108	3	5	2	5262	8396
116	2	8	2	5364	9153
124	4	4	2	5564	8302
150	4	5	2	5980	8799
160	2	10	2	6106	9918
200	10	1	0.5	6478	8660
225	5	6	0.5	6806	9483
250	7	5	1	7082	9421
275	4	9	1.5	7362	10360
300	8	6	2	7618	9921
325	8	7	0.5	7918	10283
350	8	8	1	8172	10609
375	10	8	1.5	8454	10759
385	8	10	0.5	8626	11200
393	9	10	0.5	8794	11270
394	9	10	1	8794	11270
395	9	10	1.5	8794	11270
396	9	10	2	8794	11270
397	10	10	0.5	8912	11332
398	10	10	1	8912	11332
399	10	10	1.5	8912	11332
400	10	10	2	8912	11332

The above simulation is carried out for various combinations of solar PV capacities (1–10kW), wind generator capacities (1–10 kW) and battery capacities (0.5–2 kW). Capital cost, O&M cost (@ 2% of capital cost), interest rate (10 %) and project life time (for solar PV, wind, and batteries) are considered for calculation of cost economics.

We can observe from the plot shown in Fig. 5, that the cost of water varies with selection of combination of solar PV and wind generator capacities. Also the total water produced for the whole year and the availability of plant also varies. The blue band in the plot shows that the same total water production is achievable for various cost of water (i.e.) less than INR 100, around INR 110 and at INR 225 approximately. This is due to increase in capital cost involved in increasing the solar PV and wind generator capacities. But the total water production remains in same level. This only helps to increase the availability of the plant, but significantly increases the cost.

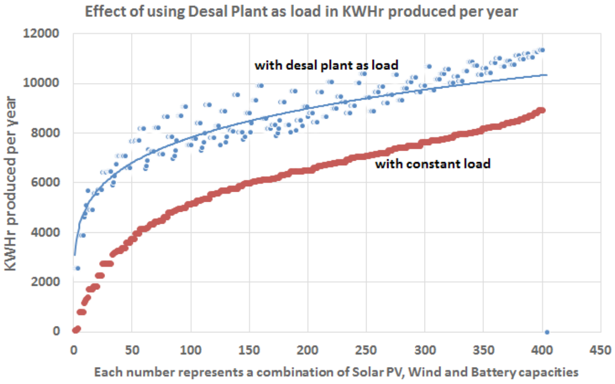

Fig. 3 Plot showing increase in kWh/y produced with BWRO plant as load.

The above knowledge enables us to select capacities on the basis of our actual requirements. We can fix up the total water required in the whole year and the maximum cost that can be afforded for producing this water. The system configuration can be selected for the necessary combination of PV-wind systems to meet our objective. Places where water cannot be stored to the required level and continuous availability of water is the main objective, the selection can be made accordingly, but at an increased cost.

5. Conclusion

In this paper, modelling of renewable energy based desalination systems with solar PV and wind turbines was presented. The above configuration was subjected to detailed simulation to analyze the performance of the system under constant load of 2 kW and a BWRO plant load of 2 kW maximum. From the results obtained, we observe that there is an average increase of kWh/y production by around 25%. Also this increase is very predominant in lower capacity ranges of solar PV, wind and batteries. In high capacity ranges, the increase in power produced more or less saturates to around 25%.

The increase in kWh/y is primarily because of better utilization of power generated in the low power period which is either used to store in battery or wasted if battery is also full. Additional batteries are required to be employed to tap full power. The battery introduces an efficiency loss of 80% in its charging and discharging cycle. Also the life of battery is limited after which the entire battery system needs to be changed.

The BWRO plant directly utilizes the power generated to produce water. This reduces the battery requirement for the system for a given kWh/y production. Thus the BWRO

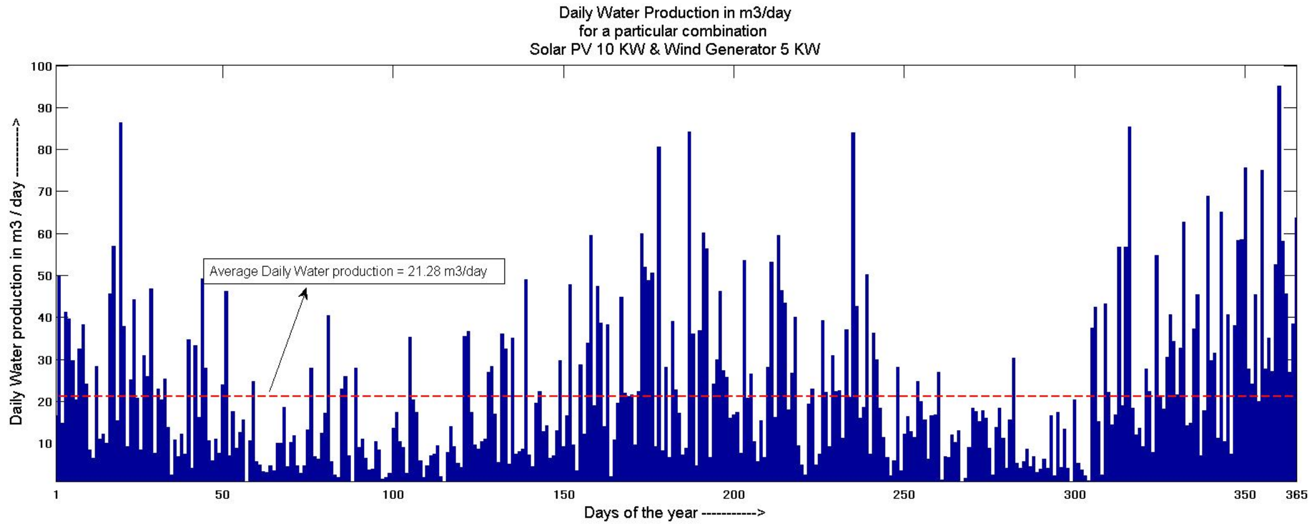

Fig. 4. Dailywater production throughout the year (in m^3/d).

Table 4
Symbols used in cost model

Symbol	Description
CC	Capital cost/kW (in INR – Indian Rupees)
CRF	Capital recovery factor
ACC	Annualized capital cost (in INR)
AMC	Annual O&M cost (in INR)
ATC	Annualized total cost (in INR)
C (PV)	PV capacity (inkW)
C (W)	Wind plant capacity (inkW)
C (B)	Battery capacity (inkW)
COE	Cost of energy / kWh(in INR)

Table 5
Simulation input parameters

Parameter	Capital cost (Indian Rupees/kW)	Life span (y)
Solar photovoltaic	50,000	20
Wind generator	180,000	20
Batteries	10,656	5

plant indirectly serves as an energy storage device. The typical values shown fairly hold well for scaling up to larger systems as solar PV and battery systems are completely modular in nature. As for as wind turbines are concerned, more economy can be achieved at higher capacities depending upon the prevailing wind data. However, an analysis like the one presented here will enable the designers to take decision on selection of appropriate configuration. Also the combination of the solar PV-wind and desalination plant capacities can be selected in such a way to meet the specific objectives based on total water production in the whole year and cost of desalinated water.

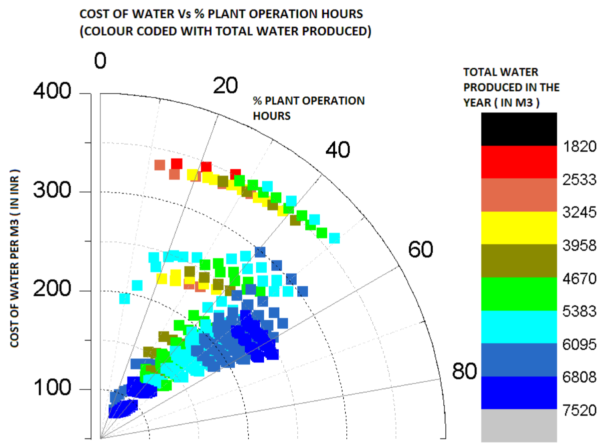

Fig. 5. Plot of cost of water per m^3 (in INR) vs. % plant availability colour coded with total water produced in m^3.

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