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Reverse Osmosis Desalination Plant Driven by Solar Photovoltaic System

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ABSTRACT: *Under the pressure due to the exhaustion of fossil fuels and global warming concerns, it is required to develop more sustainable systems to provide electrical power. This study developed a mathematical modeling for re designation of a reverse osmosis desalination plant to drive it by Solar Photovoltaic (PV). The design has run by using EXCEL software as a case study about desalination plant at the western region of Saudi Arabia. Due to the remote area and sunshine weather during most of the year in this region, it has a great opportunity to install highly efficient photovoltaic panels. Result shown that, 757 kW can be produced by photovoltaic system in that power plant.*
Keywords*:Solar PV; Power plant; Reverse Osmosis;PV efficiency; Desalination system.*

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I. INTRODUCTION

Worldwide countries suffer from severe water scarcities are increasingly dependent on desalination as a highly reliable, non-conventional source of freshwater.

Solar energy presents one of the frequent used sustainable energy sources to desalinate water. Among desalination technologies, reverse osmosis (RO) is rapidly overtaking thermal desalination process in terms of carbon emission.

Solar photovoltaic driven reverse osmosis desalination system is the most promising renewable energy. That can be potentially break the dependence of conventional desalination on fossil fuels, reduce operational costs, and improve environmental sustainability.

Omar Aboelwafa [1] investigated the literature and the application of The Rankine systems for power generation and focuses on the working fluids. This cycle is considered the best common and competitive power generation cycle to generate electricity from solar thermal energy. Work done on the solar Rankine cycle based on the working fluid used at lower temperatures and result shown that, steam Rankine cycle is less efficient and costlier.

Emily Spayde [2] evaluated the performance of a solar powered regenerative Organic Rankine Cycle (R-ORC) using five dry organic fluids: RC318, R227ea, R236ea, R236fa, and R218. The system is evaluated in two locations in the U.S.: Jackson, MS and Tucson, AZ. The output from the R-ORC performance are compared with an ORC using first and second law principles as primary energy consumption (PEC) and carbon dioxide emission (CDE).

Bertrand F. Tchanche [3] reviewed ORC principles, summaries challenges to be astounded (working fluids, small expanders design, performance map, heat exchangers integration, and project guidelines) and gives a small number of data on the ORC marketing and utilization of clean energy resources: geothermal fluids, solar irradiation, ocean thermal gradient, heat from biomass combustion and waste heat from industrial thermal processes. This paper recalls

H. Sheykhlou [4] studies the thermal system which combines an organic Rankine cycle and an ejector–refrigeration cycle. The combined cycle driven by low-temperature heat source (solar energy). energy of combined cycle is provided by the parabolic dish collectors. number of needed collectors is calculated. a simulation has been made using R123 as the working fluid. the input and output pressures of turbine on thermal efficiency, exergy efficiency and exergy destruction has been investigated.

Moslem Sharifishourabi [5] proposed and analyzed new multi-generation system through energy and exergy. These outputs include hot water, electricity, heating, cooling, dry air, and hydrogen production. the exergy results identify the generator as the module with the greatest exergy destruction rate, implication that it is the main source of irreversibility. the system is in line with the renewable energy initiatives being executed by the global community and is an important system for the future.

Yiji LU [6] presented the study of engine coolant and exhaust heat recovery using organic Rankine cycle (ORC). Eight working fluids were carefully chosen to evaluate and compare the performance of the included waste heat recovery system. case study selected a small engine as the heat source to drive the ORC system using a scroll expander for power production. The results recommend that adding a recuperator to the ORC and the overall heat demand of the system can be reduced by 12% under optimum conditions.

RuliNutranta [7] modified Rankine cycle (ORC) with working fluids, refrigerant made of organic material, such as pentane. Organic refrigerant, such as, pentane has low boiling point, therefore ORC can be utilizing in power plant that uses low temperature resources, such as solar thermal exhausted gases and geothermal wells. In this study several working fluids has been used; HCR12, HCR22, HCR134a and pentane simulated.

G. Laheurte, M. Feidt [8] study a modelling and optimization of an O.R.C. cascade; the considered case in the end mutable one, with the constraint of a given heat rate and temperature level at the hot side to valorize. The corresponding upper bound efficiency is given and optimized from a heat transfer conductance provision point of view. O.R.C. is an interesting unconventional to effective use of low temperature heat, and also of heat released from system and processes.

Jiaxin Ni, Li Zhao [9] study the daytime performance of solar-ORC system to guarantee a proper operation Created on the discretized parameter model made in Dymola, dynamic performances of a small-scale power plant driven by parabolic trough collector (PTC) under clear sky and cloudy sky conditions. The results show that degree of super heat, evaporation pressure and output power are related to direct normal irradiance (DNI) and follow the variation of DNI from morning to afternoon. The optimized system can generate 105.54 kWh and the system without control can generate 84.95 kWh.

J. Moumouh [10] review various technologies under investigation to desalinate saline water through air and using solar thermal energy. A particular emphasis will be put on the various types of solar water heaters. The Humidification-Dehumidification process presents a very exciting solution for small units (hotels, rural regions, light industry, etc.). From the present review it is found that amid top Solar collector coupled with HD desalination system is flat plate collector thermosiphon solar water heater with storage Tank, flat plate collector with filled bed solar air heater. It is necessary to indicate the best design and working conditions that give the minimum product cost.

V. Okatia,b,c [11] designed a solar water desalination system with humidification-dehumidification (HD) cycle, incorporating a solar still and a new subsurface condensation mechanism. Mass and energy balances are written for both solar humidifier and subsurface condenser in thermodynamic analysis of the system. The results of the analysis show that the rate of water production can reach above 264.86 (kg/day) and the produced water, passing over the pores on the tubes, can be used to irrigate plant roots or composed as drinking water.

Jing Lia [12] This work presents a novel approach using two-stage accumulators and steam-organic Rankine cycles (RC-ORC). The system includes unique two-step heat discharge. Heat is primarily released via water vaporization in a high temperature accumulator (HTA) to drive the RC-ORC, prominent to an HTA temperature drop of approximately 30 °C. A comparison with the conventional DSG system is conducted at a nominal power of 10 MW with an accumulator volume of 2500 m3. Thermodynamic performance of the system also investigated.

Luca Cioccolantia [13] investigated on a small-scale concentrated solar 2 kW organic Rankine cycle plant. Joined with a phase change material storage tank prepared with reversible heat. This work designed integrated system, developed by the group, to estimate the overall performance of the system to provide useful information for its imminent real operation.

D. Novalesa,b [14] Studies recuperator effectiveness differences from the sensitivity analysis, it can also be concluded that the Recompression Cycle is the best acting cycle for most of the studied cases with energy efficiencies in the range between 32.97% and 51.91%. the exergy analysis on cycle components shows that irreversibility arise mainly in the Recuperators, which means that future investigation should focus on methods to decrease irreversibility in these components

Amy M. Bilton [15] focused on improving the feasibility Small-scale photovoltaic-powered reverse osmosis (PVRO). a methodology to estimate the economic feasibility was developed. The results, reviewed here, show that the economic feasibility is a strong function of location. Results also show that growing the efficiency of PVRO systems can extend their feasibility to presently marginal or un- feasible locations.

Mahmoud Ammous [16] gathers Photovoltaic thermal collector PV/T of the frequent used energy resources to desalinate water especially with reverse osmosis desalination process. As the system is a multi-input/output/output system, a state space model based on energy balance equations is developed in order to analyze and assess the parameters performances and correlations of the system elements.

Andrea Ghermandi [17] investigated the experience with solar desalination is based on the analysis of 79 experimental and design systems globally. Solar-driven reverse osmosis desalination can possibly break the requirements of conventional desalination on fossil fuels, reduce operational costs, and improve conservation sustainability. Results show that photovoltaic-powered reverse osmosis is technically settled and at unit costs as low as 2–3 US$ m–3 economically cost-competitive with other water supply sources for small-scale systems in remote areas.

P.A. Davies [18] proposed a new system that uses a solar-Rankine cycle to initiative reverse osmosis(RO). Working fluid such as steam is expanded against a power piston that actuates a pump piston which in turn pressurizes the salt water thus passing it through RO membranes.

After reviewed the previous literature and showed the capability to sync the PV panels with desalination plant,This study analyses the sizing and efficiency of the crank mechanism, measures energy losses in the RO separation and predicts the overall performance.

1.1 Overview of The Research

Increasing overall Photovoltaic Reverse Osmosis PVRO system efficiency can possibly increase the places where PVRO systems are applied [22]. Substantial research is being done to improve the efficiency of individual system components [23], such as control system and reverse osmosis membranes; however, little research is presently being done on improving the overall system performance using solar photovoltaic.

Figure 1 explained that process description for Reverse Osmosis desalination plant as:

- Phase one Suction of the sea water by 3 pumps and then enter the phase two.
- Phase two: which consists of two stages of filters and each phase contains 4 filters, then stored in the filtered water tank.
- Phase three: suction the water from the tank by 3 RO feed pumps with 5 bar pressure through 3 Cartridge Filters.
- Phase four: pressurized water up to 64 bar by 1st pass RO high pressure (HP) pumps through 1st membrane then stored at RO permeate storage tank.
- Phase five: pressurized the water with 11 bar by 2nd pass RO high pressure (HP) pumps through 2nd membrane then stored at desalinated water storage tank.

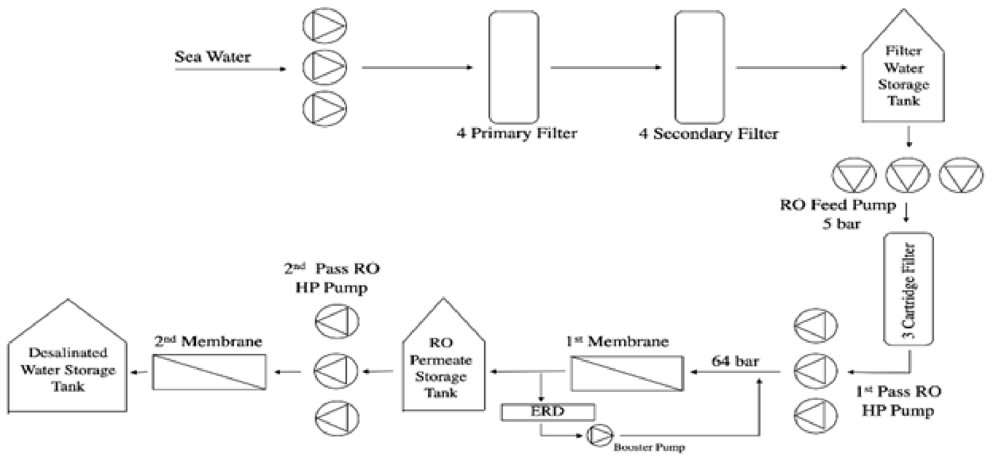

Fig.1.Reverse Osmosis (RO) Schematic Diagram

1.2 Objective

To achieve these purposes of PVRO system models, the connection between solar power and desalination plant explained below. A large-scale investigational system has been designed and fabricated to confirm the system models after re-design the power supply. Details calculation of the system re-designing and gathering data are presented. The re-designing models show good promise with primary study results while convert power supply from auxiliary power consumption of power plant to solar photovoltaic system as shown in figure: 2.

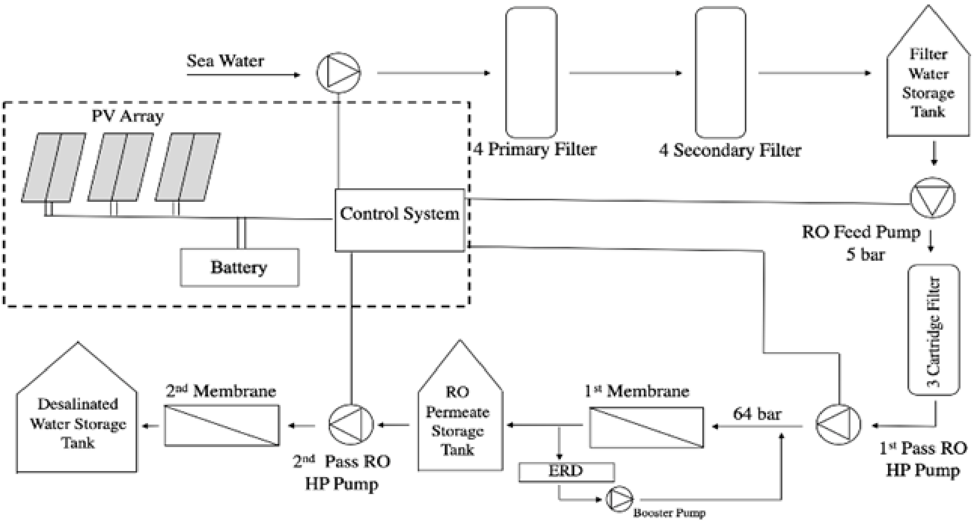

Fig. 2. PV power supply for reverse osmosis desalination plant

II. METHODOLGY

The method of this study was based on theoretical modeling to re-design of the power supply by solar photovoltaic, different parameters are presented in this section; **Solar time**, **Solar angles**, **Extraterrestrial solar radiation**, **Solar radiation on tilted surface**, **day length**, **Sunrise time**, **Sunset time**, **η**c and Ac.

Note: the following data are gathering from;

- Google earth: Latitude, longitude and ϕ:
- local power generation plant design data sheet: Equipment specification:

- Solar Time:

Solar Time = Standard Civil Time + 4 (L st – L loc) + E [25]

E = 9.87 sin(2B) – 7.53 cos(B) – 1.5 sin(B) [26]

B = 360 (n – 81)/ 364 [27]

Table 1:Solar Time Data Input

Parameter	Value
Standard Civil Time	13.5
L st	42.7
L loc	27.8
N (day)	365

Table 2: Solar Time Data Output

Parameter	Value
B	99.89
E	-3.51
Solar Time (hr.)	14.43

- Solar Angles:

cos ωs = - tanϕtanδ [28]

cos θ = sin δsinϕ cos β - sin δ cos ϕ sin β cos γ + cos δcosϕcosβcosω + cos δ sin ϕsinβ cos γcosω + cos δ sin βsinγsinω [29]

δ = 23.45 sin [360 (284+n) /365] [30]

Which:

θ = solar incidence angle, the angle between the normal to the surface and the solar ray.

δ = solar declination angle, the angle between a line extending from the center of the sun to the center of the earth and the projection of this line on the earth's equatorial plane, north positive.

n = is the number of the day in the year; n = 1 at Jan 1 and n = 365 at Dec 31.

ω = solar hour angle, the sun moves 15 degrees/hour from east to west (e.g. ω = 15º at 1:00 PM solar time and ω = -30º at 10:00 AM solar time)

γ = surface azimuth angle, the angle between south direction and the projection of the normal to the surface on the horizontal plane (γ = 0 for south facing surface).

β = surface tilt angle to the horizontal (0 ≤ b ≤ 90).

ϕ = latitude angle from the equator, - 90 ≤ f ≤ 90 (ϕ = 20º for Shoaiba).

δ = 23.45 sin [360 (284+182) /365]

$\delta = 23.14$

Table 3: Solar angle data input

Angle	Value
ϕ	20
β	20
γ	0
ω	81 at sunrise time 6:36

Table 4: Solar angle data output

Parameter	value
δ	23.14
COS θ	0.156
θ	81.09
COS ωs	-0.155
ωs	98.99
Sunset Solar Time (hr)	6:36
Sunset Local Time (hr)	7:39

- Extraterrestrial Solar Radiation:

$G_o = G_{on} \cos \theta_z = G_{sc} [1+0.033 \cos (360\, n/365)] \cos \theta_z$ [31]

Which:
G_{sc} = Solar Constant = 1353 W/ m^2[32]
G_{on} = the extraterrestrial solar radiation (G_{on}) is the solar radiation outside the atmosphere.

Table 5: Extraterrestrial solar radiation data input

Symptom	Value
n (day)	182
G_{sc}(W/ m^2)	1353
G_o(W/ m^2)	1312.52

- <u>Solar Radiation on Tilted surface:</u>

$I_T = I_b + I_d + I_r$ [33]
$I_b = I_{bn} \cos \theta$ [34]
$I_r = \rho I_h (\frac{1 - \cos \beta}{2})$ [35]
$I_d = I_{dh} (\frac{1 + \cos \beta}{2})$ [36]

<u>3.4.1 ASHRAE Clear Day Model:</u>

$I_{bn} = A\, e^{-\frac{B}{\cos \theta z}}$ [37]
$I_{dh} = C\, I_{bn}$ [38]

Table 1: ASHRAE Clear Day Model

MONTHS	A (W/ M2)	B	C
JAN	1230	0.142	0.058
FEB	1214	0.144	0.06
MAR	1185	0.156	0.071
APR	1135	0.18	0.097
MAY	1103	0.196	0.121
JUN	1088	0.205	0.134
JUL	1085	0.207	0.136
AUG	1107	0.201	0.122
SEP	1151	0.177	0.092
OCT	1192	0.16	0.073
NOV	1220	0.149	0.063
DEC	1233	0.142	0.057

Table 2: Solar radiation on tilted surface data output based on ASHRAE model

Symptom	Value
I_{bn} (W/ m^2)	496.73
I_{dh} in horizontal (W/ m^2)	67.56
I_h horizontal (W/ m^2)	199.16
I_r (W/ m^2)	11.79
I_t (W/ m^2)	136.67
I_b (W/ m^2)	77.32
I_d(W/ m^2)	47.56
COS θ z	0.265

- Day Length and Sunrise and Sunset Time:

Day Length:

$Td = \frac{2}{15} \cos^{-1} [-\tan \phi \tan\delta]$ [39]

$Td = \frac{2}{15} \cos^{-1} [-\tan (20) \tan (23.14)] = 13.19$ hr.

Sunrise Time:

trs = 12 – 0.5 * 13.19 = 5.40 = 5:24 hr. (solar time) [40]

Sunset Time:

tss = 12 + 0.5 * 13.19 = 18.59 = 18:35 hr. (solar time) [41]

Table 3: Day length, sunrise and sunset time output

Symptom	Value
T d (hr)	13.19
t_{rs} (hr)	5:24 (Solar time)
t_{ss} (hr)	18:35 (Solar time)

- Photovoltaic (PV) System Sizing

Power supply re-designing of the system depend on Reverse Osmosis Desalination Plant capacity and equipment rated power such as: feed water pumps, high pressure (HP) pump, energy recovery device, booster pump and other.

Table 4: Reverse Osmosis equipment specification

Equipment	Max. Pressure (bar)	Capacity (m3/ h)	Rated Power (kW)	Voltage (V)
3 * RO Feed Pump	9	133	45	460
3 * 1st Pass RO HP Pump	80	55.6	150	460
2 * Energy Recovery Device	82	76	0	460
2 * RO Booster Pump	83	76	18.5	460
3 * 2nd Pass RO HP Pump	15	56	45	460

III. RESULT AND DISCUSSION

This section presents following results obtained from mathematical modeling in case to evaluate solar photovoltaic collector efficiency with different solar time.

Table 9 explain about solar time, solar hour angle, solar radiation on tilted surface, efficiency and area of collector design for day No. 182 at power plant in western area of KSA.

Table 5: Solar radiation on tilted, efficiency and area of collector

Solar Time (hr)	ω (∘)	COS θz	It (W/m^2)	ηc	Ac (m^2)
5:24	-99.00	-0.01	$288 * 10^8$	0.54	0.00
6:24	-84.00	0.22	114.93	-0.19	-11.46
7:24	-69.00	0.44	194.30	0.11	12.02
8:24	-54.00	0.65	234.39	0.18	5.91
9:24	-39.00	0.81	258.68	0.22	4.51
10:24	-24.00	0.93	273.51	0.23	3.95
11:24	-9.00	1.00	280.92	0.24	3.71
12:24	6	1.00	281.59	0.24	3.69
13:24	21	0.95	275.55	0.24	3.88
14:24	36	0.84	262.30	0.22	4.36
15:24	51	0.68	240.20	0.19	5.50
16:24	66	0.49	204.23	0.13	9.56
17:24	81	0.27	136.67	-0.07	-24.65
18:24	96	0.04	0.72	-116.13	-3.01
18:35	98.75	-0.01	$373 * 10^{12}$	0.54	0.00

As shown in figure 3, **η**c has an improvement when solar time increase HPH in service by average of 2%.

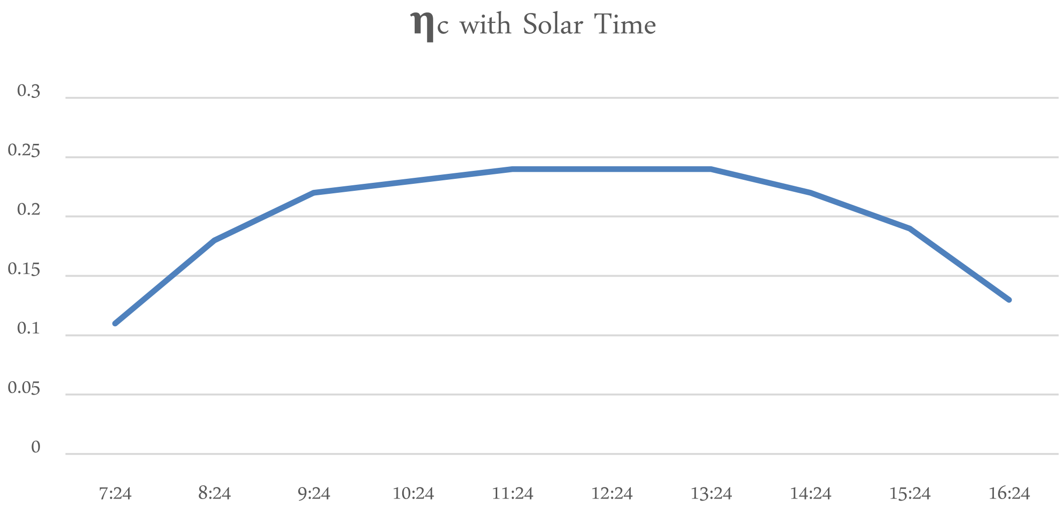

Fig.3: Collector efficiency ηc with Solar Time

The result of Power supply re-designing of the RO systemfrom plant auxiliary power consumption to self-feeding by solar photovoltaic system as following:
Daily RO system power required = [(3 * 45 kW) + (3 * 150 kW) + (2 * 18.5 kW) + (3 * 45 kW)] = 757 kWh.
Daily RO system power required = 757,000 Wh.
Average PV system output 400 Watt.

- Designing:

Solar photovoltaic system design dependent on RO plant daily power required
Load = Power required * Operating hours

No. Of PV panel = $\frac{\text{dailyload}}{(\text{operatinghou rs}\left(\frac{\text{hrs}}{\text{day}}\right)*\text{paneloutput})}$[42]

$= \frac{757{,}000 * 24}{11\left(\frac{\text{hrs}}{\text{day}}\right)* 400\ \left(\frac{\text{W}}{\text{panel}}\right)}$ = 4129.1 panels = 4130 panels.

Assume 13 hrs. Power storage battery, efficiency battery 75%, max. Depth 70%.

Storage = $\frac{18{,}168{,}000 * 0.5}{0.7*0.75}$ = 17,302,857.14 Wh.

No. Of Battery = $\frac{\text{Storage}}{\text{Ah} * \text{V}} = \frac{17{,}302{,}857.14}{208\ \text{Ah} * 6\ \text{V}}$ = 13,865 batteries (Rounded off to next whole number).

IV. CONCLUSION

This work paper presents a solar Photovoltaic Reverse Osmosis PVRO literature review and explain the RO process description which is actual gathering from local power plant in KSA.

Deferent parameter based on solar system designing were calculated such as; solar time, solar angles (θ, δ, ω, γ, β and ϕ), sunset solar time, sunset local time, extraterrestrial solar radiation (G_o) 1313.52 W/ m^2, solar radiation on tilted surface (I_{bn}, I_{dh}, I_h, I_r, I_t, I_b, I_d), the total solar radiation 136.67 W/ m^2, day length 13.19 hours, sunrise time 5:24 am and sunset time 18:35 pm. The solar PV collector efficiency and area were discussing in table 9 at the deferent time of same day.

Daily power required of RO plant is 757,000 Watt. Re-designing of power supply of Reverse Osmosis Desalination Plant from plant auxiliary power consumption to self-feeding by solar photovoltaic system. Design data sheet of RO plant major equipment (RO feed pump, energy recovery device, RO booster pump and RO high pressure pump) utilize as a data input. Solar photovoltaic system designed to generate 18 millions of Wh per day by 4,130 panels with 400-Watt capacity for each and 13,865 batteries to cover RO plant daily power required.

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