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https://doi.org/10.5109/9265

出版情報：九州大学大学院農学研究院紀要. 51 (2), pp.423-430, 2006-10-27. Faculty of Agriculture, Kyushu University
バージョン：
権利関係：

J. Fac. Agr., Kyushu Univ., **51** (2), 423–430 (2006)

Potential of Power Generation by Solar Batteries for Operating Irrigation Pumps in Ishigaki Island

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(*Received June 30, 2006 and accepted July 24, 2006*)

Electricity generated by solar batteries has many merits. Especially in a small island where there are not enough water resources, adequate and cheap electricity is prerequisite for agriculture. First, trials to estimate electricity generation by solar battery were conducted using the limited data on solar radiation energy. Second, operation times were estimated for various pumps placed in the pumping station in Ishigaki Island. It was clarified that there was a tendency that operation times calculated by estimated curves showed somewhat longer hours that of observed curves, for the smaller pumps. On the other hand, for the larger pumps, there was a tendency that operation times derived from observed curves exceeded the times derived from estimated curves. Third, a simulation was conducted for finding the suitable irrigation area supported by a self electricity generating system. It was concluded that a 15 kW pump was suitable as this was operated longer hours than other pumps and irrigated area slightly increased if rotation of irrigation was applied for the 200 kWp system. But for the 1000 kWp system, irrigated area increased effectively.

INTRODUCTION

Electricity is used for agriculture not only to deliver irrigation water but also to control valves, heater, cooler and so on. To lessen the expenses for electricity, it is required to develop new energy for supporting the farmers. Electricity generated by solar batteries has many merits. First, the solar energy resource is enormous. Second, electricity is generated by a solar battery which has no mechanical parts with noisy sound. Third, no substances are generated which pollutes the environment. Fourth, the power generation system can be controlled automatically. Fifth, the system can be placed in anywhere there is open area suitable for construction. Sixth, amount of electricity generation can be increased easily with installing additional modules. Seventh, price of modules will become cheaper by mass production. Eighth, not only direct solar radiation but also diffused radiation is effective for generating electricity. On the other hand, some demerits are existing. First, amount of generation is affected by climate conditions and season. Second, intensity of solar energy is 1.0 kW/m^2 in maximum. Third, the system to convert direct current to alternating current is necessary. Fourth, a buttery as an electricity pond is expensive. Fifth, the wide open space for constructing of the system is required if the facility become larger.

For supply to a pumping station, it is necessary to place the generation system close to the pumping station. If it is far from the pumping station, additional expenses are required to construct the deliver line for the generated electricity. If it is possible to connect with the lines of commercial electricity company, the system can be placed somewhat far from the pumping station.

In this study, some trials were conducted numerically for use of the electricity generated by solar batteries to operate the pumping station in Ishigaki Island.

MATERIALS AND METHODS

Estimating the diurnal change of solar radiation

In Ishigaki Island, weather station is providing daily solar radiation data which is prerequisite for evaluating electricity generation. It is required at least hourly changes of solar radiation as the solar radiation changes abruptly affected by the clouds, vapor and dust. In this study, following equation was used for calculating the hourly changes of solar radiation.

$$I_h = \pi \frac{Q}{2T_0} \cos\left(\pi \frac{T-12}{T_0}\right) \qquad (1)$$

where I_h is solar radiation for one hour (kWh/m^2), Q is daily total solar radiation (kWh/m^2), T_0 is potential length daytime of a day (hour), and T is arbitrary time of a day (solar hour).

Figure 1 shows the comparison between observed and calculated amount of diurnal changes of solar radiation on a fine day, cloudy day and rainy day. Though, the height of amplitude of calculated solar radiation was a little lower than the observation on a fine day August 28, estimation of diurnal change of solar radiation by eq.

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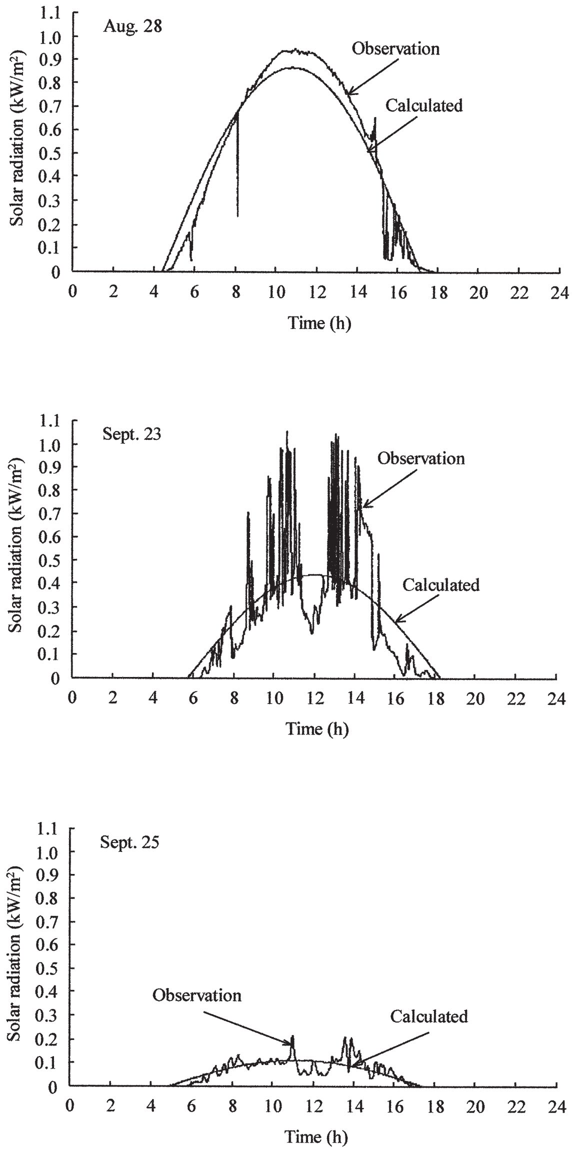


Fig. 1. Comparison of solar radiation between observation and calculation.

(1) was reasonable.

Estimation of electricity generation

The daily amount of electricity generation can be calculated using following equations.

$$P_a = QAK_tK_d \tag{2}$$

$$P = P_a P_d \eta \tag{3}$$

where, P_a is daily amount of electricity generation per unit module (kWh/kWp), A is parameter which indicates the area for peak electricity (=1.0 m²/kWp), K_t is coefficient of temperature adjustment (0.85), K_d is coefficient of direct current adjustment (0.85), P_d is capacity of solar electricity generation module (kWp) and η is average coefficient of inverter (0.85).

If the adequate values of coefficient in above equations are substituted, daily amount of electricity generated by the modular capacity of P_d (kWp) can be calculated as,

$$P = 0.85^3 QP_d \tag{4}$$

Then the amount of hourly electricity generation P_t (kWh) can be calculated as,

$$P_t = 0.85^3 P_d \pi \frac{Q}{2T_0} \cos\left(\pi \frac{T-12}{T_0}\right) \tag{5}$$

Estimation of operation duration

Operation duration of a specified pump can be estimated as shown in Figure 2. First, diurnal change of electricity generation is estimated with eq. (5). Second, the starting point (T_2) and ending point (T_1) of operation are estimated from the intersection of pump capacity line and electricity generation curve. Third, operation duration can be estimated by $T_d = T_1 - T_2$, as shown in Figure 2.

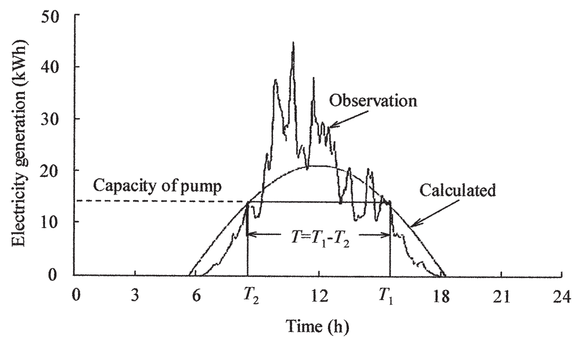


Fig. 2. Operation times of pumps, T_d.

If a capacity of a pump is assumed as P_p, starting point and ending point are derived with next equations.

$$T_1 = \frac{T_0}{\pi} \cos^{-1}\left(\frac{2T_0}{Q} \frac{P_p}{0.85^3 \pi P_d}\right) + 12 \tag{6}$$

$$T_2 = -\frac{T_0}{\pi} \cos^{-1}\left(\frac{2T_0}{Q} \frac{P_p}{0.85^3 \pi P_d}\right) + 12 \tag{7}$$

Subtracting eq. (7) from eq. (6), operation hours can be estimated as,

$$T_d = T_1 - T_2 = \frac{2T_0}{\pi} \cos^{-1}\left(\frac{2T_0}{Q} \frac{P_p}{0.85^3 \pi P_d}\right) \tag{8}$$

If actually observed curves are used, operation duration is limited to the times above the line of capacity of a pump. Referring to the Figure 2, actual operation time was considered as about 80% of the estimation.

Comparison between the actual and estimated operation duration times

The validity of estimated operation duration times were evaluated comparing the data derived from actual curve and estimated curve. The capacity of a pump was selected as 15 kW, 37 kW, 95 kW, 260 kW, 295 kW, 360 kW and 550 kW, considering the varieties in Ishigaki Island. Solar radiation data observed at every minute were used on the selected 9 days.

Operation duration times calculated from one pump

Table 1. Operation times of one pump system (unit: Hours)

Date	Weather	Capacity		Capacity of pumps						
				15 kW	37 kW	95 kW	260 kW	285 kW	360 kW	550 kW
Aug. 28	Clear	200 kWp	Obs.	11.56	9.84	3.86	0	0	0	0
			Cal.	10.35	8.95	4.85	0	0	0	0
		1000 kWp	Obs.	12.47	12.14	11.26	8.59	8.16	6.73	0.00
			Cal.	11.95	11.12	9.93	8.32	7.97	6.82	2.60
Aug. 29	Clear	200 kWp	Obs.	11.51	9.71	3.11	0	0	0	0
			Cal.	10.52	8.85	4.15	0	0	0	0
		1000 kWp	Obs.	12.46	12.12	11.19	8.40	7.93	6.40	0.00
			Cal.	12.13	11.38	9.97	8.03	7.80	6.48	1.65
Aug. 30	Clear	200 kWp	Obs.	11.38	9.35	0	0	0	0	0
			Cal.	10.38	8.20	3.05	0	0	0	0
		1000 kWp	Obs.	12.44	12.05	11.02	7.84	7.30	5.43	0.00
			Cal.	11.58	10.75	9.93	6.78	6.35	5.18	1.47
Setp. 23	Partly rainy	200 kWp	Obs.	10.46	6.70	0	0	0	0	0
			Cal.	8.57	4.97	0.85	0	0	0	0
		1000 kWp	Obs.	12.26	11.60	9.84	2.58	0	0	0
			Cal.	10.95	9.77	7.63	2.63	23.00	1.90	0.42
Setp. 24	Rainy	200 kWp	Obs.	0	0	0	0	0	0	0
			Cal.	2.50	0	0	0	0	0	0
		1000 kWp	Obs.	11.01	8.35	0	0	0	0	0
			Cal.	9.95	7.37	0.80	0	0	0	0
Setp. 25	Rainy	200 kWp	Obs.	0	0	0	0	0	0	0
			Cal.	1.37	0	0	0	0	0	0
		1000 kWp	Obs.	10.96	8.21	0	0	0	0	0
			Cal.	9.90	7.45	0.52	0	0	0	0
Setp. 26	Cloudy	200 kWp	Obs.	9.82	4.33	0	0	0	0	0
			Cal.	8.43	3.53	0.07	0	0	0	0
		1000 kWp	Obs.	12.14	11.30	9.00	0	0	0	0
			Cal.	10.98	9.47	7.40	1.75	1.53	0.90	0
Setp. 27	Clear	200 kWp	Obs.	11.26	9.03	0	0	0	0	0
			Cal.	10.80	10.30	8.95	6.98	6.60	5.07	0
		1000 kWp	Obs.	12.41	11.99	10.86	7.33	6.70	4.44	0
			Cal.	9.23	8.12	2.38	0	0	0	0
Setp. 28	Rainy	200 kWp	Obs.	6.50	0	0	0	0	0	0
			Cal.	4.85	0.40	0	0	0	0	0
		1000 kWp	Obs.	11.57	9.87	4.01	0	0	0	0
			Cal.	9.45	8.35	4.10	0	0	0	0

Obs.: Obsevation, Cal.: Calculated

system was listed in Table 1. Operation duration times calculated for two pumps system was listed in Table 2. Second pump was operated in addition to the first pump when there was some residual electricity.

There was a tendency that operation times calculated by estimated curves were somewhat longer than that by actual curves for pumps of smaller capacity. On the other hand, for larger pumps, there was a tendency that operation times derived from observed curves exceeded the operation times derived from estimated curves. Obviously the operation times of two pumps system increased doubly comparing to the one pump system for smaller pumps in the larger electricity generation module. In the smaller electricity generation module, the operation times did not increase even if two pumps system was adopted for larger pumps.

Study site

Ishigaki Island locates in latitude N24° 20" and in longitude E124° 10" and belongs to the subtropical oceanic climate area. Annual rainfall is 2,072 mm, average air temperature is 23.8°C and average relative humidity is 79%.

Main crop productions are sugar cane, pineapple, paddy rice and livestock. There is an irrigation reservoir into which water is mainly supplied by pumping from the lower river. Irrigation water is delivered through a pipe line system to the command area 2,310 ha. Thus electricity is prerequisite for pumping up and pressurizing water to deliver water first to many farm ponds and then to each field.

The price of electricity supplied by an electricity company to a pump station is 40% cheaper than the city use. Only 16 hours in a day during the night, however, is allowed to use. The pump station have 7 different types of pumps with capacity of 15 kW, 37 kW, 95 kW, 260 kW, 285 kW, 360 kW and 550 kW.

RESULTS AND DISCUSSION

Annual days of operating pumps

Two solar energy electricity generation systems different in P_d, i.e. 200 kWp and 1000 kWp, were considered to operate irrigation pumps in Ishigaki Island. Climatic

Table 2. Operation times of two pump system (unit: Hours)

Date	Weather	Capacity		Capacity of pumps						
				15 kW	37 kW	95 kW	260 kW	285 kW	360 kW	550 kW
Aug. 28	Clear	200 kWp	Obs.	21.96	16.37	3.86	0	0	0	0
			Cal.	19.80	15.57	4.85	0	0	0	0
		1000 kWp	Obs.	24.72	23.72	21.02	10.50	8.16	6.73	0.00
			Cal.	23.48	21.52	18.81	11.84	9.75	6.82	2.60
Aug. 29	Clear	200 kWp	Obs.	21.81	15.89	3.11	0	0	0	0
			Cal.	19.65	15.12	4.15	0	0	0	0
		1000 kWp	Obs.	24.69	23.64	20.82	8.40	7.93	6.40	0.00
			Cal.	23.70	21.90	18.77	10.81	7.80	6.48	1.65
Aug. 30	Clear	200 kWp	Obs.	21.39	14.49	0	0	0	0	0
			Cal.	19.08	13.13	3.03	0	0	0	0
		1000 kWp	Obs.	24.61	23.44	20.27	7.84	7.30	5.43	0.00
			Cal.	22.45	21.13	18.03	9.05	7.53	5.18	1.47
Setp. 23	Partly rainy	200 kWp	Obs.	18.47	6.70	0	0	0	0	0
			Cal.	14.80	6.79	0.85	0	0	0	0
		1000 kWp	Obs.	24.07	22.09	16.34	2.58	0	0	0
			Cal.	20.93	18.40	2.41	3.26	2.65	1.90	0.42
Setp. 24	Rainy	200 kWp	Obs.	0	0	0	0	0	0	0
			Cal.	2.50	0	0	0	0	0	0
		1000 kWp	Obs.	20.24	8.35	0	0	0	0	0
			Cal.	18.63	9.95	0.80	0	0	0	0
Setp. 25	Rainy	200 kWp	Obs.	0	0	0	0	0	0	0
			Cal.	1.37	0	0	0	0	0	0
		1000 kWp	Obs.	20.09	8.21	0	0	0	0	0
			Cal.	18.65	9.03	0.52	0	0	0	0
Setp. 26	Cloudy	200 kWp	Obs.	16.28	4.33	0	0	0	0	0
			Cal.	13.16	4.36	0.07	0	0	0	0
		1000 kWp	Obs.	23.70	21.16	12.95	0	0	0	0
			Cal.	20.91	18.00	10.83	1.78	1.53	0	0
Setp. 27	Clear	200 kWp	Obs.	21.02	13.08	0	0	0	0	0
			Cal.	17.71	13.09	2.38	0	0	0	0
		1000 kWp	Obs.	24.54	23.26	19.79	7.33	0	0	0
			Cal.	21.18	19.63	16.97	7.15	6.60	5.07	0
Setp. 28	Rainy	200 kWp	Obs.	6.50	0	0	0	0	0	0
			Cal.	5.98	0.40	0	0	0	0	0
		1000 kWp	Obs.	22.00	16.47	4.01	0	0	0	0
			Cal.	18.02	13.35	4.37	0	0	0	0

Obs.: Obsevation, Cal.: Calculated

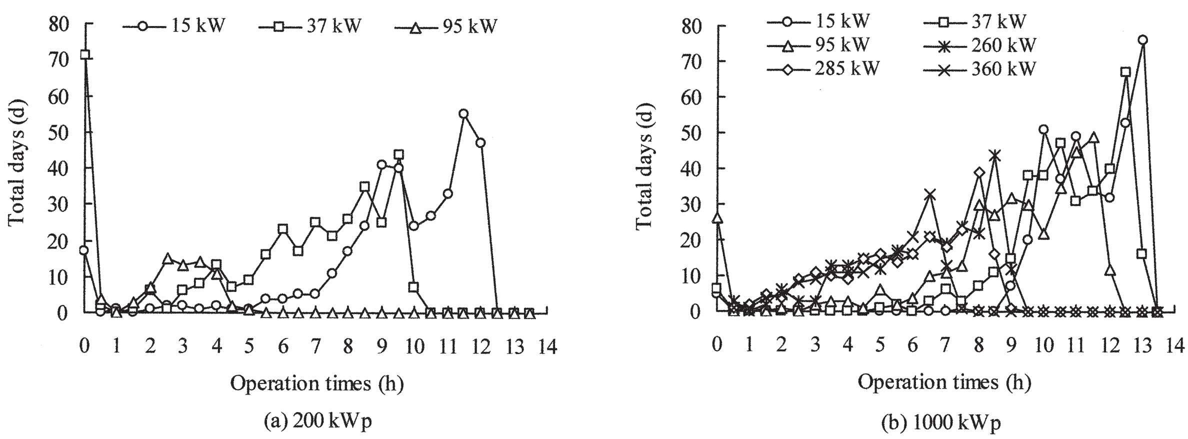
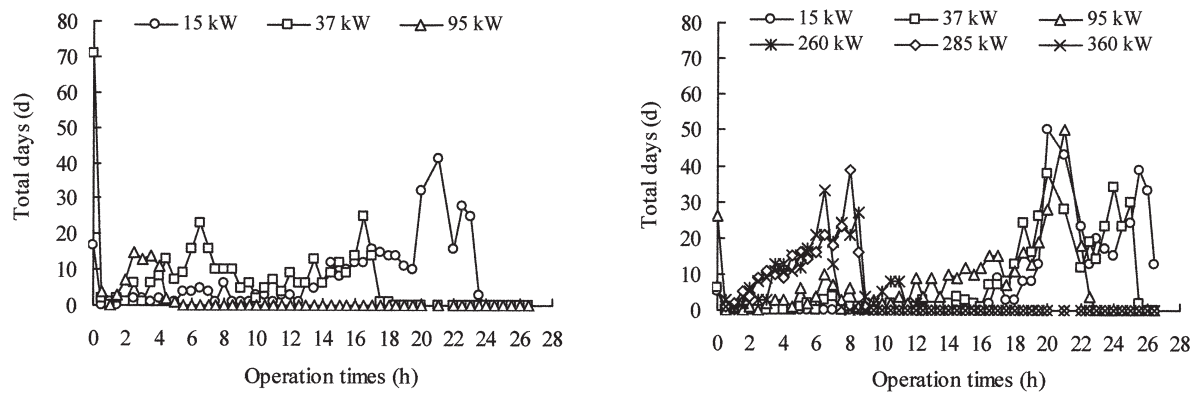


Fig. 3. Annual total days of operation times for pumps (One pump system).

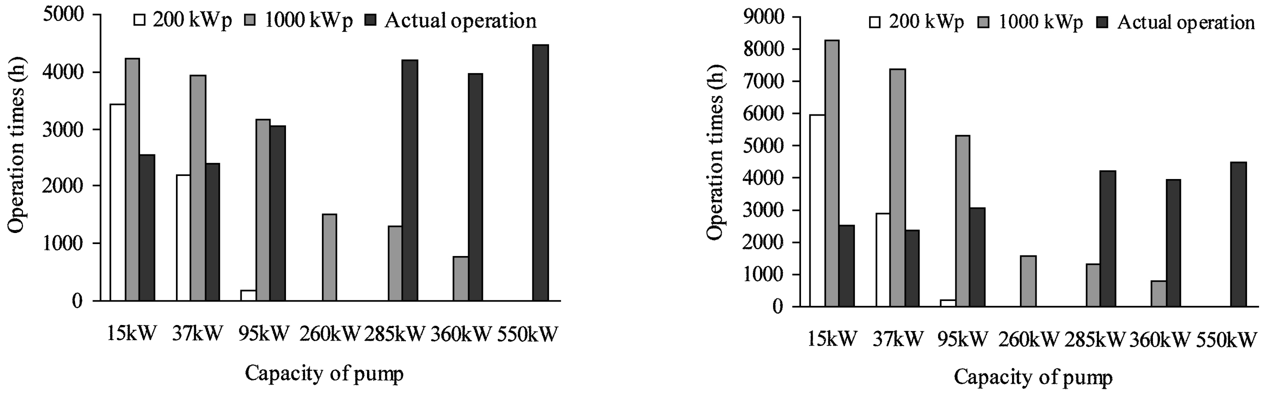
conditions were referred to the data in 1969 which was used for designing the irrigation project in this area. Figures 3 and 4 show the annual days for daily operation times of each pump capacity in one pump system and two pumps system, respectively.

In the 200 kWp solar battery systems, pumps of 15 kW and 37 kW pump capacity were operated frequently. For a 15 kW pump, annual total days of operation times of 11.5 hours was 55 days (Fig. 3a), and for two 15 kW pumps, operation times of 20.5 hours was 44



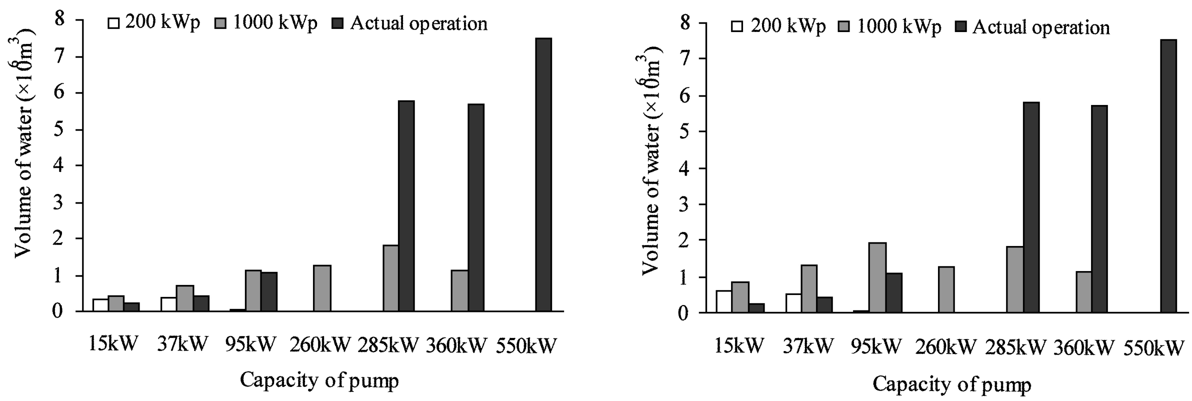
(a) 200 kWp (b) 1000 kWp

Fig. 4. Annual total days of operation times for pumps (Two pumps system).



(a) One pump (b) Two pumps

Fig. 5. Annual operation times of pumps.



(a) One pump (b) Two pumps

Fig. 6. Annual volume of pumped up water.

days (Fig. 4a). On the other hand, pumps whose capacity was larger than 95 kW were not operated in this solar battery system.

In the 1000 kWp solar battery systems, most pumps except for a 550 kW pump were operated as shown in Figures 3b and 4b. Annual days of operation times of 8 hours was 40 days for one 285 kW pump, and that of operation times of 6.5 hours was 33 days for one 360 kW pump. When two pumps were used, larger than 95 kW pumps did not show the activation.

Comparison of actual and estimated operation times

Average annual operation hours of each pump was calculated using 11 years data, 1969 and form 1979 to 1988, for the 200 kWp and 1000 kWp solar battery systems. The annual operation hours for one pump system and two pumps system were shown in Figures 5a and

5b, respectively. As actual pumps were operated only one set, 1000 kWh is enough to operate 95 kW pump, but larger than this pumps need supplemental electricity to enough operation.

Comparison of actual and estimated of pump up water

Average annual amount of pumped up water for 11 years is shown in Figure 6. If a 1000 kWp solar battery was used, amount of water pumped up by pumps whose capacity was smaller than 95 kW were completely satisfied. To cover the water pumped up by 285 kW pump, it is necessary to prepare over 3000 kWp system. Economically, it is recommendable to set a 1000 kWp battery for operating with self supplying electricity for the smaller pump system. For pumps whose capacity was lager than 260 kW, it would be better to supply commercial electricity in addition to the electricity generated by solar batteries.

Potential irrigation area by self generated electricity

Water consumption

Potential water consumption of crop field was estimated by the Penman method expressed as following equation.

$$ET_p = \left(\frac{\Delta}{\Delta+\gamma}\right)(R_n+G) + \left(\frac{\gamma}{\Delta+\gamma}\right)15.36(1.0+0.0062u_{200})(e_z^{\ 0} - e_z) \quad (9)$$

where, ET_p is potential evapotranspiration (J/cm^2/day), Δ is slope of saturation vapor pressure vs. temperature, γ is psychometric constant, R_n is net radiation (J/cm^2/day), G is soil hear flux (J/cm^2/day), u_{200}: is wind speed at the height of 200 cm (km/day), $e_z^{\ 0}$: is saturated vapor pressure at air temperature (mb) and e_z is vapor pressure of air (mb).

Daily data for 11 years provided by weather station in Ishigaki Island were used for the calculation. As the wind speed sensor was placed at 22 m above ground level, conversion to the 200 cm above ground level was conducted by using the following equation.

$$u(Z) = \frac{u_*}{k}\ln\left[\frac{(Z-d)}{Z_0}\right] \quad (10)$$

where, Z is height of wind speed sensor, d is enhanced ground level ($=0.63\ H$, H: crop height), Z_0 is roughness length ($=0.13$H), u_* is friction velocity and k is Von Karman constant.

Actual evapotranspiration was calculated with following equation.

$$ET = k_c ET_p \quad (11)$$

where ET is actual evapotranspiration and k_c is crop coefficient. Crop coefficient of sugarcane ranges from 0.8 to 0.9 depending on the growth stage.

Potential irrigation area

For estimating the potential irrigation area, area of field supported by pumps was simulated using 11 years meteorological data in 1968 and from 1979 to 1988. There was an assumption that electricity of all pumps was supplied by the 200 kWp or 1000 kWp solar battery system. Total readily available soil moisture (TRAM) was specified as 8.75 mm referring to the field observation. Irrigation was conducted when soil moisture become less than TRAM. Input water in the field was composed of rainfall and irrigation, and output water was composed of evapotranspiration and infiltration into the deep soil. In the case of rotation of irrigation, two blocks were assumed.

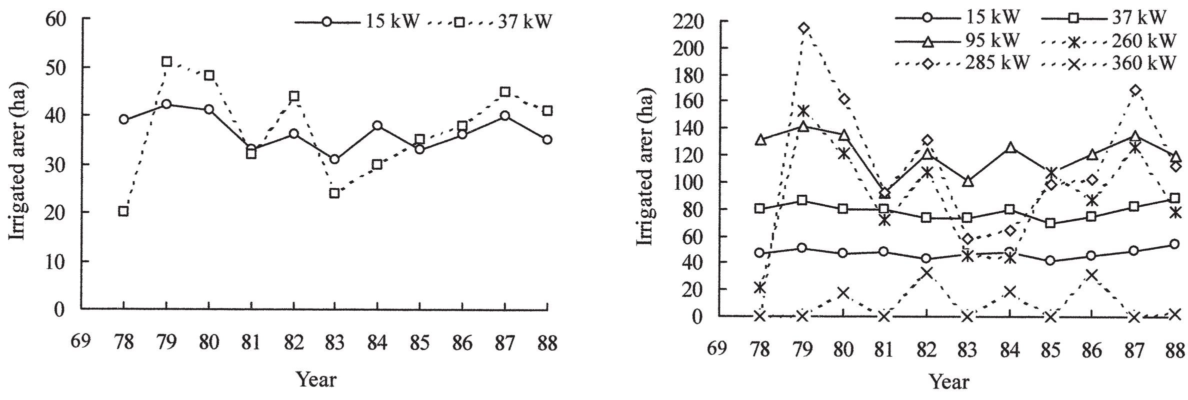
Some cases were considered as follows.

Case 1: One pump system. [Fig. 7 (1)]

Case 2: One pump system with rotation block composed of two blocks. [Fig. 7 (2)]

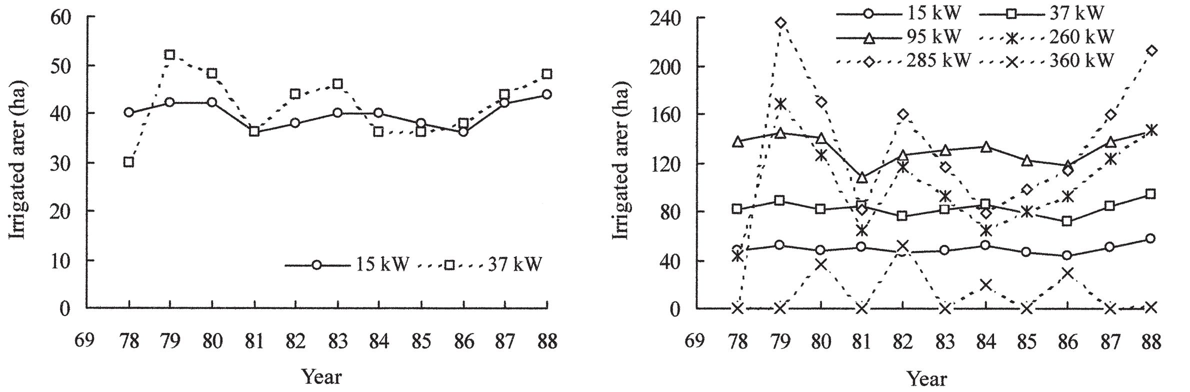
Case 3: Two pumps system. [Fig. 7 (3)]

Case 4: Two pumps system with rotation block composed of two blocks. [Fig. 7 (4)]



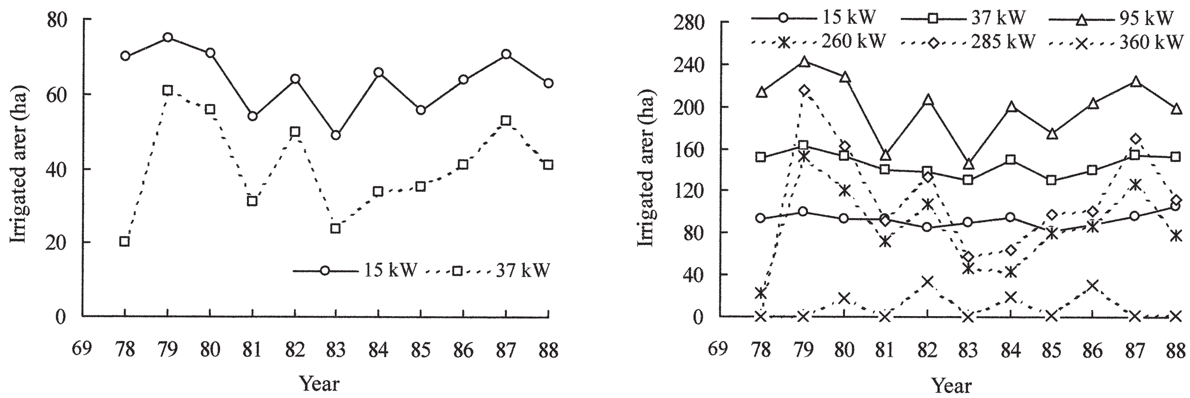
(a) 200 kWp (b) 1000 kWp

(1) Case 1: One pump system, no rotation of irrigation.



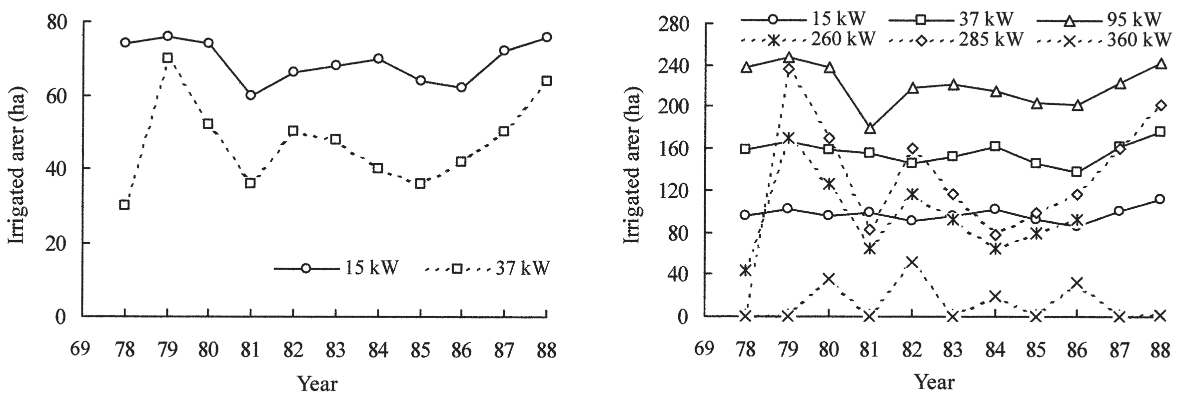
(a) 200 kWp (b) 1000 kWp

(2) Case 2: One pump system, rotation of irrigation.



(a) 200 kWp (b) 1000 kWp

(3) Case 3: Two pumps system, no rotation of irrigation.



(a) 200 kWp (b) 1000 kWp

(4) Case 4: Two pumps system, rotation of irrigation.

Fig. 7. Potential irrigation area supported by electricity generation system with solar battery.

In Case 1 with a 200 kWp solar battery, more than 30 ha field were irrigated every year by a 15 kW pump. A 15 kW pump was proper for this case as it was operated longer than other pumps as shown in Figure 5. In the Case 1 with a 1000 kWp solar battery, constant area of field was irrigated by pumps of 15 and 37 kW capacity.

In Case 2 with a 200 kWp battery, about 40 ha field were irrigated every year by a 15 kW pump and about 42 ha field were irrigated every year by a 37 kW pump. In the Case 2 with a 1000 kWp solar battery, about 130 ha were irrigated every year constantly with a 95 kW pump.

In Case 3 with a 200 kWp battery, about 60 ha field were irrigated every year by two 15 kW pumps. The use of 35 kW pumps, however, did not show the effect on the increasing the area. In the Case 2 with a 1000 kWp battery, about 150 ha were irrigated every year constantly with two 37 kW pumps.

In Case 4 with a 200 kWp battery, about 70 and 50 ha field were irrigated every year in the 15 kW and 37 kW pump systems, respectively. The 15 kW pump was proper as this was operated longer hours than others. In the Case 4 with a 1000 kWp battery, about 220 ha were irrigated every year constantly with two 95 kW pumps.

CONCLUSIONS

There was a tendency that operation times of pumps calculated by estimated curves of solar radiation was somewhat longer than that calculated by observed curves for pumps of smaller capacity. On the other hand, for larger pumps, there was a tendency that operation times derived from observed curves exceeded the operation times derived from estimated curves. Obviously the operation times of two pumps system increased doubly comparing to the one pump system for smaller pumps with a larger electricity generation module. In the smaller electricity generation module, the operation times did not increase even if two pumps system was adopted for larger pumps. Irrigation area was slightly increased by applying rotation of irrigation.

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