EU PVSEC 2015
Conference 14 – 18 Sep 2015
Exhibition 15 – 17 Sep 2015
European PV Solar Energy Conference and Exhibition
CCH Congress Centre Hamburg • Hamburg • Germany

USE OF SOLAR PV ENERGY TO REPLACE NUCLEAR POWER IN TAIWAN

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ABSTRACT:

The present study shows that performing energy saving retrofit in air conditioning (A/C) and lighting then utilizing solar PV energy to supply the remaining load demand in grid can reach non-nuclear goal in Taiwan. An office was chosen as the demonstration site (D-1). Four energy-saving retrofits on air conditioning and lighting results in 65% energy saving. A 6 kWp solar PV system for self-consumption and without feeding energy back to grid is further installed to replace additional 20% energy to reach 85% total energy saving. The total investment for solar PV system and energy-saving retrofit is USD30,000. The net total energy saving in 20 years is USD80,000, including M&O cost.

If energy-saving in air conditioning and lighting can reach 60% as D-1 did in the whole country, the nuclear power (18% electricity) can be abandomed. Several scenarios to reach non-nuclear goal are proposed. The energy storage for each 3 kWp PV unit is estimated around 4-6 kWh. Heat storage can be utilized to reduce cost dramatically as it is 10 times cheaper than battery.

Keywords: PV System, Solar Home System, Hybrid PV

1 INTRODUCTION

Since Taiwan is located in subtropical area, there is a peak load around 13:00 during summer around 34GW. From a long-term study, the power consumption of air conditoning contributes about 9 GW. Energy saving of air conditioning systems is thus most important.

Taiwan Government has set up a energy-efficiency classification for all air conditioners since 2010. Five categories are defined according to the energy efficiency ratio (EER) (W/W) and cooling capacity. See Table 1. However, EER of majority of air conditioners in the market or ever installed is below 3.5 (Category 3~5) . In 2010, 70% of air conditoners belongs to Category 5. Large potential of energy saving is feasible since the EER of the most advanced air conditioner in the market is higher than 5.6.

Table 1: Category of air conditioners

Brand	Cooling capacity, kW	EER (W/W)				
Category		5	4	3	2	1
Integral-type	<2.2	<2.95	2.95~3.1	3.1~3.25	3.25~3.4	>3.4
	2.2~4.0					
	4.0~7.1					
	7.1~10					
Split-type	<4.0	<3.45	3.45~3.69	3.69~3.93	3.93~4.17	>4.17
	4.0~7.1	<3.2	3.2~3.42	3.42~3.65	3.65~3.87	>3.87
	>7.1	<3.15	3.15~3.37	3.37~3.59	3.59~3.81	>3.81

Besides, lighting consumes about 10~15% energy in Taiwan. It is known that LED (light-emitting-diode) can save more than 50% lighting energy. Thus, lighting energy saving using LED is also feasible.

The cost of solar PV energy is reduced dramatically recently to bring the grid-parity age to come. Energy from solar PV is equal or cheaper than from the grid.

High-efficiency air conditioning, LED lighting, and low-cost solar PV are all technically mature and available in the market for energy saving.

The purpose of the present work is to demonstrate that, the utilization of solar PV energy in buildings for peak shaving, associated with energy-saving retrofit, can solve the energy shortage problem when nuclear power is abandoned in Taiwan (Figure 1).

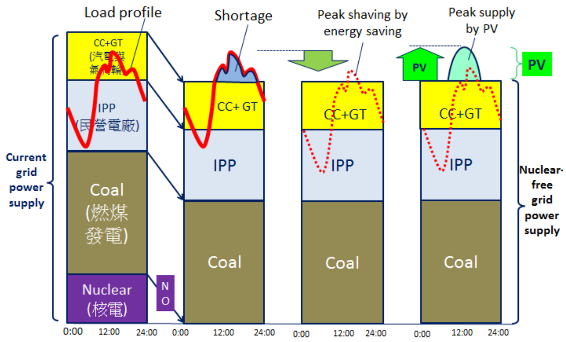

Figure 1: Schematic diagram showing peak saving by energy saving and peak supply by PV to abandom nuclear power.

2 ENERGY-SAVING RETROFIT OF OFFICE

2.1 Energy consumption before energy-saving retrofit

The office of the Department of Mechanical Engineering, National Taiwan University, with 150m^2 floor area and occupied by 15 employees, was chosen as the demonstration site (D-1). The major energy consumption of the office comes from air conditoning, lighting, and PC. The power and daily energy consumption of air conditioners, lighting, and laptop PC was calculated and listed in Table 2. It is seen that the total power consumption for air conditioners, lighting, and PC reaches 10.16 kW and the daily total energy consumption reaches 81.3 kWh. 64% energy is consumed by air conditioners.

2.2 Energy-saving retrofit and energy consumption

To reduce energy consumption, four retrofitting was carried out: (1)air conditioning system is renewed with high-efficiency split-type air conditioner (Hitachi RAC-22NB) with COP 5.6; (2)lighting is retrofitted with LED luminaire with 100 Lm/W; (3)all lap-top computers are changed into notebook PC; (4)the window glass is covered with low-E film to block IR part of solar radiation penetrating into the office. The above four retrofits results in 65% energy saving as shown in Table 3, at average power 3.6 kW and daily energy consumption 28.6 kWh/day.

Table 2: Energy consumption before retrofit.

Daily consumption @8 h/day			
Equipment		Power input, kW	Daily energy, kWh/day
I. Air conditioning			
Room 1:	One split-type MW3299 BFR: cooling 7.3kW with power input 2.5kW, COP 2.92	2.5	20
	One window-type : cooling 5.8 kW win power input 2.0 kW, COP 2.9	2	16
Room 2:	One window-type MW550BR: cooling 5.8kW, power input 2kW, COP 2.9.	2	16
Energy consumption		6.5	52
Estimated cooling load, kW		18.9	
II. Lighting			
Room 1:	Recessed fluorescent (47W) 26 sets	1.222	9.8
Room 2:	Recessed fluorescent (47W) 4 sets	0.188	1.5
Energy consumption		1.41	11.3
III. PC			
Room 1:	13 laptop PC, 150W each	1.95	15.6
Room 2:	2 laptop PC, 150W each	0.3	2.4
Energy consumption		2.25	18
Total energy consumption (air conditioners, lighting, PC)		10.16	81.3

3 SOLAR PV SYSTEM INSTALLATION

A 6 kWp solar PV system is installed to replace additional 20% energy. That is, 85% energy is saved in total.

The solar PV system is an isolated-type hybrid solar PV system (HyPV) which operates under Stand-alone PV Mode or Grid Mode, automatically (Figure 2). No solar PV energy is fed back to grid. When solar power generation and battery storage is sufficient, it operates under Stand-alone PV Mode and the load is powered completely by solar energy. When solar power generation and battery storage is not sufficient, it will switch to Grid Mode and the load is powered completely by grid. The intelligent controller (MCU) performs optimal switching between Stand-alone PV Mode and Grid Mode to reduce cycling. The microprocessor- based MCU also carries out solar charging and system protection control, etc.

The HyPV utilizes nMPPO (near maximum-power-point operation) system design [1] to eliminate the conventional MPPT (maximum-power-point tracking control) but still keep optimal performance. This reduces MPPT energy loss and cost and increases the reliability. The HyPV also utilizes direct PV charging control technique for battery to avoid energy loss and malfunction of conventional charger. This reduces cost and increases reliability.

Table 3: Enegy consumption before and after energy-saving retrofit.

Before energy-saving retrofit				**After energy-saving retrofit**			Energy saving
Old equipment		Power input, kW	Daily energy, kWh/day	New equipment	Power input, kW	Daily energy, kWh/day	
(1)Air conditioner							
Room 1:	One split-type MW3299 BFR: cooling 7.3kW, COP 2.92	2.5	20	Five Hitachi split-type RAC 22NB: cooling 2.2kW ea, COP 5.6	2	16	20%
	One window-type : cooling 5.8 kW, COP 2.9	2	16				
Room 2:	One window-type MW550BR: cooling 5.8kW, COP 2.9	2	16	One Hitachi split-type RAC22NB: cooling 2.2kW ea, COP 5.6	0.4	3.2	80%
	Energy consumption	**6.5**	**52**		**4.4**	**19.2**	**63%**
(2)Lighting							
Room 1:	Recessed T8 fluorescent (47W) 26 sets	1.222	9.8	Recessed T8 LED (30W): 20 sets	0.6	4.8	51%
Room 2:	Recessed T8 fluorescent (47W) 4 sets	0.188	1.5	Recessed T8 LED (30W): 4 sets	0.12	0.96	36%
	Energy consumption	**1.41**	**11.3**		**0.72**	**5.76**	**49%**
(3)PC							
Room 1:	13 laptop PC, 150W each	1.95	15.6	13 NB, 30W each	0.39	3.12	80%
Room 2:	2 laptop PC, 150W each	0.3	2.4	2 NB, 30W each	0.06	0.48	80%
	Energy consumption	**2.25**	**18**		**0.45**	**3.6**	**80%**
Total energy consumption (air conditioners, lighting, PC)		**10.16**	**81.3**		**3.57**	**28.6**	**65%**

Based on running time 8 h/day

The design of solar PV system is shwon in Table 4. To increase power generation, 1A-3P (one-axis 3-position) sun tracker is used to mount PV panels. The energy generation will be increased by 25% in Taipei [2]. The solar PV system is divided into two 2.94 kWp subsystems. Subsystem No.1 supplies 4 air conditioners (220VAC). Subsystem No.2 supplies power to drive 2 air conditioners (220VAC) and LED lighting and PC's (110VAC) (Figure 3). The installation is as shown in Figure 4 and 5.

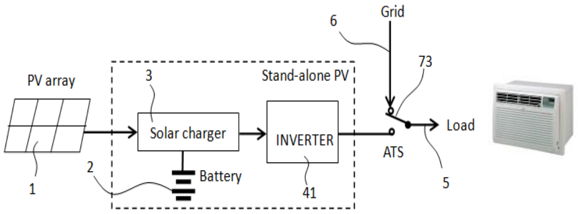

Figure 2: Hybrid solar PV system (HyPV).

The design of 5.88 kWp solar PV system is shwon in Table 4. To increase power generation, 1A-3P (one-axis 3-position) sun tracker is used to mount PV panels. The energy generation will be increased by 25% in Taipei [2]. The solar PV system is divided into two 2.94 kWp subsystems. No.1 supplies 4 air conditioners (220VAC). No.2 supplies power to drive 2 air conditioners (220VAC) and LED lighting and PC's (110VAC) (Figure 3). The installation is as shown in Figure 4 and 5.

Table 4: PV system design.

Solar PV system:	
(1)energy generation capability, kWh/kWp-yr	900
(2)PV installed capacity, kWp	5.88
(3)system loss	10%
(4)power enhancement by 1A-3P	1.25
(5)average daily generation, kWh/day	16.31
(6)highest daily generation, kWh/day	24.47
(7)lowest daily generation, kWh/day	2.35
(8)max load, kWh/day	28.6
Battery storage:	
(1) Li-battery capacity, kWh	2.88
(2) running time at full load, hr	0.8
(3) running time for A/C, hr	1.2
(4) running time for lighting, hr	4.0

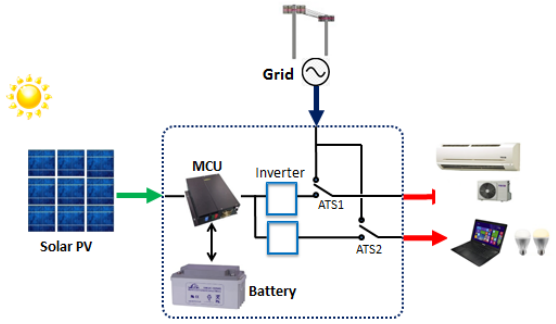

Figure 3: HyPV system (No.2) with 220/110V output.


Figure 4: HyPV system (No.2) output.

4 ECONOMIC FEASIBILITY

The economic analysis (Table 5) shows that the total energy saving through retrofit and PV installation reaches 85% in Taipei (poor solar area) and 96% in Tainan (rich solar area). This indicates that the present demonstration system (D-1) can approach zero-energy office if installed in a solar rich area. The payback time is 8 yr in Taipei and 7.5 yr in Tainan.

Table 5: Economic analysis.

Office hour: 8 h/d, 22 d/mon 1 USD = 32NT		Before retrofit		After retrofit (Taipei)			After retrofit (Tainan)		
		Load power (kW)	Daily load (kWh/day)	Load power (kW)	Daily load (kWh/day)	Reduction	Load power (kW)	Daily load (kWh/day)	Reduction
Total consumption (A/C, LED, NB)		10.16	81.3	3.57	28.6	65%	3.57	28.6	65%
Energy-saving (A)	Grid power (kWh/mon)	1,788		628		65%	628		65%
	Unit price (NT/kWh)	5.78		4.7			4.7		
	Monthly bill (NT/mon)	10,338		2,953		71%	2,953		71%
PV supply (B)	PV generation (kWh/mon)	-		359			560		
(A)+(B)	Grid power (kWh/mon)	1,788		269		85%	69		96%
	Unit price (NT/kWh)	5.78		3.27			3.27		
	Monthly bill (NT/mon)	10,338		881		91%	224		98%
	Monthly energy saving (kWh/mon)	-		1,519		85%	1,720		96%
	Monthly bill reduction (NT/mon)	-		9,457		91%	10,114		98%
	20-yr total saving (NT)			2,269,633			2,427,339		
	Initial investment (NT)			906,400			906,400		
	Yearly return on investment (%/yr)			7.52			8.39		
	Payback time (yr)			8.0			7.5		

5. SYSTEM PERFORMANCE RESULTS

The installation of HyPV system including measuring system was completed in July 2014. The performance was monitored continuously from August, 2014.


Figure 5: Chassis of HyPV for MCU, inverter and battery etc.

For collecting field data, the demonstration system (D-1) was installed in Taipei and completed in July, 2014. Figure 6 shows the 5-month operation for No.1 unit which is used to supply 4 air conditioners. According to statistical data from the government monitoring network around Taiwan, the daily PV energy generation per unit PV installation is 2.47 kWh/kWp per day (900 kWh/kWp-yr). Figure 7 shows that the 5-month performance of No.1 obtains 2.17 kWh/kWp per day in average which is 12% lower than the statistical data. This is due to low load energy consumption in fall season while air conditioner is not used.

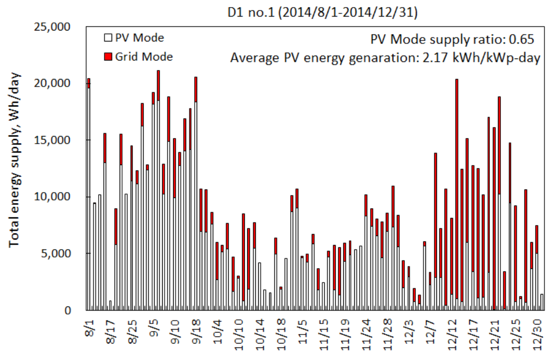

Figure 6: Long-term performance in No.1 unit.

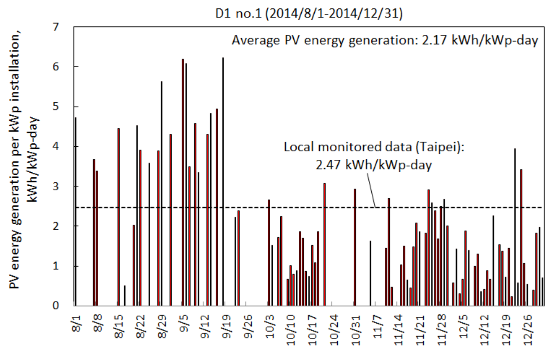

Figure 7: PV generation per kWp installed in No.1 unit.

The daily total energy supply (PV-Mode and Grid-Mode) of No.2 unit is shown in Figure 8. It reaches 2.67 kWh/kWp per day, 8.1% higher than the statistical result. This is due to the fact that the load energy of LED lighting and NB is supplied by No.2 unit which is not changed all year round.

Table 6 is the long-term results in PV energy generation and solar fraction. It shows that the PV energy generation per PV installed reaches 2.42 kWh/kWp per day, approaching the statistical result (2.47). This means that no PV energy generation loss for the whole D-1 system, even it is operated only in weekdays and at low load condition in fall season.

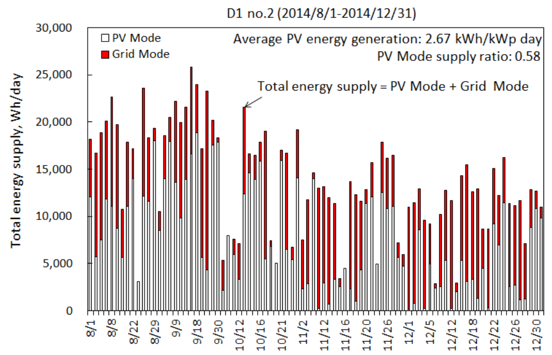

Figure 8: Long-term performance of No.2 unit.

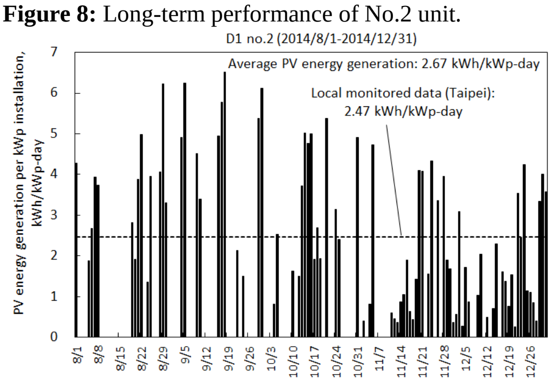

Figure 9: PV generation per kWp installed in No.2 unit.

Table 6: Total performance of D-1 system in 2014.

D-1	No.1 PV generation per kWp installation, kWh/kWp-day	No.1 Solar fraction	No.2 PV generation per kWp installation, kWh/kWp-day	No.2 Solar fraction	No.1 PV generation loss, %	No.1+No.2 PV generation per kWp installation, kWh/kWp-day	No.1+No.2 Solar fraction
2014/8	3.71	0.88	3.5	0.61	-	3.61	0.745
2014/9	4.4	0.87	4.67	0.68	8.6	4.54	0.775
2014/10	1.59	0.75	3.7	0.7	52.7	2.65	0.725
2014/11	1.77	0.73	2.15	0.48	17.7	1.96	0.605
2014/12	1.21	0.29	1.95	0.4	33.3	1.58	0.345
Average	2.17	0.65	2.67	0.58	18.8	2.42	0.615

Figure 10 shows that the 7-month total energy supply (load) of D-1 in 2015 is lower than the estimation (28.6 kWh/day), except in summer. The PV-Mode supply ratio is 0.75. The load demand in March is quite low which increases the PV generation loss. However, the PV energy generation reaches 20.94 kWh/day in summer (June and July), 28% higher than average prediction. Figure 11.

The design of D-1 system is based on the concept of PV energy for self-consumption and small battery storage to reduce cost. The battery is used as a buffer to stabilize the instantaneous load only. The long-term test results for a year shows that the PV energy generation loss is low.

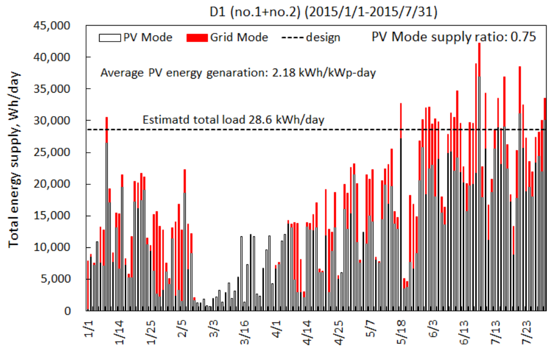

Figure 10: Total energy supply (load) of D-1 in 2015.

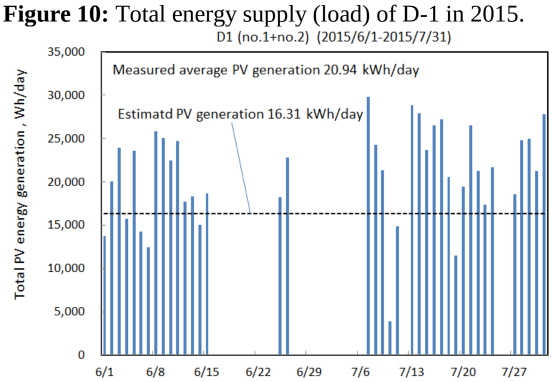

Figure 11: Overall performance of D-1 in 2015.

6 REPLACING NUCLEAR POWER BY ENERGY-SAVING AND SOLAR PV INSTALLATION

6.1 Peak shaving by E-saving and PV installation

The above demonstration project of D-1 System has shown that a great energy reduction, over 85%, can be achieved from energy-saving retrofit (65%) and PV installation (20%). The technology is mature and all the hardware supply is ready in market.

The grid load-time distribution curve of Figure 12 shows that about half nuclear power (2.5 GW) is used to supply the peak-load demand (34.5GW in 2015) for about 120 hours per year, or 1.5 h/d in summer.

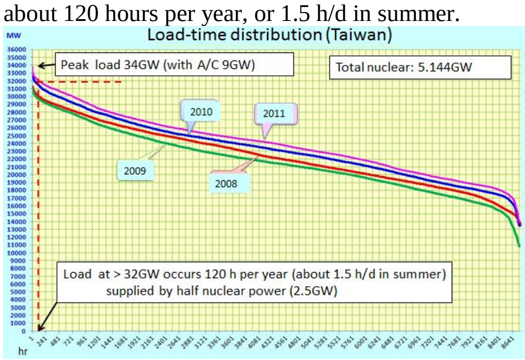

Figure 12. Grid load-time distribution curve.

As is known that air conditioning consumes about 9 GW power during peak hour. Conservatively, about 20~50% energy of A/C and lighting can be saved, that is, 1.8~4.5 GW (i.e. 35~87% of the total nuclear power installed capacity 5.144GW). The analysis shows that shows that the time to achieve the non-nuclear goal is 6.1 years with 30.3% energy saving target of air conditioning and lighting and 3.03GWp PV installation. See Figure 11 This scenario is based on the PV installation rate 500MWp/y which is the present condition and the A/C energy saving is at a rate 0.45GW(5%) per year which is achievable from the demonstration system D-1. The actual average PV generation in Taiwan is 1,250 kWh/y per kWp installation.

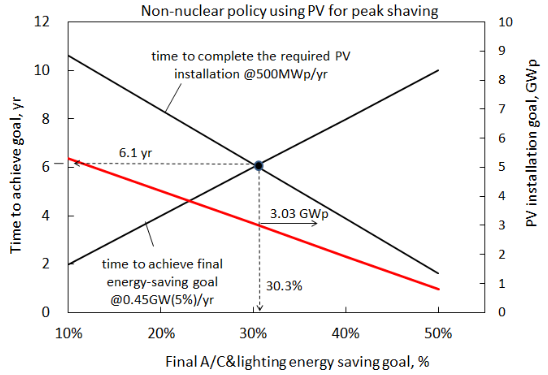

Figure 13. Time to achieve peak shaving by E-saving and PV installation.

Table 7 shows that increasing annual PV installation will decrease the required E-saving target and PV installation, and the time to reach the non-nuclear target.

Table 7: Time to reach goal, at 0.45GW(5%)/y E-saving

Annual PV installation, r_{pvo}, GWp/y	Energy-saving target e_{so}, %	Time, yr	Target PV installation, P_{vinsto}, GWp
0.5	0.303	6.1	3.03
0.75	0.245	4.9	3.67
1	0.206	4.1	4.12
1.5	0.156	3.1	4.68

6.2 PV supply for base load

It is quite controversial about the feasibility to use PV to replace the base-load power by nuclear plant, since solar PV energy is not stable and not evenly distributed in a day. However, this can be overcome through energy storage. An analysis based on the yearly energy balance of the national grid can be used to find out a feasible non-nuclear policy. Figure 14 shows that time to achieve base-load replacement by E-saving and PV installation alone is 11.5 and 8 years for PV installation rate 500 and 1,500MWp/y, respectively. The A/C and lighting energy saving target is 58% and 43% with PV installation 6 and 12 GWp, respectively.

If wind energy is added, time to achieve base-load replacement by E-saving and PV and wind installation is 9 and 7 years for PV installation rate 500 and 1,500MWp/y, respectively. The wind power installation is set at 2.6GW, half of government target 5.2GW by 2030. The A/C and lighting energy saving target is 49% and 37% with PV installation 4 and 10 GWp, respectively. See Figure 15.

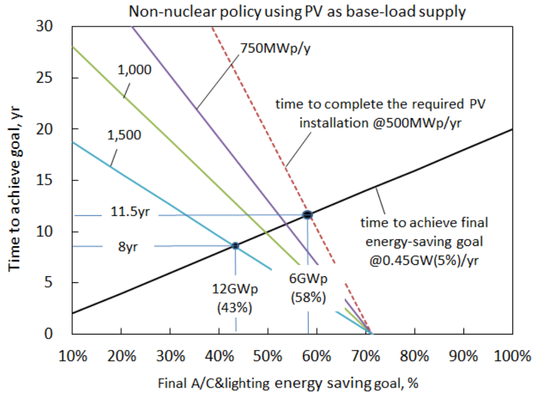

Figure 14. Time to achieve base-load replacement by E-saving and PV installation.

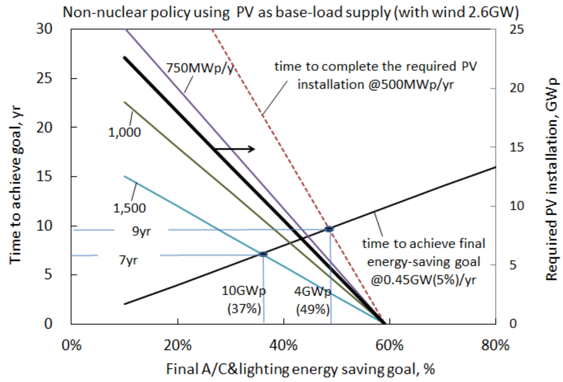

Figure 15. Time to achieve base-load replacement by E-saving and PV installation with wind energy.

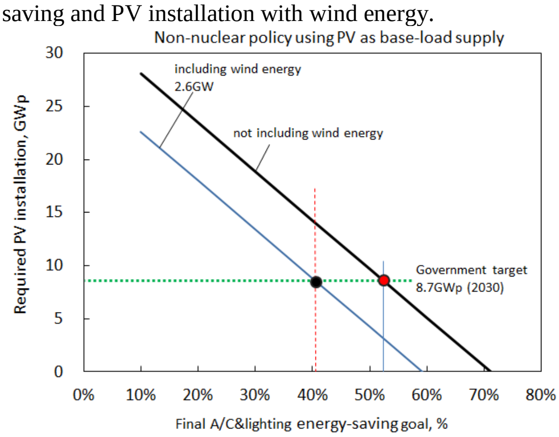

Figure 16. PV installation for base-load replacement by E-saving and PV installation.

Taiwan government announced a target of PV installation 8.7GWp by 2030. The required energy saving of A/C and lighting will be 41% and 52% with and without wind energy, respectively. Figure 16. Both are achievable from the result of demonstration system D-1. According to the building statistics, the roof area of new buildings in next 10 years will be enough to install the PV system.

Energy storage is needed for PV to replace base-load energy supplied by nuclear. The calculation is based on the storage ratio of total PV energy generated and the PV installation per unit (kWp). Figure 17 shows that the required energy storage capacity for each 3 kWp PV unit is between 4~6 kWh for 40% and 60% storage ratio of PV generated energy, respectively. This is feasible and even cheaper if using thermal storage.

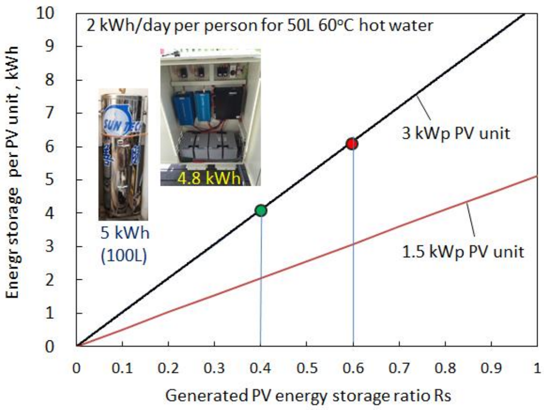

Figure 17: Required energy storage capacity

6.3 Non-nuclear grid policy

It can be summarized from the above analysis that there are several scenarios to achieve non-nuclear grid:

Scenario I (for peak-shaving): 3.03GWp PV installation, 30.3% energy saving of A/C and lighting, 6.1 yr

Scenario II (for base-load replacement): 6 GWp PV installation, 58% energy saving of A/C and lighting, 11.5 yr @500MWp/y

Scenario III (for base-load replacement): 4 GWp PV installation, 2.6GW wind energy, 49% energy saving of A/C and lighting, 9 yr @500MWp/y

Scenario IV (for base-load replacement): 8.7 GWp PV installation (government target), 2.6GW wind energy (half government target), 41% energy saving of A/C and lighting, 8 yr @500MWp/y

For base-load replacement by PV, the required energy storage for each 3 kWp PV unit is between 4 and 6 kWh. Thermal storage can be utilized to reduce cost dramatically as it is 10 times cheaper than battery.

7 CONCLUSIONS

The present study shows that, performing energy saving retrofit then utilizing solar PV energy to supply the remaining load demand in grid can solve the energy shortage problem, if nuclear power was abandoned in Taiwan. An office located in Taipei with 150m^2 floor area and 14 employees was chosen as the demonstration site (D-1). Four energy-saving retrofitting on air conditioning, lighting, PC, and anti-IR film on window glass results in 65% energy saving. A 6 kWp solar PV system is further installed to replace additional 20% energy. That is, 85% energy is saved in total. The solar PV system is an isolated-type hybrid solar PV system (HyPV) which operates under Stand-alone PV Mode or Grid Mode, automatically, by a power controller. No solar PV energy is fed back to grid. The total investment for the solar PV system and the retrofit for energy saving is around USD30,000. The net total energy saving in 20 years is USD80,000, including M&O cost. System D-1 has been run more than one year. The solar PV system supplies about 60% final energy demand of the office.

If energy-saving in air conditioning and lighting can reach 60% as D-1 did in the whole country, the nuclear power (18%) can be abandomed by using solar PV installation to supply the remaining load demand with proper energy storage.

For peak-shaving purpose, 3.03GWp PV installation and 30.3% energy saving in A/C and lighting, will achieve the non-nuclear goal in 6.1 yr.

For replacing base-load energy from nuclear power, 6 GWp PV installation and 58% energy saving in A/C and lighting will achieve the non-nuclear goal in 11.5 yr at PV installation rate 500MWp/y. If wind energy is encountered with target 2.6GW, 4 GWp PV installation and 49% energy saving in A/C and lighting will achieve the non-nuclear goal in 9 yr at PV installation rate 500MWp/y.

For base-load replacement by PV, the required energy storage for each 3 kWp PV unit is between 4 and 6 kWh which is about the same as electricity energy consumption (3-5kWh per day) of a family in hot water supply. Thus heat storage can be utilized to reduce cost dramatically as it is 10 times cheaper than battery.

8 ACKNOWLEDGEMENT

This study was supported by National Energy Program II, MOST 103-3113-E-002-006 made by Ministry of Science and Technology, Taiwan.

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