IEA INTERNATIONAL ENERGY AGENCY

Sustainability Conditions for PV Hybrid Systems: Environmental Considerations

PVPS

PHOTOVOLTAIC
POWER SYSTEMS
PROGRAMME

Report IEA-PVPS T11- 03:2011

International Energy Agency

Photovoltaic Power Systems Program

Sustainability Conditions for PV Hybrid Systems:

Environmental Considerations

IEA PVPS Task 11

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This technical report has been prepared under the supervision of PVPS Task 11 by:

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Contents

1. Foreword

The International Energy Agency (IEA), founded in November 1974, is an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD) which carries out a comprehensive program of energy co-operation among its member countries. The European Commission also participates in the work of the IEA.

The IEA Photovoltaic Power Systems Program (PVPS) is one of the collaborative R&D Agreements established within the IEA. Since 1993, the PVPS participants have been conducting a variety of joint projects in the application of photovoltaic conversion of solar energy into electricity. The mission of the IEA PVPS program is: *To enhance the international collaboration efforts which accelerate the development and deployment of photovoltaic solar energy as a significant and sustainable renewable energy option.*

The IEA PVPS Program aims to realize the above mission by adopting four objectives related to reliable PV power system applications for the target groups of governments, electricity utilities, energy service providers and other public and private users.

1. To stimulate activities that will lead to a cost reduction of PV power systems applications.
2. To increase the awareness of PV power systems' potential and value and thereby provide advice to decision makers from government, utilities and international organizations.
3. To foster the removal of technical and non-technical barriers of PV power systems for the emerging applications in OECD countries.
4. To enhance co-operation with non-OECD countries and address both technical and non-technical issues of PV applications in those countries.

The overall program is headed by an Executive Committee composed of one representative from each participating country, while the management of individual research projects (Tasks) is the responsibility of Operating Agents. By mid 2010, thirteen Tasks were established within the PVPS program.

The overall goal of Task 11: “PV Hybrid Systems within Mini-grids” is to promote the role of PV technology as a technically relevant and competitive source in mini-grids. It aims at enhancing the knowledge-base of multi-source power generation systems including PV and associated electric distribution networks. The objectives of the Task are to:

- define concepts for sustainable PV hybrid mini-grids taking into account local factors (specificity of the application, financing regimes, location, others);
- provide recommendations on individual designs (mix of technologies, architecture, size, performances, other) in order to achieve high penetration level of PV as a mean to improve quality, reliability and economics of electrification systems such as mini-grids;
- assess the potential of technologies to be mixed with PV for hybridisation; and,
- compile and disseminate best-practices on PV hybrid power systems.

The current members of the IEA PVPS Task 11 are:
Australia, Austria, Canada, China, France, Germany, Italy, Japan, Malaysia, Spain, and United States of America.

This report focuses on the environmental sustainability of PV hybrid systems with an emphasis on the potential for reducing greenhouse gas emissions by replacing diesel mini-grid systems with PV diesel hybrid mini-grid systems.

The technical report has been prepared under the supervision of PVPS Task 11 by Noboru Yumoto of Energy & Environment Institute, Inc., Tokyo, Japan.

The report expresses, as nearly as possible, the international consensus of opinion of the Task 11 experts on the subject dealt with. Further information on the activities and results of the Task, and the Task’s other published reports, can be found at: http://www.iea-pvps-task11.org and http://www.iea-pvps.org.

2. Executive SUMMARY

Photovoltaic (PV) hybrid mini-grid systems are used to provide grid quality electricity to small islands and remote isolated areas/facilities 24 hours a day. PV hybrid mini-grid systems have unique environmental characteristics not found in other PV power systems, such as solar home systems (SHS) and grid-connected systems, because of the combination of PV, other power generation technologies, and energy storage.

Integrating PV into a small diesel mini-grid power system can significantly reduce the system's greenhouse gas (GHG) emissions. GHG emissions reduction of a diesel power system when combined with PV are attributed to eliminating inefficient use of diesel generators, avoiding dump load, and supplementing diesel power generation with PV-generated power when conditions allow. According to the case study in this report, supplementing diesel power generation with PV accounts for 84.9% of the reduction, eliminating inefficient use of diesel generator accounts for 7.7%, and avoiding dump load accounts for 7.3%. The case study shows diesel fuel consumption of a PV diesel hybrid system is 33% lower than a diesel power system.

GHG emissions reduction potentials vary among different PV power systems. GHG emissions reduction potential, per unit PV output in kWh, is highest with a SHS, lowest with a grid-connected PV system, and intermediate for PV diesel hybrid systems.

A life cycle analysis of GHG emissions reduction by a PV diesel hybrid system was conducted to confirm the result of the above case study. The analysis showed that the weighted average life cycle GHG emissions factor of a PV diesel hybrid system is 25.9% lower than for a diesel power system, even using very conservative assumptions.

The study recommends replacing diesel power mini-grids with PV diesel hybrid mini-grids as an effective measure for reducing diesel fuel consumption and GHG emissions, and supplying 24-h electricity services to small islands and other isolated remote areas/facilities.

3. Scope and objective

Three major PV-based power systems are examined in this study: 1) solar home systems (SHS), 2) grid-connected PV systems, and 3) PV hybrid mini-grid systems. Solar home systems are commonly used for rural electrification to replace kerosene lamps in developing countries. Grid-connected PV systems are becoming popular in developed countries to reduce fossil fuel consumption. PV hybrid mini-grid systems are used to provide 24-h grid quality electricity in small islands and remote isolated areas/facilities. PV hybrid mini-grid systems have unique environmental characteristics compared with other PV power systems because of the combination of PV, other power generation technologies, and energy storage (lead acid battery is commonly used).

The objective of this report is to identify the unique environmental characteristics of PV hybrid systems among various PV power systems. The most common and mature PV hybrid mini-grid systems are PV diesel hybrid mini-grid systems. These systems are widely used to supply electricity in small islands and remote isolated areas/facilities, mainly in developing countries. PV diesel hybrid systems have been realized as a potential and feasible solution to improve electricity supply and increase hourly service to a 24-h basis without a significant increase in diesel fuel consumption. Therefore this report focuses on environmental characteristics of PV diesel hybrid systems among various PV hybrid systems.

4. Comparisons of environmental characteristics of PV power systems

Table 1 shows comparisons of the environmental characteristics of three PV power systems. Significant environmental characteristic differences exist in GHG emissions reduction and battery recycling.

Table 1. Comparison of environmental characteristics of PV power systems

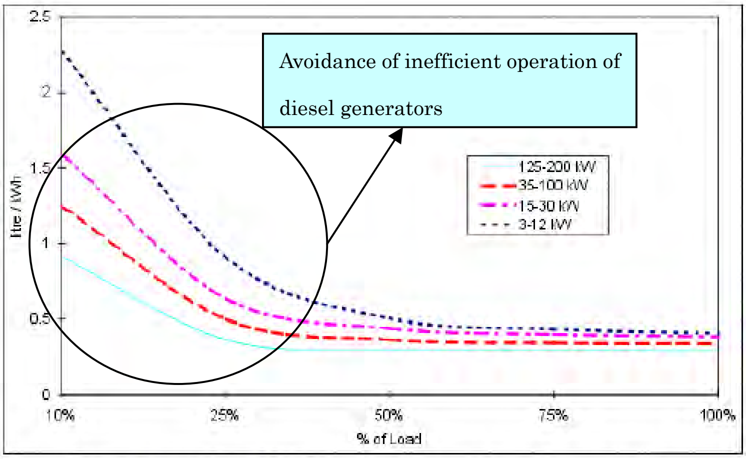
	Stand-alone systems		Grid-connected PV system
	SHS	***PV hybrid mini-grid***	
Main market	Rural electrification in developing countries. Generally, electricity supply is limited during the night time hours.	24-h electricity supply in small islands, remote areas, and isolated facilities, such as resorts, hotels, and large farms, etc.	Electricity supply to electric power utilities and/or electricity supply for own use with back-up by electric power utilities.
GHG emissions reduction mechanism	Replacement of kerosene consumption for lighting.	Reduction of diesel fuel consumption of diesel generators.	Reduction of GHG emissions from thermal power plants which are supplying electricity grid.
Battery use	Electricity generated by PV is stored in batteries to provide electricity during night time hours.	Batteries are often used to store excess electricity during the day time hours and to provide electricity during night time hours to avoid inefficient operation of diesel generators.	Batteries are not necessary.

4.1 GHG emissions reduction mechanisms of PV diesel hybrid mini-grid system

GHG emissions reductions in PV diesel hybrid mini-grid systems are realized by reductions of diesel fuel consumptions through the following mechanisms:

GHG emissions reduction by PV electricity (renewable energy effect). GHG emissions are reduced because of the replacement of diesel-generated power by GHG-free PV power generation. This GHG emissions reduction mechanism is the same as the GHG emissions reduction mechanism of grid-connected PV power systems, although the fossil fuel being displaced may be different.

GHG emissions reduction by avoiding inefficient use of diesel generator. A PV diesel hybrid system is able to stop operation of diesel generators during low electricity load hours because PV diesel hybrid systems can store excess electricity in batteries (or other storage devices) and, consequently, provide electricity from batteries during low electricity load hours. Note that some diesel systems use PV as a fuel saver, but do not operate in true hybrid mode and do not necessarily include storage. The fuel efficiency of diesel generators is dependent on the ratio of electricity load to the rated capacity of the generators. Diesel generators are designed to achieve highest efficiency at the rated capacity of the generators. Figure 1 shows a fuel efficiency curve by the diesel generator size and the above mentioned ratio. The fuel efficiency of a diesel generator declines sharply when the ratio falls below 50%. Inefficient use of small diesel generators is very common in the 24-h electricity supply of small islands and remote isolated areas, since the daily load profile is poor and diesel generators are few. Typically, one generator and one stand-by generator exist in these locations, making group management of the generators not possible. Note that generators are now becoming available which can run more efficiently at lower loads. These provide an even better solution for hybrid systems, since storage can be reduced.



Diesel Genset Fuel Efficiency vs. Capacity Used [Royer, 1999]

Figure 1. Fuel efficiency of small diesel generators[1]

GHG emissions reduction by eliminating dump load. GHG emissions are reduced by avoiding the use of dump loads. Dump loads are used to continue the operation of diesel generators when electric load is lower than the minimum recommended load of the diesel generators. Typically, electric heating elements are used to heat up water and raise the electric load. Dump loads are commonly used in diesel mini-grids to provide a 24-h electricity supply. In the Kingdom of Tonga, the Ha'apai outer islands dump loads consume 31% to 46% of the electricity generated to maintain the operation of diesel generators, even though the diesel generators are stopped during very low load hours.

[1] RETScreen software online user manual, Photovoltaic Project Model, RETScreen international

Ha'apai outer islands electrification project

Four small outer islands in Ha'apai island group, Kingdom of Tonga, have been electrified by AUSAID (Australian Agency for International Development). The project installed two diesel generators with underground distribution lines on each island. Dump loads have been installed in each power plant to maintain operation of diesel generators under low load conditions. The dump loads are switched on to bring the operating load up to 90% for one hour per day to prevent carbon build up and glazing of cylinders of the diesel generators. The dump loads are also used to keep electric load higher than the minimum load of the diesel generators.

The four island grids were commissioned in November 2003. According to the report, "Review of Options for Future Power Generation and Community Support Services" (August 2004), the electricity demand and dump load consumption of each island is shown below.

	Daily maximum load (kW)	**Daily minimum load (kW)**	**Rated capacity (kW)**	**Operating hours (Hours/day)**	**Ratio of dump load (% in kWh)**
Nomuka	14	4	50kW 32kW	7 (Additional 4.5 hours on Fridays)	31
Ha'afeva	8	3.5	32kW 25kW	6.5	36
'Uiha	17	6	50kW 32kW	15	36
Ha'ano	13	8	50kW 32kW	12	46

The capacity of the load bank is up to 18kW.

4.2 Battery recycling of PV hybrid mini-grid system

Energy storage is necessary with PV stand-alone power systems to balance intermittent PV power and fluctuating electricity load. Lead acid batteries are commonly used as energy storage for both SHS and PV hybrid systems. The life of lead acid batteries is generally 2 to 10 years, which is much shorter than the life of a PV panel. Therefore, stand-alone PV power systems need battery replacement several times during the system lifetime. This is a disadvantage of PV applications for stand-alone power systems compared to grid-connected PV power systems. Proper waste treatment, ideally recycling of used batteries, is required to avoid pollution by toxic lead plates.

Most lead acid batteries for stand-alone PV power systems are collected at used car battery recycling centers. However, small islands and isolated areas where PV hybrid systems are commonly competitive with diesel generators, may not have car battery recycling systems (Figure 2) because of the high transportation cost of used car batteries and/or insufficient used car batteries to warrant such facilities (Figure 3). Where there are no battery recycling centers available, it is necessary to establish battery recycling measures, such as adding battery recycling cost to monthly electricity tariff, or depositing money in advance of commissioning the system for future battery recycling, when planning PV hybrid power systems.

Figure 2. Collected and abandoned batteries for SHS in small, outer island in the Kingdom of Tonga.

5. Analysis of GHG emissions reduction of PV diesel hybrid systems

Potential GHG emissions reduction by PV diesel hybrid systems, compared to diesel-only power systems, is analyzed to identify contributions quantitatively of each GHG emissions reduction mechanism described in Section 2.1.

First, a PV diesel hybrid system is designed using HOMER[2] software. HOMER simulates many different system configurations, disregards infeasible configurations (those that do not satisfy the user-specified constraints), ranks the feasible configurations according to total net present cost and presents the one with the lowest total present cost as the optimal system configuration. To evaluate GHG emission reductions by each mechanism, hourly diesel fuel consumption of the PV diesel hybrid system is calculated using a simple formula based on the fuel efficiency curve of a typical Japanese 100 kW diesel generator. Minimum electricity load of the diesel generator is assumed to be 30% of the rated capacity. A dump load is used when electricity demand is below the minimum load in the diesel-only system. Diesel fuel consumption due to the dump load is calculated by multiplying daily dump load electricity consumption and the fuel efficiency at 30% load ratio of the diesel generator. Then, the difference of diesel fuel efficiency between the PV diesel hybrid system and diesel-only power system is calculated. The fuel efficiency of the diesel-only power system is calculated excluding dump load electricity consumption and diesel fuel consumption for the dump load.

GHG emission reductions from eliminating the inefficient use of the diesel generator are calculated by multiplying electricity generated by the diesel generator of a PV hybrid system by the difference of fuel efficiency of both systems. Finally, diesel fuel reduction is calculated as the difference between total diesel fuel reduction by PV diesel hybrid power system and total diesel fuel reductions by avoidance of dump loading and elimination of inefficient use of the diesel generator. To confirm consistency of the estimates of diesel fuel reductions between HOMER software and the simple formula, diesel fuel consumptions of PV diesel hybrid power systems estimated by both models is confirmed to differ by less than 5%.

[2] http://www.homerenergy.com/

Figure 3 shows the daily load profile used in the analysis. PV diesel hybrid power systems are expected to be used in developing countries and therefore the daily load profile is assumed to be evening peak.

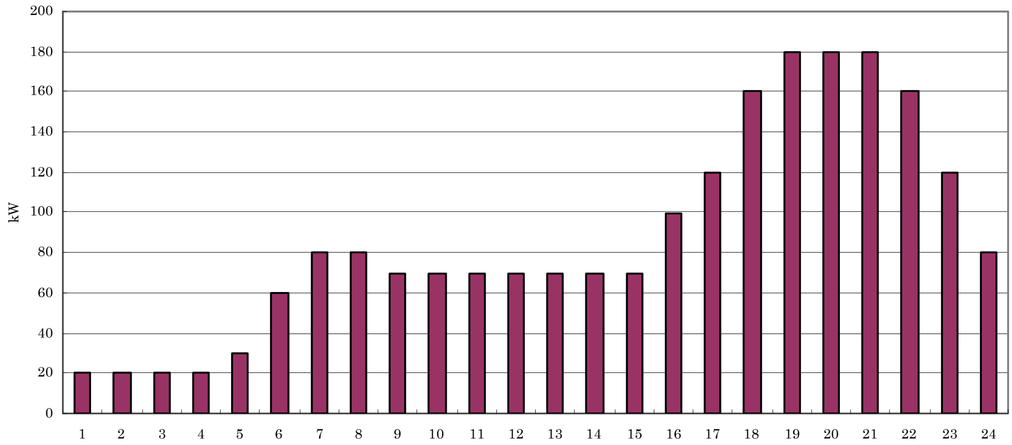


Figure 3: Daily load profile

Solar radiation data and diesel fuel price in the Republic of Botswana are used for this analysis because Botswana is one of the countries with the highest potential for solar energy. Solar radiation is very high and fuel is expensive because of the long distance fuel has to travel. Botswana has set a goal to be the center of excellence for solar energy technology. [3] The country has been involved in PV rural electrification projects since the early 1990's.

Optimal system design is decided by HOMER. The derating factor of PV power generation is assumed to be 0.7. Figure 4 shows the PV diesel hybrid system design by HOMER software and Table 2 shows the optimal design[4] for the electricity load profile shown in Figure 3.

[3] Vision 2016: Towards prosperity for all, Presidential task group for long term vision for Botswana, September 1997

[4] The assumptions on costs of equipment: Diesel generator: US$750/kW, PV: US$9,000/kW, Lead acid battery: US$1,200/battery (1900Ah), Inverter: US$500/kVA

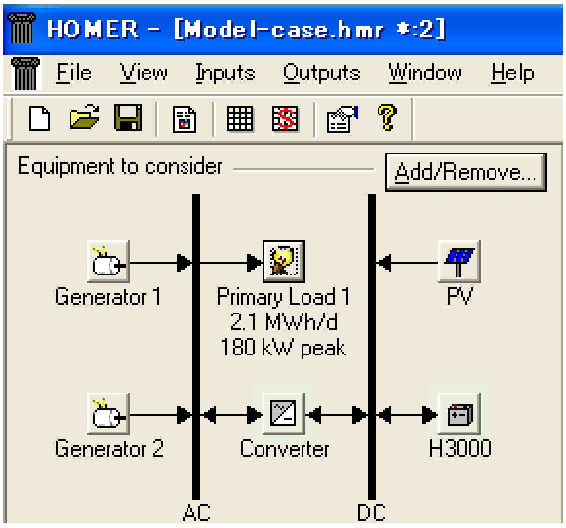


Figure 4. PV diesel hybrid system model

Table 2. Specification of the PV diesel hybrid power system

	Capacity	**Reference**
Diesel Generator	100kW, 2 units	Diesel fuel price: US$1.63/L (August, 2008 price)
PV	150kWp	Annual average solar radiation: 5.88kWh/m2/day Average daily PV output: 687kWh/day
Lead Acid Battery	304kWh	Battery loss: 30%
Inverter	100kW	PV generator is connected to batteries through a DC bus.

Figure 5 shows the fuel efficiency curve of 100 kW Japanese diesel generator.

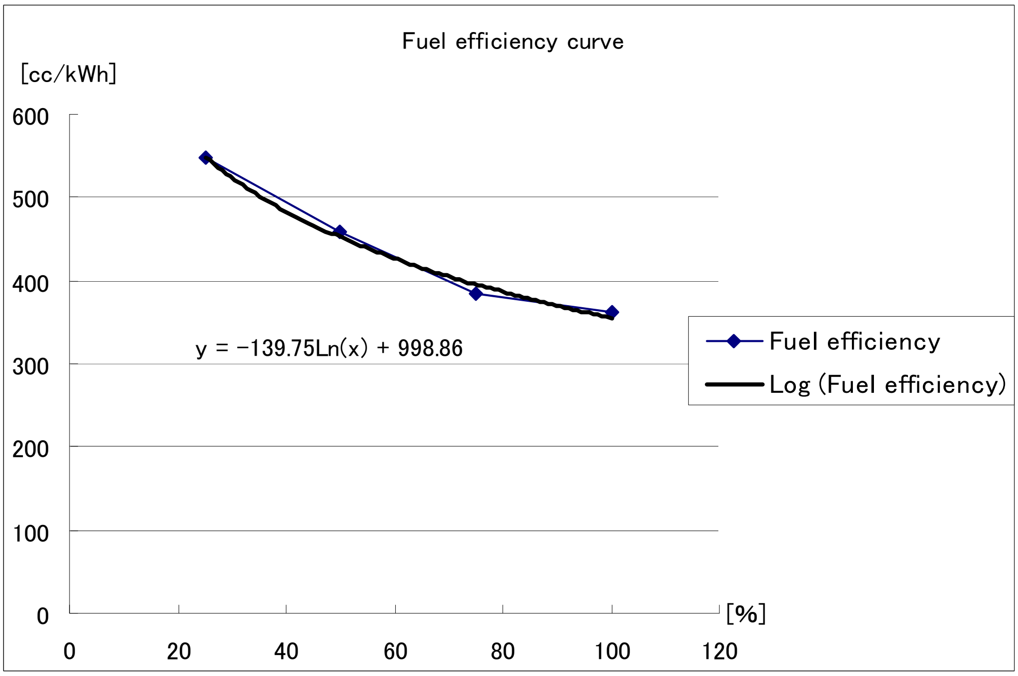


Figure 5. Fuel efficiency curve of a typical 100kW diesel generator

Figure 6 shows an hourly electricity supply portfolio estimated by the simple formula. The operating strategies of the simple formula are to maximize the use of PV power and to eliminate the use of dump load. Diesel generators stop operation for five hours during the night when electricity load is below the minimum load of the diesel generators and for six hours during the day when PV power is enough to supply electricity to the load. During these shut-down hours, batteries and PV supply electricity to the load. Diesel generators are operated at higher than 70% load to the rated capacity and inefficient use of diesel generators is avoided.

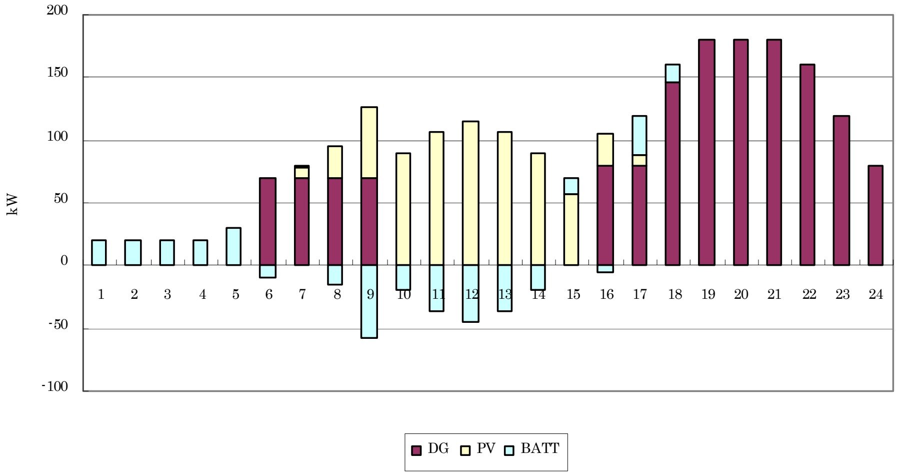


Figure 6. Electricity supply portfolio of PV diesel hybrid system

The diesel fuel consumption of the diesel power system is estimated as 858 L/day and the diesel fuel consumption of the PV diesel hybrid system is estimated at 570 L/day — 33% lower than the diesel power system. Table 3 shows GHG emissions reduction by each mechanism. GHG emissions reductions as a result of supplementing PV power generation accounts for 84.9% of total reductions, eliminating inefficient use of diesel generator accounts for 7.7%, and avoiding dump load accounts for 7.3%. Thus the PV diesel hybrid power system has unique advantages to reduce GHG emissions efficiently compared with the simple use grid-connected PV power systems at the user end, because of the effects of the combination of PV and batteries. The GHG emissions reduction potential of power generation from the PV hybrid power system is estimated as 1.13 kg-CO2/kWh.

Table 3. GHG emission reductions of PV diesel hybrid system

Mechanism	Reduction of GHG emissions[5] (kg/day)	Ratio (%)
Renewable energy effect	683	84.9
Elimination of inefficient use of diesel generator	62	7.7
Avoidance of usage of dump load	59	7.3
Total	804	100

Electrification of small outer islands in developing countries, such as the Southern Pacific island countries, is commonly assisted by donors. The system design of donor projects is usually based on future electricity demand forecasts. Also, the growth rate of electricity demand in outer islands of small island countries is often lower than the donor's forecast because of the migration of households from outer islands to main islands. Therefore in most cases, power supply systems are oversized at the commissioning stage.

To evaluate the advantages of PV diesel hybrid systems versus diesel power systems when power system is oversized to electricity load, GHG emissions reduction between PV diesel hybrid systems and diesel power systems are compared with the assumption that real electricity demand is 20% lower than the forecasted demand. This is equivalent to electricity demand of the commissioning year, assuming that electricity demand is growing 3.71%/year in five years to reach the forecasted demand. Figure 7 shows an electricity supply portfolio of a PV diesel hybrid system in the case of over sizing. Here, diesel generators stop operation for six hours during the night and eight hours during the day, resulting in the PV diesel hybrid system diesel fuel consumption being 43% lower than the diesel power system. Table 4 shows GHG emission reductions by each mechanism. GHG

[5] GHG emission factor of diesel fuel is taken from 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Chapter2, Table2.2

emissions reduction as a result of supplementing PV power generation accounts for 80.4%, eliminating inefficient use of diesel generator accounts for 9.3%, and avoiding dump load accounts for 10.3%. In the case of an oversized diesel power system, dump load consumption increases sharply. Therefore, GHG emission reductions by the PV hybrid system are increased. This effect is caused by energy storage in batteries. The GHG emission reduction potential of power generation in PV hybrid systems is estimated as 1.30 kg-CO2/kWh.

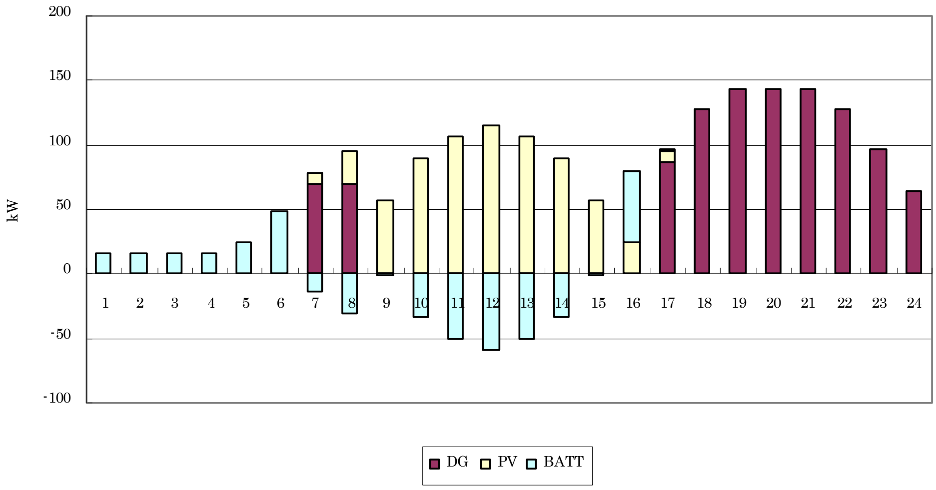


Figure 7. Electricity supply portfolio of PV diesel hybrid system (In case of 20% over sizing)

Table 4. GHG emission reductions by PV diesel hybrid system (In case of 20% over sizing)

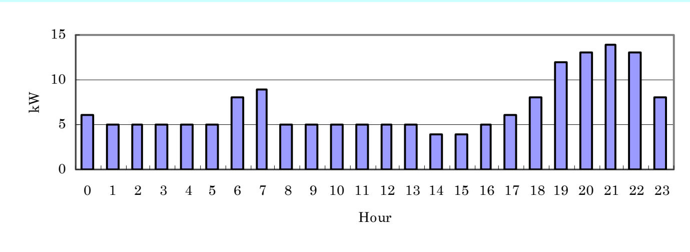
Mechanism	Reductions of GHG emission[6] (kg/day)	Ratio (%)
Renewable energy effect	716	80.4
Elimination of inefficient use of diesel generator	81	9.3
Avoidance of usage of dump load	91	10.3
Total	888	100

The following case study is conducted to confirm the GHG emission reduction effects of PV diesel hybrid system to replace oversized diesel power systems.

[6] GHG emission factor of diesel fuel is taken from 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Chapter 2, Table2.2

Case study: GHG emission reductions of a PV diesel hybrid system against a diesel power system in Nomuka Island, Kingdom of Tonga

Nomuka Island in the Ha'apai island group of the Kingdom of Tonga is electrified by a diesel power system. The diesel power system consumes a significant amount of diesel fuel for dump load because of oversized diesel generators. To increase hourly electricity supply to a 24-h continuous supply without a significant increase in fuel cost, the PV diesel hybrid power system is studied. This study assumes that the 50 kW diesel generator is replaced with a smaller diesel generator, while the 32 kW diesel generator continues to be operated. The optimal system design is identified by HOMER. The following figure shows the daily load profile and the following table shows the specifications of the PV diesel hybrid system. The penetration rate of PV is 84%.



Daily load profile

Component	Rated capacity	Reference
Diesel generator	32 kW、10 kW	Diesel fuel price: US$1.255 /L (November, 2009 price)
PV	70 kWp	Annual average radiation : 4.487 kWh/m²/day
Lead acid battery	684 kWh	
Inverter	20 kW	

GHG emissions of the PV hybrid system are 86% below the diesel power system (32 kW & 10 kW). GHG emissions of the PV hybrid power system are 91% below the current oversized diesel power system (32 KW & 50 kW).

The preceding analyses show that PV diesel hybrid systems can reduce GHG emissions further if existing diesel generators are used inefficiently. The case study in Nomuka Island, kingdom of Tonga, shows a significant GHG emissions reduction potential by PV diesel hybrid system through replacement of oversized diesel power systems. The Nomuka Island case study assumes continued use of a smaller 32 kW diesel generator. However the smaller 32 kW diesel generator is still oversized compared with the peak load in the island. Therefore the optimal design of PV hybrid system identifies relatively large size of PV generator and batteries to minimize the inefficient use of the oversized 32 kW diesel generator.

Canada's first battery-free PV diesel mini-grid system was implemented in the Nemiah Valley of British Columbia[7], in the Fall of 2007. The system installed 27.36 kW of distributed PV systems on the roof of six (6) houses in a small stand-alone power system (peak load of ~75 kW). A 95 kW diesel generator was used to provide electricity in the power system before the project. A 30 kW diesel generator was added to the power system, as well as the PV system, to eliminate the use of dump load during weeknights and weekends. The project also implemented commercial load control measures to switch off unnecessary loads. Because of elimination of costly batteries, PV output needed to be curtailed about ten (10) %. This project confirmed that PV diesel hybrid systems without batteries could reduce fuel consumption significantly. In the first year of operation, fuel consumption was reduced by 26,000 liters and GHG emission was reduced by 73,000 kg. Replacement of diesel power generation by PV power generation contributed 22.7%, avoidance of inefficient use of diesel generator by addition of a 30 kW diesel generator contributed 34.6% and energy efficiency measures contributed 42.8% of the total fuel reductions.

The case studies show that GHG emissions reduction of PV diesel hybrid systems is heavily influenced by the system configurations. The best system configuration for a particular PV diesel hybrid system is dependent on load profile, fuel oil price, efficiency of diesel generator and prices of PV power systems and batteries.

[7] International R&D Collaboration on Photovoltaic Hybrid Systems within Mini-grids, Sophie Pelland, CanmetENERGY, Varennes Research Centre, Natural Resources Canada, CETC Number 2011-015 / 2011-03-30

6. Comparison of GHG emissions reduction among PV power systems

PV GHG emissions reduction is different among various PV power systems. GHG emissions reduction by solar home system (SHS) is caused mainly by replacement of kerosene consumption for lighting. According to the Japan International Cooperation Agency study report[8], the average monthly kerosene consumption of each household in Botswana is estimated at 6L/month. When kerosene consumption is replaced by a 50 Wp SHS, GHG emissions reduction is estimated as 2.68 kg-CO2/kWh[9]. GHG emissions reduction with the use of PV diesel hybrid systems is estimated at 1.13 kg-CO2/kWh as explained in section 3. When the system design is over capacity, GHG emission reductions of the PV diesel hybrid system is higher than the above mentioned emission reduction factor. GHG emissions reduction of grid-connected PV power systems depend on the power generation portfolio of the electricity grid. Electricity supply in Botswana is 100% dependent on coal power plants. Generally, the GHG emission factor of coal power plants in the world is 0.8-1.0 kg-CO2/kWh. Figure 8 shows comparisons of GHG emissions reduction by each PV power system.

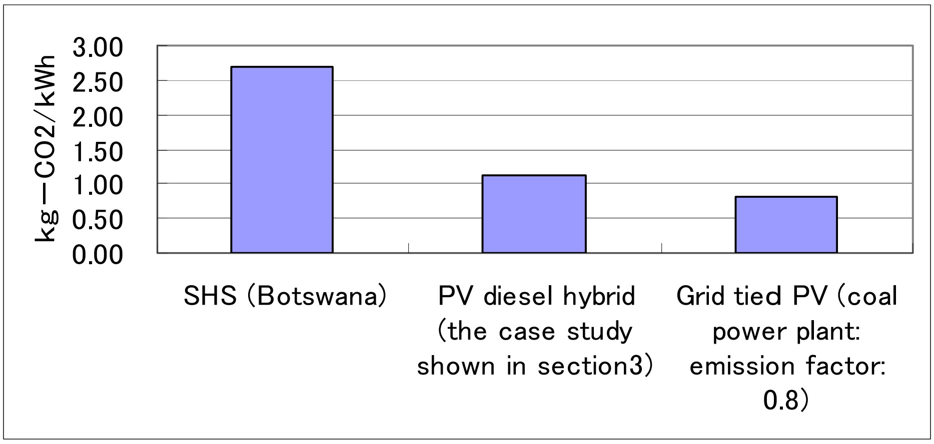


Figure 8. GHG emissions reduction potentials of PV power systems

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[8] Final report for the master plan study on PV rural electrification in the Republic of Botswana, February 2003, Japan International Cooperation Agency

[9] Annual electricity supply by 50Wp SHS is estimated as 72 kWh.

7. Life cycle analysis of GHG emissions reduction from PV diesel hybrid systems

GHG emissions reductions from the use of PV diesel hybrid systems are estimated in section 3 with the assumption that operating GHG emissions of PV power system are zero. Taking into account life cycle GHG emissions of PV power systems, such as GHG emissions of manufacturing silicon ingots, GHG emissions of PV power systems are not zero. IEA PVPS Task12 is currently conducting various life cycle analyses that describe energy, material, and emission flows in all stages of the life of PV. According to the IEA PVPS Task12 website, Figure 9 shows the carbon footprint (life cycle GHG emissions) of rooftop PV power systems.

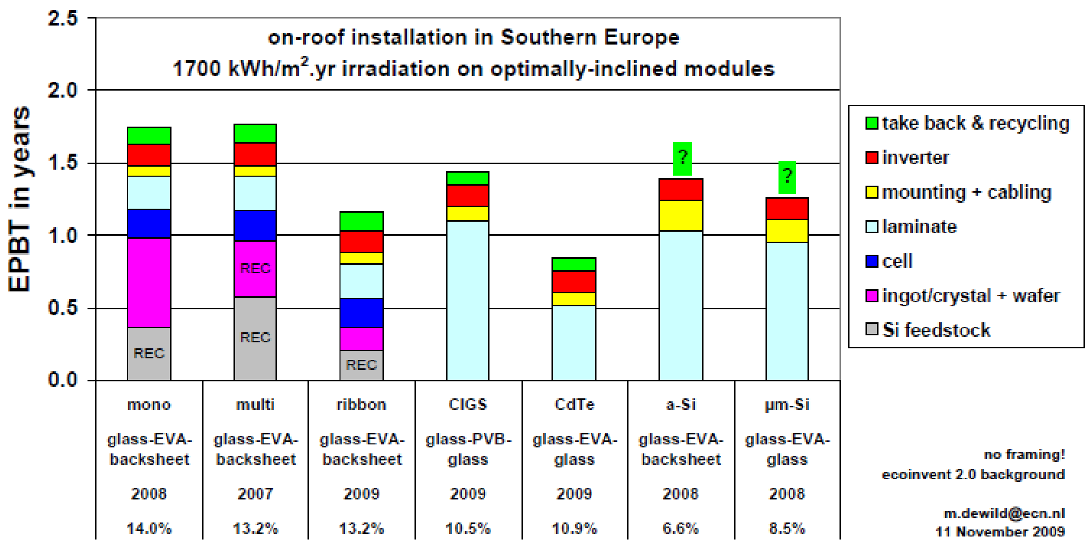

Figure 9. Carbon Footprint of rooftop PV Systems – technology comparison[10]

Table 5 shows estimates of life cycle GHG emissions of various PV power systems. Life cycle GHG emissions are different by estimated years of life, countries, and technologies. Life cycle GHG emissions vary from 12.5 to 104 g-CO2/kWh, so a figure of 38 g-CO2/kWh is chosen to estimate life cycle GHG emissions reduction of PV diesel hybrid power systems, reflecting the literature on the latest Japanese PV technologies. This estimate is consistent with the carbon footprint of rooftop PV

[10] De Wild-Scholten, Sustainability: Keeping the Thin Film Industry Green, 2nd EPIA International Thin Film Conference, Munich, 2009

systems as shown in Figure 9.

Table 5. Life cycle GHG emissions of PV power generation

Reference	GHG emissions (g-CO2/kWh)	Year of publication
Evaluation of Power Generation Technologies based on Life Cycle CO^2 Emissions – Updated for State-of-the-art Plants-[11]	38 (multi-cryst Si, 3.84kW roof top PV with power conditioner, 30 years life)	2010
Life Cycle Assessment of Present and Future Photovoltaic Systems[12]	33.0 (single crystal, present) 12.3 (c-S_i ribbon, 2025) 4.6 (CdTe, 2025)	2007
Greenhouse-gas emissions from solar electric and nuclear power: A life-cycle study[13]	22~49 (average USA)	2007
Energy Use and Greenhouse Gas Emission in the Life Cycle of Thin Film CdTe Photovoltaics[14]	24 (average USA)	2005
Comparison of energy systems using life cycle assessment: A special report of the World Energy Council[15]	12.5~104	2004

There is less information published on the life cycle GHG emissions of diesel generators than the life cycle GHG emissions of PV power systems. Life cycle GHG emissions of diesel power generation are estimated at 649-787 g-CO2/kWh, according to a report written by Hydro Quebec[16]. According to the fuel efficiency of a 100 kW diesel generator shown in Figure 5, GHG emissions at 90% load to the

[11] Eiichi Imamura, Koji Nagano, Central Research Institute of Electric Power Industry, Japan, July 2010
[12] M. Raugei, P. Frankl, E.Alsema, M. De Wild-Scholten, V. Fthenakis, H.C. Kim, AIST Symposium“ Expectations and Advanced Technologies in Renewable Energy, Chiba, Japan, October 2007
[13] Vasilis M. Fthenakis, Hyung Chul Kim, Energy Policy 35(2007) 2549-2557
[14] Vasilis M. Fthenakis, Hyung-Chul Kim, Proceedings of Symposium G-Life Cycle Analysis, November-December, 2005
[15] World Energy Council, July 2004
[16] Greenhouse Gas Emissions (Emissions from Power Generation Options)

rated capacity is 1,023 g-CO2/kWh. Taking into account indirect GHG emissions, such as generator manufacturing emissions, the life cycle GHG emissions of a 100 kW diesel generator should be higher than 1,023 g-CO2/kWh. A conservative estimate of 787 g-CO2/kWh is chosen to estimate life cycle GHG emissions of PV diesel hybrid systems.

Life cycle GHG emissions by energy storage are estimated based on the following formula proposed by a Japanese report.[17] The relationship between life cycle GHG emissions of electricity supplied through energy storage and those of grid electricity (electricity input to energy storage) is defined by the following formula.

$$(Rbattery - Rgrid) \times Eout = R_{grid} \times E_{loss} + \beta\,(Cmaterial \pm Cmanufacturing)$$

This formula is transformed to the following formula to calculate life cycle GHG emission factors of energy storage.

$$R_{battery} = \frac{R_{grid} \times E_{loss} + \beta(C_{material} + C_{manufacturing})}{E_{out}} + R_{grid}$$

Where $R_{battery}$: Life cycle GHG emission factor of batteries

R_{grid} : Life cycle GHG emission factor of electric power grid (electricity input to batteries)

β: number of batteries in 10 years (assuming that life of batteries is 10 years)

C: GHG emission factor of materials and manufacturing of batteries

E_{loss}: electricity loss

E_{out}: electricity output from batteries

According to the same Japanese report, an inventory analysis of lead acid battery is shown at Table 6.

[17] Energy and environmental analysis of batteries for electric load leveling using LCA method, Keisuke Kajiyama, Keiichi Okajima, Yohji Uchiyama, Journal of Life Cycle Assessment Japan, Vol.2, No.4, October 2006

Table 6. Result of inventory analysis of lead acid batteries

Charging Capacity (kWh)	Weight (kg)	β $C_{material}$	β $C_{manufacturing}$	E_{in} (MWh)	E_{loss} (MWh)	E_{out} (MWh)
47	1339	13,473	5,104	137	27	110

Life cycle GHG emissions of lead acid batteries in PV power systems are calculated applying life cycle GHG emission factors of the PV power system (38 g-CO2/kWh) to R_{grid}: Thus life cycle GHG emissions of lead acid batteries is estimated as 216 g-CO2/kWh. Similarly, life cycle GHG emissions of diesel generators are taken as 1,149 g-CO2/kWh.

Life cycle GHG emissions from PV diesel hybrid systems shown in Figure 6 are calculated as weighted average emission factors of each power supply technology. Life cycle GHG emissions from PV diesel hybrid systems are 25.9% lower than diesel generators. This reduction ratio is 7% lower than the reduction ratio shown in section 3, because of the conservative assumption of life cycle GHG emissions of a diesel generator.

Table 7. Life cycle GHG emission factors of PV diesel hybrid power systems

	PV	**Lead acid battery**		**Diesel generator**	**Weighted average emission factor**
		PV	*Diesel*		
Electricity supply (kWh/day)	453	161	10	1,476	
Emission factor (g-CO2/kWh)	38	216	1,149	787	583

8. Conclusions

Integrating PV into small diesel mini-grid power systems can significantly reduce the system’s GHG emissions.

GHG emissions reduction of a diesel power system when combined with PV are attributed to eliminating inefficient use of diesel generators, avoiding dump loads, and supplementing diesel power generation with PV-generated power when conditions allow. These combined GHG emission reductions are effects of the combination of PV and energy storage.

In general, traditional diesel mini-grids supply electricity only during peak load hours. To increase electricity supply to 24-h service by these systems, significant increase of diesel fuel consumption and GHG emissions by inefficient use of diesel generators and dump loads are unavoidable.

Therefore, to replace diesel power mini-grids with PV diesel hybrid mini-grids is recommended as an effective measure to reduce diesel fuel consumption and GHG emissions in small islands and other isolated remote areas/facilities and to provide 24-h electricity services.