Rural Electrification in the Mekong Countries with Photovoltaic Diesel Generator Hybrid Systems

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ABSTRACT

In rural areas of the Mekong Countries, the problem of supplying electricity to rural communities is particularly alarming. Supplying power to these areas requires facilities that are not economically viable. However, government programs are underway to provide this product that is vital to community well being. A national priority of Mekong Countries is to provide electrical power to people in rural areas, within normal budgetary constraints. Electricity must be introduced into rural areas in such a way that maximizes the technical, economic and social benefit. Another consideration is the source of electrical generation and the effects on the natural environment. This paper presents the economic study of the PV Diesel Hybrid System (PVHS) for rural electrification in this region.

Keywords: *Mekong, Technical, Economic, PV-diesel hybrid system, Rural electrification.*

1. INTRODUCTION

The Mekong Countries includes by six nations: The Kingdom of Cambodia, the Yunnan province of the People's Republic China, the Lao PDR, the union of Myanmar, The Kingdom of Thailand and the Socialist Republic of Vietnam. It is a vast area that possesses an enormous wealth and variety of natural resources, including a rich agricultural base, timber, fisheries, minerals, and energy in the form of hydropower, coal, and petroleum reserves. These resources fuel economic development and support rural livelihoods in an interrelated fashion.

The Mekong Countries cover a land area of some 2.3 million square kilometers. They share area borders with China in the north, the South China Sea in the south, Vietnam in the east and Myanmar (Burma) and Thailand in the west (Fig. 1). The population of the Mekong region is about 250 million; with 65.7 million of whom live within the hydrological basin of the Mekong River. Population growth is rapid and will likely continue in Laos, Cambodia, Myanmar and Vietnam. The regional population growth rate averages approximately two percent, although there are marked variations, such as in some of the upland areas of Laos and Vietnam, where higher rates are not common. The region also has an enormously wide range of different population densities. Laos, for example, has only 19 people per square kilometer, while Vietnam ranges from 300-500 people per square kilometer [1].

Approximately 200 million people of the Mekong Countries population live in rural areas. Of that number only 10% in Cambodia, Lao, Myanmar and Vietnam have access to the electric grid. The governments of the Mekong Countries have very strong policies to provide electricity to people in those areas. However, there are many problems with the implementation process, such as insufficient finances, unclear planning and lack of proper technology. Almost all rural electrification projects concentrate on conventional methods such as grid extension. This technology is not proper in some locations, such as in Laos and Myanmar, where almost all land areas are still covered by abundant forests. Grid extension may be a cause of environmental effect and not economical enough because not many people actually live in those area.

Fig. 1 Map of the Mekong Countries.

The Mekong Countries have very rich potential for renewable energy, on that can be developed for rural electrification projects. Renewable energy is widespread in this region and can be found at all locations. It should be considered for power generation because many technologies in this time can be converted into electrical energy such as photovoltaic (PV) generator, wind turbine, hydro generator and biomass conversion technology. One solution for rural electrification in this region is to select the proper renewable energy conversion technology.

This study focuses on photovoltaic generator technology. Long experience has shown that this technology is a one of the most efficient for rural electrification. Although many limitations of photovoltaic still exist, such as reliability when compared with a diesel generator, the latter also has many disadvantages. Therefore, a combination of photovoltaic and diesel generators is one of the suitable solutions for rural electrification in the Mekong Countries.

The photovoltaic diesel hybrid system (PVHS) is relatively new technology for this region. There is not much technical experience for application in rural area. No data indicates that this technology is suitable for rural areas in this region and it is quite difficult to use the experience from other regions to correlate. The Mekong region has specific conditions that are different from other regions, so this study concentrates on the suitability of the PVHS for rural electrification in the Mekong region.

2. RURAL ELECTRIFICATION SITUATIONS

For the poor, a major priority is the satisfaction of such basic human needs as food, health , job, services, education, housing, clean water and sanitation. Energy plays an important role in ensuring delivery of these services.

Low energy consumption is not a cause of poverty, and energy is not a basic human need. However, lack of energy has been shown to correlate closely with many poverty indicators. Addressing the problems of poverty means addressing its many dimensions. At the household level, although it is not recognised explicitly as one of the basic needs, energy is clearly necessary for the provision of nutritious food and clean water to live.

In most rural households, particularly the poorest, the amount of useful energy consumed is less than what is required to provide a minimum standard of living. This has led to 'norms' being used by planning agencies when evaluating energy demand in rural areas.

In rural areas of Mekong Countries, the problem of electricity supplying rural communities is particularly alarming. Supplying power to these areas requires facilities that are not economically viable. However, government programs are under way to provide this product that is vital to community well being. Table 1 shows the estimates of rural household access to electricity.

Table 1 Estimates of rural household access to electricity [2-6].

Country	Rural access
Cambodia	13%
Laos	9%
Myanmar	0.2%
Thailand	99%
Vietnam	14%
Yunnan, China	89%

A national priority of Mekong Counties is to provide electrical power to people in rural areas, within normal budgetary constraints. Electricity must be introduced into rural areas in ways that maximize the technical, economic and social benefit. Another consideration is the source of electrical generation and the effects on the natural environment.

3. SOLAR ENERGY RESOURCE

Mekong Countries have very high levels of solar radiation, particularly in the southern region. The maximum average temperature during the hottest months, March to June, is 31 degrees Celsius, with a mean annual temperature of about 16 degrees Celsius in the northern regions. Measured on a horizontal surface, daily solar radiation in the south (Cambodia and Vietnam) ranges from 6.5 kWh/m^2 in April and May to 4.5 kWh/m^2 in December, with an average of 5.5 kWh/m^2. The central regions (Laos and Thailand) have a similar pattern ranging from 4.5 to 6.3 kWh/m^2 over the same months, with average of 5.0 kWh/m^2. The northern region (Yunnan and Myanmar) ranges from 5.6 to 7.0 kWh/m^2 over the same months, with an average of 6.0 kWh/m^2 [7-9].

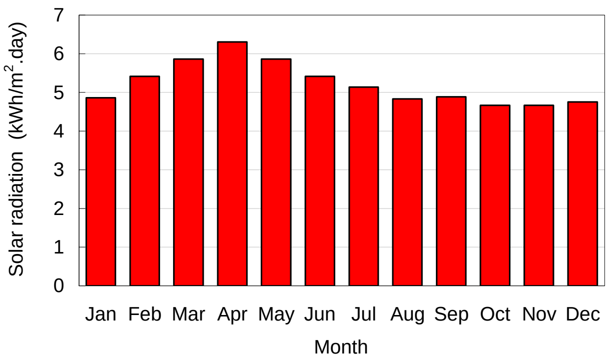

Fig. 2 Solar radiation on horizontal surface of Thailand [10].

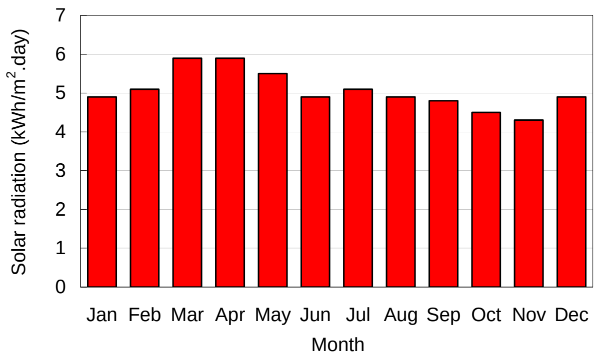

Fig. 3 Solar radiation on horizontal surface of Cambodia [11].

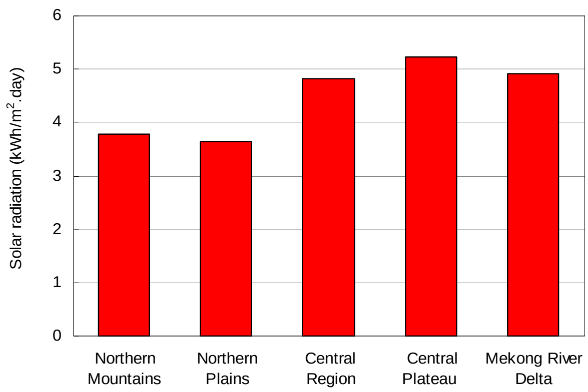

Fig. 4 The average solar radiation in the typical regions of Vietnam [12].

4. PVHS CONCEPT FOR MEKONG COUNTRIES

Renewable energy can be efficiently integrated in off-grid regions. In order to offer an uninterruptible power supply, PV hybrid systems equipped with batteries or combustion engines are applied. The Modular Systems Technology, which supports the design of modular construction kits in different power ranges, has been developed [13].

The prototype of a hybrid system for the Mekong Countries is different from the conventional type. This system concept was invented by the Institut für Solare Energieversorgungstechnik (ISET). The system is called the modular expandable AC-coupled hybrid system, and is characterized by a stipulated energy coupling (AC-bus bar with e.g.

230/400V, 50Hz), a standardized information exchange and a supervisory control. This approach allows for an adaptable and expandable system structure, thus covering almost every supply situation; but it means that the generators integrated into the system have to be equipped with special control features [14].

According to the actual demand, PV generators can be connected to the AC bus in the same way as standard grid-connected systems. In other words, the string concept for inverters, which has been successfully introduced to grid-connected PV systems, can be used in stand-alone plants as well. Special care has to be taken when using several bi-directional inverters (battery inverter) in parallel. In this case the parallel bi-directional inverters have to divide the loads equally in both directions in case of equal nominal power or proportionally to this figure in case of different values. Conventionally, this requirement can be performed using a master slave concept. With a novel approach, it could be demonstrated that by parallel operating of bi-directional inverters can be performed without using any communication between those units [15]. In this paper the PVHS as mentions is only referring to this hybrid concept.

5. ECONOMICS STUDY OF PVHS IN THE REGION

The basis of most engineering decisions is economics. Designing and building a device or system that functions properly is only part of the engineer’s task. The device or system must, in addition, be economic, which means that the investment must show an adequate return. In this study the model is based on the use of conventional life-cycle costing economics. That is, the model economic routine performs a first level economic evaluation of a PV system. This includes yearly cash flows, the present value of system costs, incomes and levelized annual costs. In addition, the analysis has been designed to allow for a side-by-side comparison of the economics of a hybrid power system with those of a diesel-only powered system and grid extension.

Total capital cost

As detailed below, the cash flow analysis produces year-by-year detailed figures for project incomes and disbursements. The disbursements are separated into the following categories: installed capital costs/annuity payments, fuel costs, operation and maintenance expenses, and equipment replacement costs.

Installed Capital Cost is the initial venture capital for a PVHS, including equipment costs, installation expenses, tariffs, shipping costs, and possibly the cost of extending a distribution network from the PVHS to the consumer loads. While every effort has been made to identify the major capital costs, this paper uses a “balance of system” term, $C_{Cap,BOS}$, in order to account for any capital costs which are unique to the user's application. Therefore the system-installed capital cost, $C_{Cap,tot}$ is given by [16-17]:

$$C_{Cap,tot} = C_{Cap,PV} + C_{Cap,Inv} + C_{Cap,Diesel} + C_{Cap,Batt} + C_{Cap,BOS} + C_{Cap,Inst} + C_{Cap,Oth} \qquad (1)$$

where:

$$C_{Cap,Inst} = C_{Inst,PV} + C_{Inst,Batt} + C_{Inst,Inv} + C_{Inst,BattInv} + C_{Inst,Batt} + C_{Inst,Diesel} \qquad (2)$$

$$C_{Cap,Inv} = C_{Cap,Inv} + C_{Cap,BattInv} \quad (3)$$

$$C_{Cap,Oth} = C_{Ship} + C_{Oth} \quad (4)$$

Where $C_{Cap,PV}$ is the capital cost of PV array, $C_{Cap,Inv}$ is the capital cost of inverter (grid inverter & battery inverter), $C_{Cap,Diesel}$ is the capital cost of diesel generator, $C_{Cap,Batt}$ is the capital cost of battery storage, $C_{Cap,Inst}$ is the installation cost, $C_{Cap,Oth}$ is the capital cost of other (tax etc.), and C_{Ship} is shipping cost.

Annual cost

These consist of regular maintenance costs and fuel costs (diesel generator) over the years. The actual data of annual maintenance and fuel cost on systems installed is different for each location. Therefore the system annual cost model, $C_{ann,tot}$ is given by [16-17]:

$$C_{ann,tot} = C_{ann,PV} + C_{ann,Batt} + C_{ann,Inv} + C_{ann,Diesel} + C_{ann,Sys} + C_{ann,Fuel} + C_{ann,Oth} \quad (5)$$

where:

$$C_{ann,Fuel} = C_{Fuel/L} \times FuelConsump \times Hr_{Diesel} \quad (6)$$

$$C_{ann,Inv} = C_{ann,Inv} + C_{ann,BattInv} + C_{ann,Chg} \quad (7)$$

Where $C_{ann,Fuel}$ is the annual cost of fuel, *FuelConsump* is the diesel engine fuel consumption rate and Hr_{Diesel} is the hour operation of the diesel generator.

Replacement cost

Replacement costs are slightly more complex, in that they involve regular cash payments, not truly annual. The main components of the system have to be replaces during the life- time of the system. In order to convert replacements costs into annual ones, the replacement annual cost (C_{Repl}) equation is given by [16-17]:

$$C_{Repl,Diesel} = C_{OH} \times (PWF, i, n) \quad (8)$$

$$C_{Repl,Batt} = C_{Batt} \times (PWF, i, n) \quad (9)$$

$$C_{Repl,Inv} = (C_{Inv} + C_{BattInv} + C_{Chg}) \times (PWF, i, n) \quad (10)$$

$$C_{Repl,Oth} = C_{Oth} \times (PWF, i, n) \quad (11)$$

$$C_{Repl,tot} = C_{Repl,Diesel} + C_{Repl,Batt} + C_{Repl,Inv} + C_{Repl,Oth} \quad (12)$$

Where: $$PWF = F\left[\frac{1}{(1+i)^n}\right] \tag{13}$$

$$i = \frac{i_f - f}{1+f} \tag{14}$$

Where *PWF* is the present-worth factor, *F* is future money, *n* is the component lifetime in year, *I* is the actual interest rate (% per year), i_f is the interest rate (% per year), *f* is the inflation rate (% per year).

Present value of the annualized cost and salvage value

The series-present-worth factor (*SPWF*) translates the value of a series of uniform amounts *C* into the present worth. The present worth of the series can be found by applying the *PWF* to each of the *C* amount [16-17]:

$$C_{ann,PW} = \left(C_{ann,tot} \times \left(SPWF, i, n\right)\right) \tag{15}$$

$$SPWF = A\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right] \tag{16}$$

$$C_{Sal,PW} = C_{Sal} \times \left(PWF, i, n\right) \tag{17}$$

Where *A* is the annual money, *n* is the system lifetime (years) and C_{sal} is the salvage value.

Life cycle cost (LCC)

The methodology used to define the LCC is a multi-step process, as presented above. This process requires sets of data from fielded systems and the development of a sophisticated database tool for analysis of the data. LCC determines which power supply systems can be cost-competitive with other energy options [16-17].

$$LCC = C_{Cap,tot} + C_{ann,PW} + C_{Re\,pl,PW} - C_{Sal,PW} \tag{18}$$

Levelized cost of energy (COE)

Another levelized calculation concerns the cost of energy, COE. The total levelized cost of energy is given by [16-17]:

$$COE = \frac{LCC}{\left(E_{Prod} \times SysLife\right)} \tag{19}$$

Where E_{Prod} is the energy that the system generated in one year (kWh/y) and *SysLife* is the system lifetime (years).

6. A CASE STUDY OF PVHS IN THE MEKONG COUNTRIES

The case study of rural electrification in the Mekong Countries presents an economic performance and sensitivity analysis of three different locations from selected Mekong Countries. Ban Pang Praratchatang (BPP) village in Thailand, Samaki village in Cambodia and Thapene village in Laos have been selected as cases for this pre-feasibility analysis because relevant literature for pre-electrification with PV systems and renewable energy systems is available. BPP was selected because there has been a development project with a PV system, and monitoring data is available for this system under the framework of a MGCT project [18]. Samaki was selected because there has been a development project with a PV system and monitoring data is available for this system under the Ministry of Industry, Mines and Energy (MIME) project [12] and Thapene was chosen because base and survey data were available from the School of Renewable Energy Technology (SERT) and the Council on Renewable Energy in the Mekong Countries (CORE).

In this study, the economics performance and sensitivity analysis of PVHS, PV system (PVS), Diesel generator system (DGS) and Grid Extension (GE) were studied.

PVHS for each village

A PVHS for electricity generation is assumed to be installed at the BPP, Samaki and Thapene village. The configurations of each system are presented in Table 2.

Table 2 PVHS configurations for the study.

	BPP	Samaki	Thapene
PV generator (kWp)	1.95	1.5	9
Diesel generator (kW)	5	5	8
Battery storage (kWh)	20	15	90
Power conditioning			
- Grid connected inverter (kW)	1.7	1.5	9 (3 x 3 unit)
- Battery inverter (kW)	3.3	3.3	9.9 (3.3 x 3 unit)

Economics performance results of PVHS at BPP

In this section, the economic performance study results of the PVHS at BPP are presented. The results presented are based on LCC and COE. The different assumptions of the economic parameters are considered. Table 3 shows the sums of the cases of difference of an assuming (case 1-6 is PVHS, case 7 is PVS, case 8 is DGS and case 9 is GE).

An analysis of the LCC of the different system assumptions is explained in Fig. 5. This figure shows that in the LCC of cases 1 – 3 the PV array and power conditioning represents a basic share in the energy levelized cost. In this case, the power conditioning share is about 20% of the LCC and has a COE of 0.60 – 0.55 €/kWh, caused by the high unit cost of (imported components from Europe). In cases 4 – 7, the cost of power conditioning is reduced by 27% by using local components to a COE of 0.52 – 0.47 €/kWh. These results match the obtained values from the actual PV system cost analysis of Thailand [19]. Comparing with the PVHS COE, the result shows that PVHS has a more attractive COE than PVS and GE. In this case, it shows a very attractive COE of DGS. The DSG gives a higher COE when the surplus energy is taken into account. Surplus energy from DGS is almost 1.3 times the daily energy demand of the system, which means energy loss is 3,578 kWh/y.

Table 3 Comparison of the difference assumption of the PVHS, PVS, DGS and GE at BPP.

Description	Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8	Case9
PV investment cost (€/kW)	3,000	3,000	3,000	2,600	2,600	2,600	3,000	-	-
Diesel generator (€/kW)	400	400	400	400	400	400	-	400	-
Battery storage (€/kWh)	160	160	160	140	140	140	160	-	-
Power conditioning (€/kW)	1,007.2	1,007.2	1,007.2	732	732	732	1,007.2	-	-
Grid extension (€/km)	-	-	-	-	-	-	-	-	14,000
Transformer (30 kVA)	-	-	-	-	-	-	-	-	600
BOS (%of investment cost)	15	15	15	17	17	17	10	50	5
O&M (%of investment cost)	16	16	16	19	19	19	4	196	3
Replacement cost (%of investment cost)	30	30	30	27	27	27	34	20	5
Interest rate (%)	5	7.5	10	5	7.5	10	5	5	5
Inflation rate (%)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Initial investment cost (€)	18,886	18,886	18,886	16,330	16,330	16,330	15,586	4,000	37,600
LCC (€)	26,150	24,924	23,914	22,661	21,595	20,722	21,292	13,040	36,300
COE (€/kWh)	0.60	0.57	0.55	0.52	0.49	0.47	0.61	0.74	0.65

Note: 1 € = 50 Baht / Import tax = 30% for battery and inverter/ Vat 7%

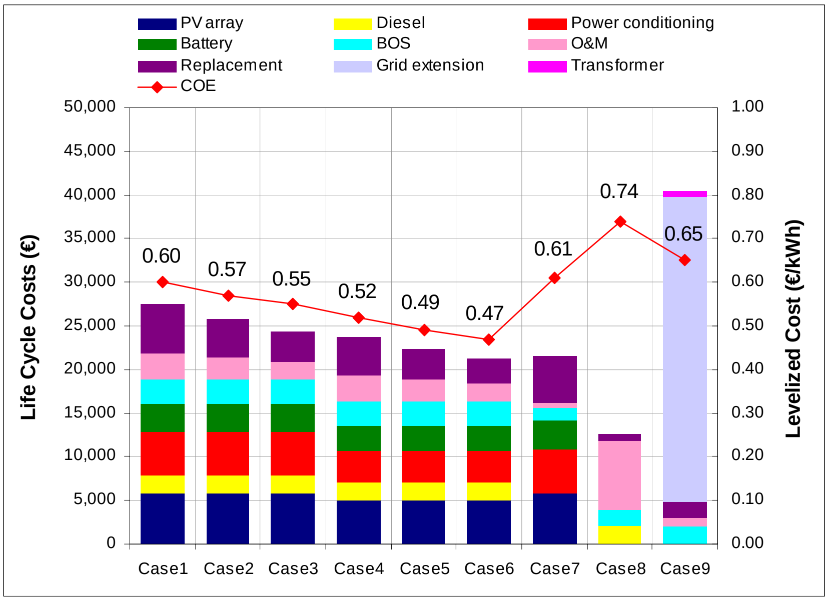

Fig. 5 LCC analysis of different assumptions at BPP.

Economics performance results of PVHS at Samaki

Table 4 shows the summary of the different cases (case 1-6 is PVHS, case 7 is PVS, case 8 is DGS and case 9 is GE). An analysis of the LCC of the different system assumptions is explained in Fig. 6. This figure shows that the LCC in cases 1 – 3 of the PV array and power conditioning represents a basic share in the energy levelized cost. In this cases, the power conditioning share is about 20% of LCC and has a COE of 0.69 – 0.62 €/kWh, caused by the high unit cost of imported components from Europe. In cases 4 – 7 the cost of power conditioning is reduced by 27% to a COE of 0.60 – 0.54 €/kWh by using components from neighboring countries. These results match the obtained values from the actual PV system cost analysis of Cambodia [12]. Compared with the PVHS COE, the result shows that PVHS has a more attractive COE than PVS and GE. In this case it shows a very attractive COE of

DGS. The DSG matches power to the load demand of Samaki better than other power supply systems (in this study the environmental cost is not taken into account).

Table 4 Comparison of the different assumptions of the PVHS, PVS, DGS and GE at Samaki.

Description	Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8	Case9
PV investment cost (€/kW)	3,000	3,000	3,000	2,600	2,600	2,600	3,000	-	-
Diesel generator (€/kW)	400	400	400	400	400	400	-	400	-
Battery storage (€/kWh)	160	160	160	140	140	140	160	-	-
Power conditioning (€/kW)	1,019	1,019	1,019	737	737	737	1,019	-	-
Grid extension (€/km)	-	-	-	-	-	-	-	-	14,000
Transformer (30 kVA)	-	-	-	-	-	-	-	-	600
BOS (%of investment cost)	17	17	17	20	20	20	10	55	5
O&M (%of investment cost)	25	25	25	29	29	29	4	178	3
Replacement cost (%of investment cost)	30	30	30	27	27	27	34	18	5
Interest rate (%)	5	7.5	10	5	7.5	10	5	5	5
Inflation rate (%)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Initial investment cost (€)	16,580	16,580	16,580	14,330	14,330	14,330	13,480	4,000	37,600
LCC (€)	24,685	23,246	22,101	21,369	20,154	19,182	17,856	8,279	68,026
COE (€/kWh)	0.69	0.65	0.62	0.60	0.57	0.54	0.75	0.51	1.28

Note: 1,000 Riels = 0.20 € / Import tax = 30% / Vat 10%

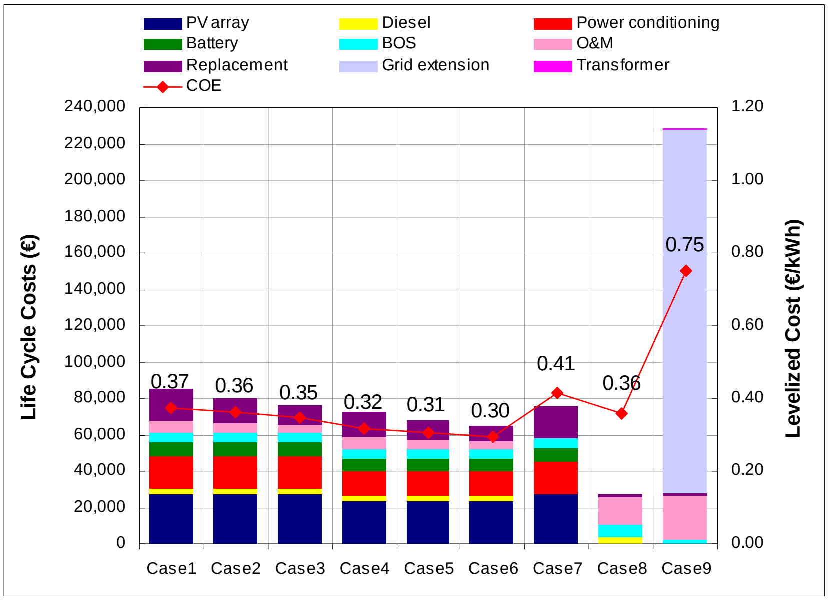

Fig. 6 LCC analysis of different assumption of Samaki.

Economics performance results of PVHS at Thapene

Table 5 shows the summary of the cases with different assumptions, similar to the previous section. Fig. 7 shows an analysis of the LCC of the different technology power system assumptions. This figure shows that in cases 1 – 3, the PV array and power conditioning represent a basic share in the energy levelized cost. In these cases, the PV array is about 44% of LCC and power conditioning (imported components from Europe) is 29% of LCC and has an average COE of 0.36 €/kWh. In cases 4 – 7, the PV array share is about 45%, the cost of power conditioning is reduced by 26% by using components from neighboring countries, and an average COE is 0.31 €/kWh. Comparing with the PVHS COE, the result shows that PVHS has a more attractive COE than PVS and GE.

Table 5 Thapene comparison of the different assumptions of the PVHS, PVS, DGS and GE.

Description	Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8	Case9
PV investment cost (€/kW)	3,000	3,000	3,000	2,600	2,600	2,600	3,000	-	-
Diesel generator (€/kW)	400	400	400	400	400	400	-	400	-
Battery storage (€/kWh)	160	160	160	140	140	140	160	-	-
Power conditioning (€/kW)	948	948	948	705	705	705	948	-	-
Grid extension (€/km)	-	-	-	-	-	-	-	-	10,000
Transformer (30 kVA)	-	-	-	-	-	-	-	-	600
BOS (%of investment cost)	8	8	8	10	17	17	8	62	1
O&M (%of investment cost)	11	11	11	13	19	19	1	145	12
Replacement cost (%of investment cost)	22	22	22	26	27	27	29	15	1
Interest rate (%)	5	7.5	10	5	7.5	10	5	5	5
Inflation rate (%)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Initial investment cost (€)	61,115	61,115	61,115	51,920	51,920	51,920	57,815	10,500	202,600
LCC (€)	80,468	77,355	74,708	68,429	65,785	63,548	71,166	15,650	185,887
COE (€/kWh)	0.37	0.36	0.35	0.32	0.31	0.30	0.41	0.36	0.75

Note: 1,000 Kip = 0.1 €

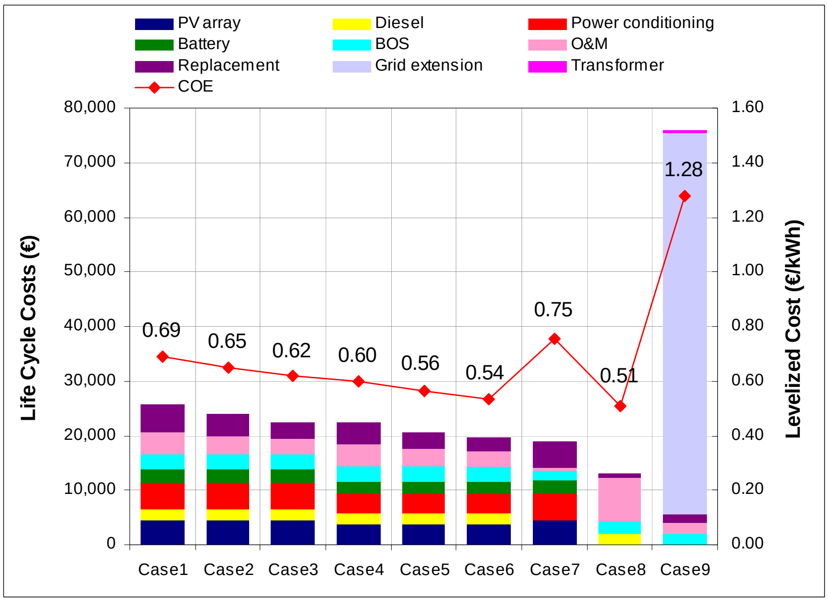

Fig. 7 Thapene LCC analysis of different assumption.

7. CONCLUSIONS

PVHS can meet increasing energy demand at relative cost reduction to the user, improving this system's competitive standing over DGS, which can suffer long down-time caused by maintenance needs, part failures and fuel shortfalls. COE of the PVHS in this study moved from 0.30 to 0.69 €/kWh, PVS is 0.41 – 0.75 €/kWh, DGS is 0.36 – 0.74 €/kWh and GE is 0.65 – 1.28 €/kWh.

Most of the current PV projects have been made without a technical and economic pre-feasibility study. Nevertheless, the rate of system failures in even these systems is less than that of small diesel generator system for rural electrification. This is an indication of the reliability of the PV. The combination of PV and diesel generator, the hybrid system; presents an attractive option for rural electrification of the Mekong Countries. But in real situations, there are still many problems that, need to be studied in the future, such as actual system operation and reliability. System developments are not enough for PV rural electrification projects. If PVHS is promoted following the principles of proper design and adequate maintenance is performed; the number of satisfied users will increase. PVHS is not the only choice for rural electrification, but it is one of the proper choices for the Mekong Countries. Other renewable energy options such as wind, biomass and hydro power need to be studied in the future.

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