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Development of Software for Life Cycle Cost Analysis of Solar Photovoltaic (PV) and Diesel Generator Systems in Nigeria

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Authors' contributions

This work was carried out in collaboration between all authors. Author CCM designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors OUO and ECN managed the analyses of the study. Authors CCM and ECN prepared the final manuscript. All authors read and approved the final manuscript.

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ABSTRACT

The human and economic development of any nation is largely tied to the availability of energy, hence the need for an adequate supply of electricity by reliable energy systems. Nigeria's economic growth is undermined by the epileptic nature of its electricity supply system. Consequently, the populace is forced to turn to alternative sources of power. However, this presents another problem - conflict of choice between available options for power generation. There is, therefore, the need to assist electricity consumers in Nigeria make better and cost-effective choices in this regard. In this paper, a software computer program is developed to determine/compare life cycle cost (LCC) of solar photovoltaic (PV) and diesel generator systems as preferences for electricity generation in Nigeria. The software is developed through an approach involving load determination, energy resources determination, system sizing and a typical residential building. The key methodology adopted is evolutionary prototyping which focuses on vertical dimension approach. Typical load

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description of a household located in Amawbia Awka of Anambra state in Nigeria was used to test the efficiency of the source code. The initial cost and life cycle cost for the two systems over a period of 30 years was ascertained. The test results showed the solar PV system to be a more cost-effective solution than the diesel generator based on total life cycle costs. The study recommends among others, the need to increase awareness of the long-term benefits of solar energy systems as an alternative source of electricity in Nigeria.

Keywords: Life cycle cost; software; solar; photovoltaic; diesel generator; renewable energy; alternative power generators.

1. INTRODUCTION

Access to clean and affordable power supply is crucial to fostering social and economic development and to achieve the Sustainable Development Goals. Efficient electrification programs are required to ensure that people are electrified in a sustainable manner [1]. Nigeria's power generation system has not been one marked with significant success. Inadequacies characterize the system at all levels (generation, transmission and distribution) leaving a huge deficit of energy demand. At present, about twenty million households out of about one hundred and fifty million inhabitants lack access to grid electricity and for those with access, the supply is grossly epileptic [2].

Frequent outages which are typical of the country's electric power system has compelled a large percentage of the populace to rely on diesel-powered generators [3,4], with a few subscribing to solar energy solutions. The advocacy for a clean source of energy (solar) and the large statistics of diesel generators being used as an alternative for power generation by Nigerians informed the consideration of solar PV and diesel generators as options for power source in this study. However, there exists a difficulty of choice between these two electrification options. This conflict is instigated by the cost of acquisition and efficiency of the system. Although life cycle cost analysis helps to make a cost-effective choice, the complexity and time-consuming nature of the techniques involved in life cycle cost analysis stand as a deterrent to an average Nigerian in making a choice of a cost-effective alternative power generation system. It is in this light that a software for life cycle cost analysis (LCCA) of solar PV and diesel generator power systems is developed in this paper. Depending on the user's load requirements, selected location, material, and criteria, the software developed in this paper shows cost difference between photovoltaic energy systems and diesel generators as well as cost variation in different designers' specifications for either of the systems.

Research has been ongoing in the area of life cycle cost analysis of different renewable energy systems and conventional energy sources. Refs [5–10] affirmed the need for the adoption of solar energy as alternative energy systems. Software and different simulation tools have been developed and employed in life cycle cost analysis of alternative power generation systems [11,12]. However, the software developed for life cycle cost analysis in this paper differs from others in the capacity that it was developed considering sensitive input variables (like solar radiation, diesel fuel price) unique to Nigeria. It also demonstrates, for educational purposes, a practical approach to implementing prototyping software development model.

2. MATERIALS AND METHODS

The electrification cost for a household utilizing solar PV and diesel generator energy sources were determined. The household is situated in Amawbia, about 3 km from Awka (Longitude 7.07ºE, Latitude 6.21ºN) in Nigeria. The area receives a daily 6 hours of peak sunlight through the year [13]. For the life cycle cost methodology, the present worth technique was implemented. The systems were compared based on service life, rather than on the classical utility approach of cost per KWh.

This study adopted the requirements engineering (RE) process to complement Object Oriented (OO) modelling using the Unified Modeling Language (UML). We incorporated case diagram and activity diagrams as the unified modelling language tool.

The RE process, supported by the UML, generated structured layers of textual requirements at each level of development. The key methodology employed for providing a structured approach to the UML was evolutionary prototyping which focused on vertical dimension approach. With this, the study presents a logical detail of the data processing function of the software to be developed.

2.1 Mapping Prototype and Requirements Engineering

Evolutionary prototyping utilized for this design provides flexibility in the prototype when the requirements that are fully understood are added.

Fig.1. shows the interrelationship between the prototype segments and the requirement engineering development process. It further reveals the separation of problem and solution domains within the RE layers. As displayed by the representation, the associations made are between the work product models generated through the evolutionary prototyping requirements gathering, analysis and prototype construction segments and the various input models at each RE layer.

2.2 Problem Analysis

Sizing of the PV system components, as well as the present worth calculations, were carried out using standard design procedures [14,15]. Diesel generator system sizing and the present worth calculations were realized using [11,14,15].

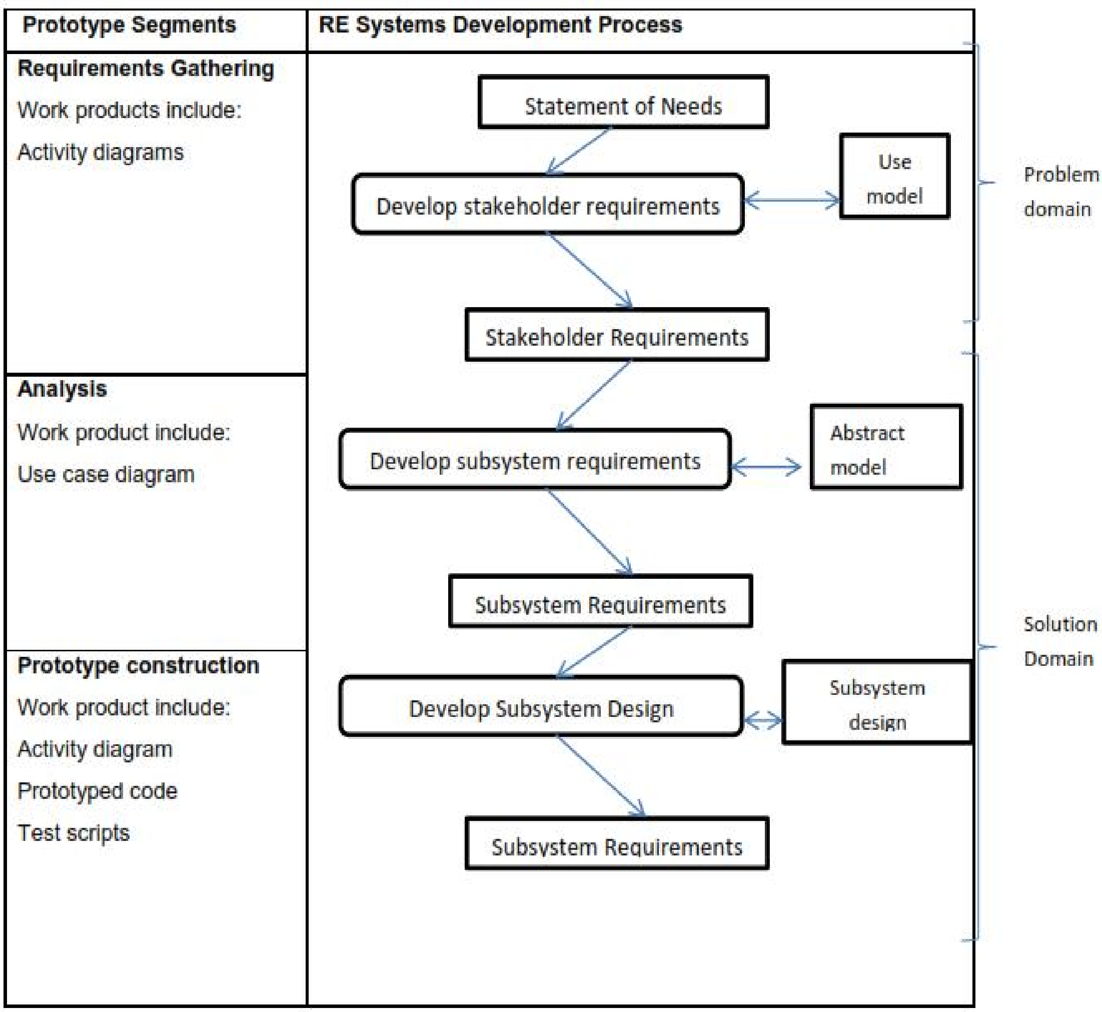

Fig. 1. Mapping prototype segments to requirement engineering process. It shows the interrelationship between the prototype segments and the requirement engineering development process

This paper used 5% of the generator capital cost as a single routine service cost. The life replacement cost of the top cylinder was obtained by first finding the cost of top cylinder overhaul. 2.5% of the capital cost of the generator was used as the cost of a single top cylinder overhaul. Overhaul of the generator top cylinder is performed six times a year based on the maintenance specification of the selected generator. Hence the annual cost of top cylinder

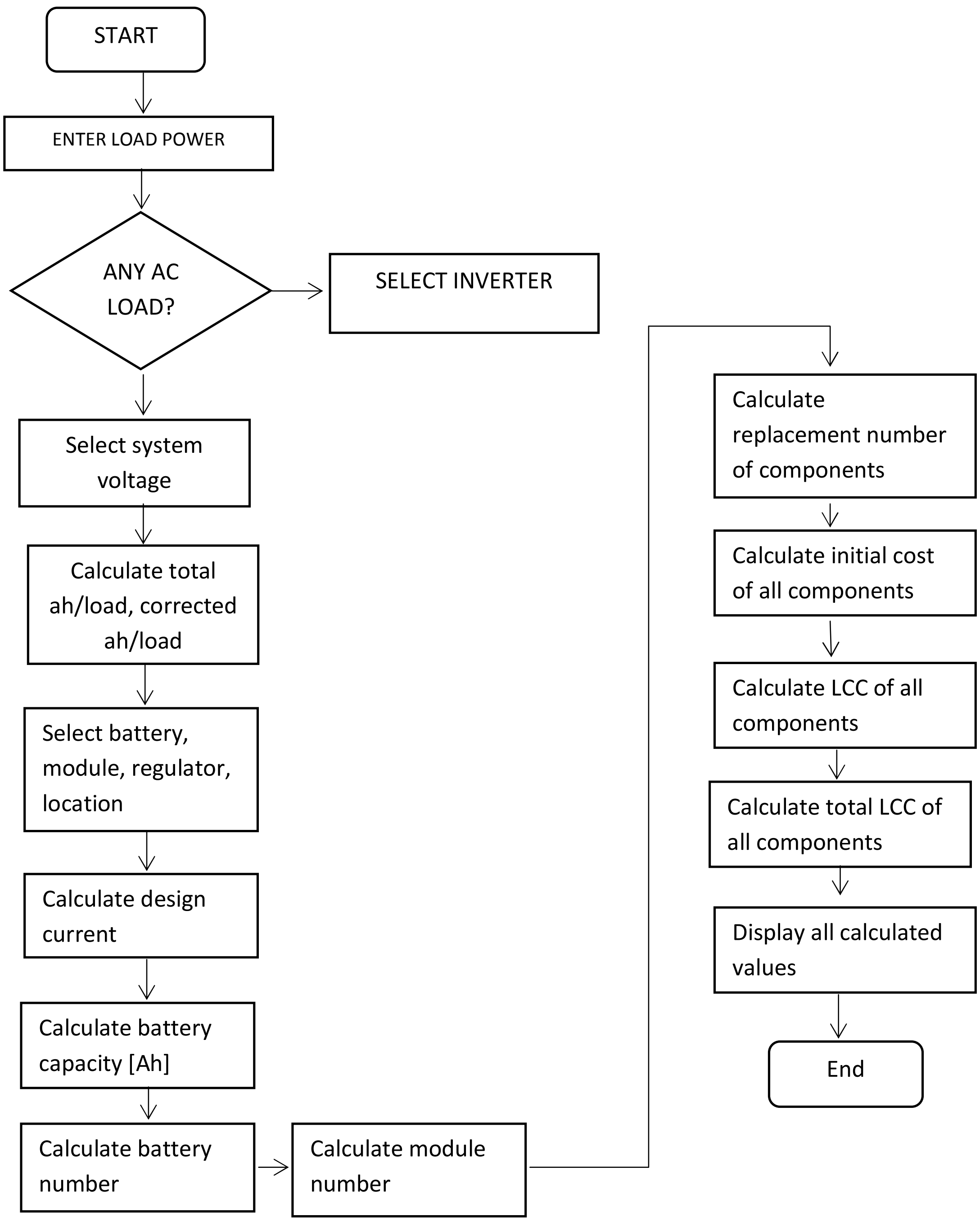

Fig. 2. Activity diagram for LCC of Solar PV system. It illustrates laid down steps taken to obtain the life cycle cost of a solar PV system

overhaul was obtained by multiplying the number of overhauls per year by the single cost of an overhaul. The life replacement cost of the engine is obtained by first finding the cost of a complete engine overhaul. 6% of the capital cost of a generator was set as the cost of a single engine overhaul. The operation of engine overhaul is effected seven times before each replacement based on the maintenance specification of the selected generator. The percentage of the generator capital cost used for single routine service cost, single top cylinder cost and single engine overhaul cost were estimated based on the local market for generator service and overhaul cost in Nigeria. The salvage cost used was 20% of the original equipment price.

Based on the realistic assumption, the efficiency factors to account for losses in the wiring and battery were estimated to be 0.98 and 0.9 respectively. The battery was selected such that its nominal voltage does not exceed the selected system voltage. Considering the peak sun hour/ day of Amawbia, the work assumed five days of autonomy.

Maximum depth of discharge of 0.7 and temperature derate factor of 1.0 were applied for the selected battery type.

The module was selected such that its nominal voltage does not exceed the selected system voltage. The controller for this solar PV design was selected such that the control voltage is compatible with the nominal system voltage. It is also capable of handling the maximum current from the PV array.

The local costs of PV systems and diesel generators were deduced from quotations of local suppliers. The diesel generator costs 200000 naira, module costs 30000 naira, inverter costs 80000 naira, charge controller costs 5000 naira, battery costs 30000 naira per unit. The study uses estimates of general inflation rate of 11.61%, fuel inflation rate of 14.77% and investment rate of 14% [16,17].

The activity diagram for LCCA of solar PV and diesel generator system is shown in Fig. 2. and Fig. 3. respectively.

2.3 Analysis in the Solution Domain: Functional Specification

An illustration of the functional specification for LCC analysis of solar PV and diesel generator systems is depicted in Fig. 4.

The software at default will provide options for the user to obtain any of the following: the life cycle cost analysis of a solar PV system, obtain the life cycle cost of a diesel generator, and compare the life cycle cost of a diesel generator to that of a solar PV system.

Given the methodology adopted by this paper, the software developed is done on a command line interface. Hence, the values that are meant to be in the database and fixed value editing window are inputted by the user in the command line.

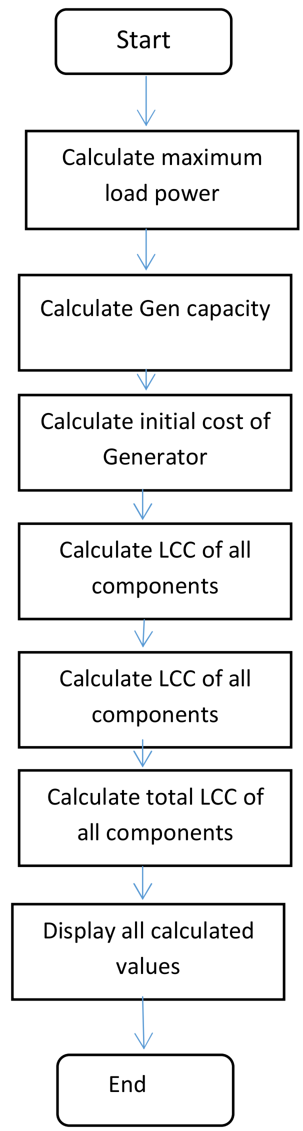

Fig. 3. Activity diagram for LCC of diesel generator system. It illustrates laid down steps taken to obtain the life cycle cost of a solar PV system

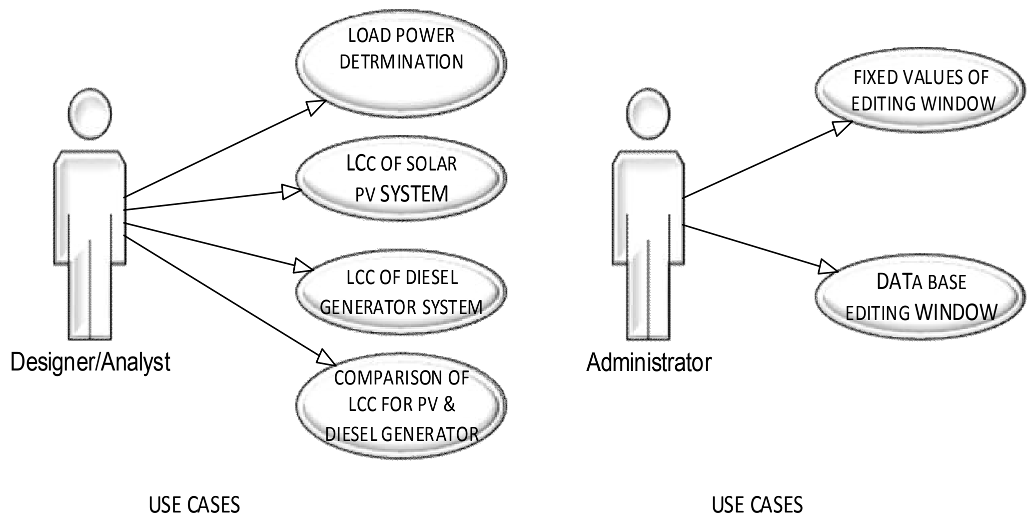

Fig. 4. Use case diagram for LCC analysis of solar PV and diesel generator software. It shows the functional specifications of the developed life cycle cost analysis software

3. RESULTS AND DISCUSSION

The results discussed in this paper were obtained from the load, inverter, module, battery, controller and generator specifications as shown in Table 1, and Tables 4-6 in appendix.

From Table 1, the daily load demand of the household is 2,074 W. Considering loss factor,

Daily Load (watt-hour) = 2,074 X 1.2 = 2,488.8 (watt-hour)

With the adjusted daily load demand of 2,488.8 (watt-hour), a 2500 W inverter with 24V nominal voltage was selected.

The LCC of solar PV system and the LCC of the diesel generator system for the household used as case study is shown in Table 7 and Table 8 respectively.

The values of LCC quoted in Table 2 and Table 3 highlight that using a Solar PV system as an alternative for electricity generation is cost effective compared to the diesel generator option. Though the capital cost for the PV system is higher (42.276% of total LCC) than that of the diesel generator (0.88% of LCC), the cost of diesel over the period of the lifetime of the system used in this study is 75% of the total LCC of a diesel generator, which is very high compared to the PV system with zero cost of energy. Furthermore, we noted that it costs more to maintain a diesel generator over a long period of time than to maintain a PV system, while it costs more to replace the components of a PV system than to replace those of a diesel generator system.

Table 1. Load description for a household in Amawbia, Awka, Anambra state

Load description	Quantity	Dc load power(W)	Ac load power(W)	Daily duty cycle (Hours/day)	Weekly duty cycle (Days/wk)
Lights [DC]	5	24	N/A	4.0	7
Incandescent Light [DC]	1	100	N/A	1.0	7
Ceiling fan [DC]	2	15		4.0	7
Radio [DC]	1	24		1.0	7
Pressing Iron [AC]	1	N/A	1000	0.25	7
Television[AC]	1	N/A	150	3.0	7
Refrigerator[AC]	1	N/A	350	4.0	7
Lights [AC]	3	N/A	100	0.20	1

Table 2. Summary of solar PV system life cycle cost

Item	Amount (Naira)	Present worth (Naira)	Percent total LCC (%)
Capital Cost	1,885,000	1,885,000	42.276
Operation & Maintenance	20,000	516,154	11.576
Replacement cost	425,000	2,074,104	46.517
Salvage	377,000	16,468	0.369
Total Life Cycle Cost		4,458,791	100.00

Table 3. Summary of diesel generator life cycle cost

Item	Amount (Naira)	Present worth (Naira)	Percent total LCC (%)
Capital Cost	213,000	213,000	0.88
Annual fuel cost	525,600	18,495,797	75.97
Annual service cost	180,000	4,645,387	19.08
Replacement cost	1,151,045	993,290	4.08
Salvage	42,600	1,860	0.01
Total Life Cycle Cost		24,345,614	100.000

In a country like Nigeria where the growth of solar PV system is hindered by perceived high cost of system components, the result of the study discloses that it is not wise to use procurement costs as the primary criteria to make a choice of an alternative power generation system. Rather, other important factors like fuel and maintenance cost, battery replacement cost, time value of money, as well as system life span should be taken into account This provides an analytical study and estimate of total costs of which a choice of a cost-effective power generation system depends on.

Every power supply owner wants a cost-effective and efficient system. The biggest overriding factor is that all systems regardless of the power source should make energy conservation a top priority. The less power needed, the lesser the amount that must be produced and stored. This can reduce the size, cost, and weight of the power generation system. Consequently, there is need for individuals and government to start massive investments in solar PV system as an alternative for generating electrical energy in residential buildings so as to minimize cost and maximize the free solar energy.

4. CONCLUSION

This paper presents a software for analyzing life cycle cost of two alternatives of power supply – diesel generator and PV systems. The use of this software enables the user to understand the lifetime costs of each of the alternatives. Thus the user is empowered to make better cost-effective choices for alternative energy solutions. The paper also presents a test case result from the software. We recommend that software for life cycle cost analysis of electricity generation alternatives be made readily available to Nigerians, to enable them carry out life cycle cost analysis at their convenience. Thus, the individual may become fully aware of the long-term benefits or otherwise of the power alternative - solar PV generation systems or diesel generators- they intend to acquire.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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APPENDIX

Inverter, Battery, Module, Controller and Generator Specifications

Table 4. Selected inverter specification

Inverter specifications
Make Photocomm: (2500 W)
Model: 24/48
Wave form: Sine wave
Input Voltage (DC): 24 (V)
Output voltage (AC): 120/240 (V)
Surge capacity: 14,400 (W)

Table 5. Selected battery specification

Battery information	
Make	Trojan
Model	L-16
Type	Lead Antimony
Nominal Voltage (V)	6
Rated Capacity (AH)	420

Table 6. Selected module specification

PV Module information					
Make/Model	Siemens M75			Nominal volts	12
Length	48	width	13	Thickness	1.5
Weight	12 lbs.			Bypass diode	Y N
Voltage	**At STC**	**Open circuit**	**At highest expected temperature**		
(V)	15.9	19.8	14.4		
Current	At STC	Short circuit			
(A)	3.0	3.4			

Table 7. Selected controller specification

Controller
Make/model: Bobier Electronics NDR-30
Rated Voltage: 24 V option
Rated controller value: 30 A

Table 8. Selected generator specification

Three phase 5KVA diesel generator
Make/model: AD5800DSEA
Power Output: 4-7 kw, 50/60 HZ
Full tank capacity:16litres
Operating hour of 1 tank:15 hours
Fuel consumption: 2 litre/hour
Hours of generator operation before servicing: 250 hours
Hours of engine operation before overhaul: 600 hours
Hours of cylinder operation before overhaul:150 hours

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