HIGH PENETRATION PV-BATTERY-BIODIESEL HYBRID SYSTEM FOR THE ACHIEVEMENT OF CERO EMISSION ELECTRICITY GENERATION IN THE GALAPAGOS ISLANDS

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Abstract

Situated in the Pacific some 1,000 km from the South American continent, the Galapagos Islands have been inscribed in the UNESCO world heritage since 1978. Later on, in 2007 UNESCO put the Galápagos Islands on their List of World Heritage in Danger. On 29 July 2010, the World Heritage Committee decided to remove the Galapagos Islands from the list because the Committee found significant progress had been made by Ecuador in addressing these problems.[1] One of these measures was the launch of the cero fossil fuels for Galápagos policy. As results of this the hybrid system project for the Isabela Island was launched. The objective of this project is the cero emission electric generation for this Island by means of the use of PV power, diesel generators running on biofuels and batteries to ensure the stability of the system and to increase the PV penetration.

1. Introduction

As a result of the fuel spill produced by the tankers Jessica and Taurus in 2001 and 2002, the Ecuadorian Government and the German Government through the KFW agreed the implementation of a hybrid system project to satisfy the electricity demand in Puerto Villamil at the Isabela Island in the Galapagos Archipelago which should be based only on renewable energies.

Later on, in the year 2007, the Ecuadorian Government has launched the policy “Cero combustibles fósiles en las Islas Galápagos al 2020”. This policy promotes a radical change in the vision regarding the energy production in the Galapagos Islands. As part of this policy, the Ecuadorian Government remarks the necessity of developing adequate programs and projects to reduce electricity consumption and use the renewable energy resources of the Galapagos Islands with the purpose to eradicate the use of fossil fuels. This program comprises the following strategic actions:

- The gradual elimination of diesel as a part of the electricity generation and it’s substitution by solar and/or wind energy. It also included the use of bio fuels to deal with the fluctuating character of the PV and wind energy providing electric energy in a reliable way.

- The gradual substitution of inefficient appliances for efficient appliances (refrigerators, AC, etc), in order to reduce electricity consumption.

As a result of this policy different projects have been launched in the different Islands in order to turn the actual fossil fuel electricity generating facilities into a zero emission concept to 2020, based on the use of renewable energy resources. According to this, currently in the Galapagos Islands are developing the following projects:

- Baltra Wind Park (2,25 MW) on Baltra Island
- Baltra Photovoltaic Plant (0,2 MWp + energy storage 1,0 MW) on Baltra Island
- Puerto Ayora Photovoltaic Plant (1,5 MWp) on Santa Cruz Island
- Interconnection system Baltra with Santa Cruz
- Isabela Hybrid System (1,0 MWp + energy storage 0,50 MW + thermal plant 1,320 MW)
- Substitution of inefficient appliances (refrigerators)
- Substitution of conventional street lighting system with energy efficient lights

[1] http://whc.unesco.org/en/news/636

With an extension near to 4640 km², the Isabela Island is the biggest Island of the Galapagos archipelago and the third most populated with more than 2500 inhabitants. Due to the rapid increase in the touristic activities, the electricity demand has been growing at very high rates during the last years. The expected peak load demand in 2017 will be around 1MW. Due to its high PV potential, a hybrid system using diesel generation running with jatropha oil, PV and batteries is proposed in order to achieve the cero emission electricity generation goal. Different concepts were analyzed in order to fin the option with the lowest operation cost and the highest PV penetration.

The electric company of Galapagos (Elecgalapagos) is in charge of the electricity generation, distribution and commercialization in the Galapagos Islands. The electricity is generated basically with diesel generators. The diesel is transported from the continent. Isabela electric system includes 667 clients and a power plant with an effective power of 790 kW. The power plant consists of 3 diesel generators which have more than 40,000 hours of operation.

In order to minimize the fuel consumption, the integration of PV is proposed. During the maximal radiation hours, the system is expected to work based on a battery inverter as grid former. An energy storage system is dimensioned in order to supply the load during the day and to save energy during the peak time at night in order to reduce as much as possible the thermal plant generation. The diesel generators will be running with jatropha oil in order to avoid environmental risks during the transportation and to have a cero emission system. Different system options were analyzed in terms of production costs, and fuel saving potential.

2. Load assessment and solar radiation estimation

Fig. 1. shows the actual power demand in Isabela. The Galapagos have two seasons: a rainy season from July to December and a dry season from January to June. During the dry season a higher demand between 12 and 18 hours can be observed due to air conditioning requirements.

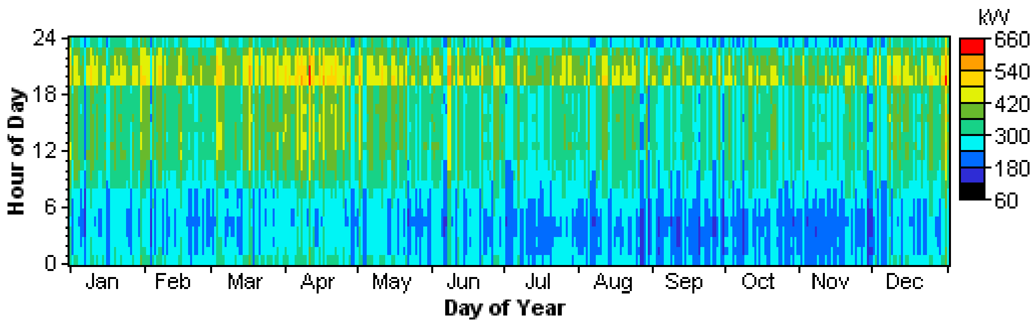

Fig. 1: Actual electricity demand in Isabela Island

The consumer group is predominantly residential, with significant growth of the hotel business. The commercial and industrial consumption is not significant. Projects proposed and approved by the Governing Council of Galápagos and the Municipality of Isabela, cannot be considered a mayor requirement. Anyway this information was considered for setting the projected demand.

Energy efficiency opportunities

Conversion of incandescent lamps to compact fluorescent lamps:
The survey found that there were about 42.4 kW which could be replaced with 14.6 kW giving a saving of 27.8 kW. If these lamps work 4 hours a day could save 40,678 kWh per year. In reference to the total annual demand of energy, the potential saving is about 1.6%

Appliances:
The estimated consumption in appliances (including air conditioning), represents 70% of total energy demand and the estimated savings (5% for some appliances) corresponds to 2.9% of total demand. It is possible to apply the governmental policy for substitution of old refrigerators and air conditioning equipment, mainly in hotels.

Public lighting:
Replacement of sodium 150 W lamps with 70 W LED's lamps is also an opportunity for reducing public street lighting consumption.

The load increase was predicted using measurements from year 2005 to 2010 as shown in Fig. 2. Considering different scenarios of energy efficiency an increment of the annual peak load of 9% is considered.

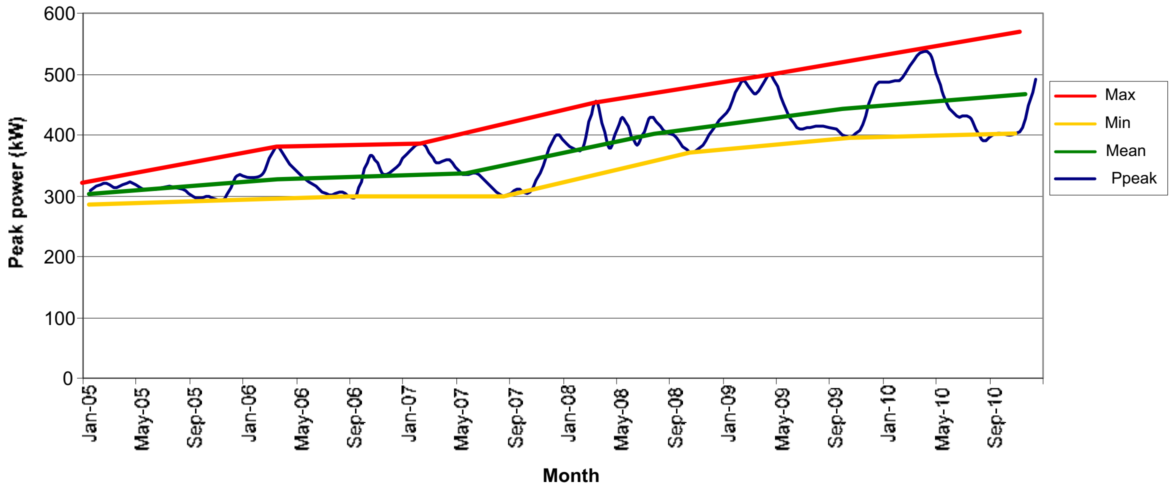

Fig. 2: Load increase tendency in the last years in Isabela

Based on statistical information from the INEC (Instituto Nacional de Estadísticas y Censos), EEPG (Empresa Eléctrica Provincial Galápagos), Hotel Chamber information as well as the operational plans of the Municipality of Isabela and the Galapagos Governing Council, the electricity demand of Isabela Island for the next 10 years was projected. Based on different scenarios, it was detected that the maximum demand in the period from 2017 to 2018 will raise at a rate close to 9% (8.63%) per annum, therefore, the demand can be found in the 977 kW to 1058 kW range. The energy consumption, for the same years will be in the range of 5120 Mwh to 6622 Mwh.

Another important aspect in order to design the system is the behaviour of the load during one standard day. In fig 3, it can be observed how the load behaves along one typical day in a week and in the weekend. These profiles were obtained in a measurement campaign in September and October 2010.

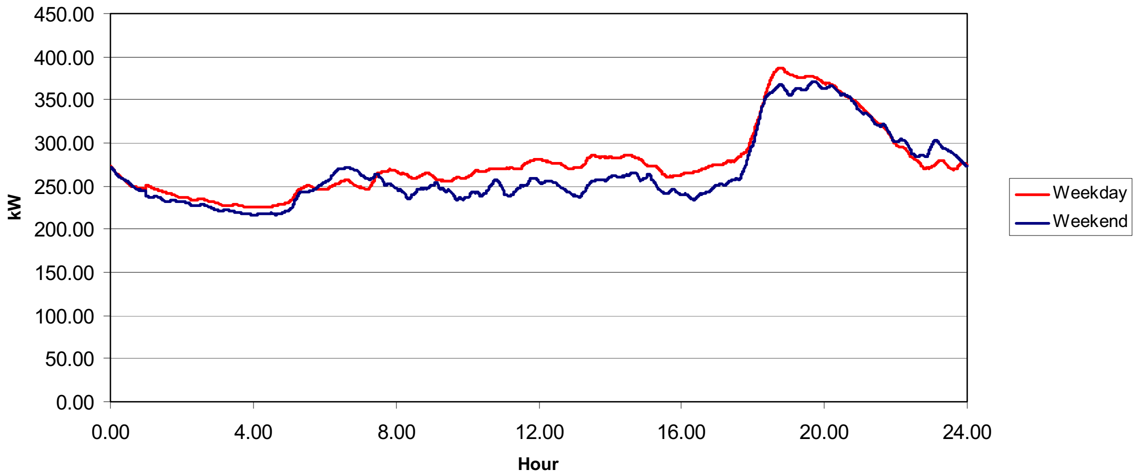

Fig. 3: Load behaviour over the day

For the assesment of the solar resource two sources of data were used: radiation measurements and heliophany measurements. Since the heliophany data was available from the Charles Darwin foundation[1] since 1979, it was used to estimate the long term behaviour of the radiation considering different climatic phenomena like el niño. In fig 4. can be observed the expected average solar radiation for one typical year.

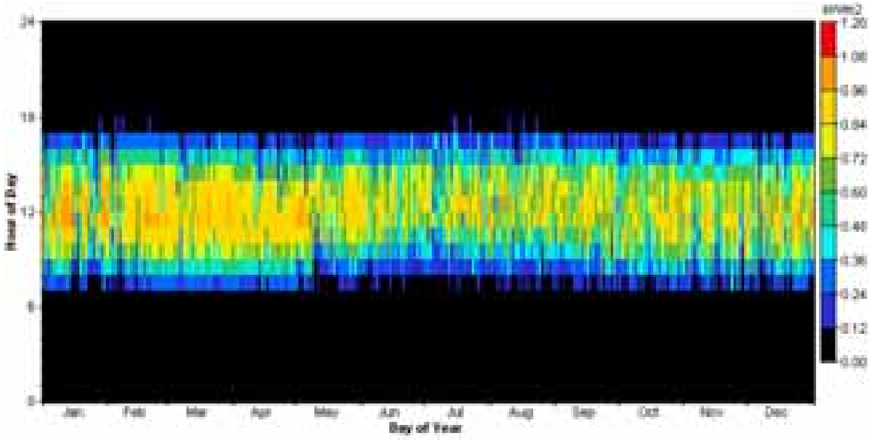

Fig. 4: Radiation conditions in Isabela island during one complete year.

The radiation measurements were taken from a pyranometer installed directly in the island. The radiation data was used together with the heliophany data in order to obtain an estimation of the solar resource.

3. Use of jatropha oil in diesel generators

3.1 Physical and chemical properties

The physical and chemical properties of jatropha oil mainly depend on the type and quality of seeds, the conditions during plant growth, harvesting time of the nuts, post-harvest treatment (pressing, oil extraction method) and refinement. The colour of the oil varies from light to dark yellow. The density varies between 910 and 930 kg/m³ and the kinematic viscosity at 50°C is approximately 32 centistokes (cSt) and a flash point range of 210-270°C.The lower heating value ranges between 36 and 39 MJ/kg. The Cetane Number (measure of ignition delay in IC engines) varies between 44 and 55. The optimum range for diesel engines is 45 to 50.

3.2 Oil processing

The jatropha oil processing is still under research by numerous entities all over the world to determine the most efficient and economic process for pressing (e.g. pre-treatment of seeds, pressing pressure, pre-heating of seeds, etc.) and refining high quality jatropha oil for efficient thermal utilization in the automotive sector (truck and car jet engines) and the power generation sector (high-speed and medium-speed diesel engines).

German research teams recommend that the jatropha oil quality shall be benchmarked against the requirements of the rapeseed standard (DIN 51605) , which should result in achieving good quality jatropha oil for combustion in e.g. diesel engines. Standardization activities are presently on the way in Germany (DIN 51623) and Europe (standard CEN WS 56) to define the quality for different plant oils including jatropha oil.

3.3 Storage, transportation and pumping

Pure vegetable jatropha oil underlies a stronger ageing effect (hazardous to diesel engines) compared to e.g. diesel fuel, due to its enzymatic, catalytic and oxidative properties. It is therefore recommended to limit the storage to approx. 6 months, strongly depending on the prevailing storage conditions and the initial quality of the jatropha oil. Since temperature and solar radiation have a strong impact on the storage stability of jatropha oil, such impacts must be mitigated as far as possible. Consequently, the most appropriate storage

[1] http://www.darwinfoundation.org/

location would be an underground tank. Above ground tanks should be shaded, white painted and be designed as vertical tanks with a preferably small air-oil contact surface to mitigate oxidation processes. Tank materials can be conventional steel (as per API 650), stainless steel (but not necessary) or High-Density-Polyethylene (HDPE). Level measurement devices within tanks must be suitable for jatropha oil operation.

For pumping, transportation and storage of pure vegetable jatropha oil it is strongly recommended to consider the following recommendations to prevent deterioration of the oil's quality:

- avoid contact of the oil with catalytic active metals like copper, copper alloys and non-ferrous metals like brass;
- avoid water contents;
- seals and gaskets shall be of jatropha oil resistant, like Viton;
- flowmeters must be suitable for jatropha oil operation; ultrasonic devices should be preferred.

However, additives like vitamin E improve the storage durability of jatropha oil by means of enhancing its oxidation stability.

3.4 Running diesel engines using jatropha oil

The main difficulty in operating diesel engines with vegetable oils like jatropha oil lies in the high viscosity, density, flammability and certain chemical components and elements like fatty acids and phosphor. Diesel-PPO (pure plant oil) mixtures with up to 10% PPO will not need any modification on the diesel engine to efficiently operate. Above this rate it is recommended to adapt the fuel system and the diesel engine. The modifications are usually tested in long engine operation runs and field observations on an iterative process until the optimum solution for trouble free and efficient operation of an engine type and PPO-fuel is found.

Medium-speed and low-speed diesel engines can easily operate continuously on PPO supposing that the gasket and sealing materials and metals specifications were considered for PPO operation. Key for effective, economic and trouble free operation of high speed diesel engines (to be differentiated between indirect and direct injection engines) are high quality jatropha oil (as per DIN 51605), modification of mechanical parts of the engine and reprogramming of the engine's operation parameters via the Electronic Control Unit (ECU) as below mentioned. The modifications must however enable the efficient engine operation on diesel fuel as well on PPO.

High quality jatropha oil:

- High Phosphate and Calcium/Magnesium content in the oil will block and "poison" high-end exhaust gas after-treatment systems, particulate filters, catalysts and cause heavy deposits on piston crowns, piston rings, glow plugs, turbo chargers, fast deterioration of lube oil (high acidity) and consequently reduce the engine's life span and availability and increase maintenance and repair requirements of the engines.

Main modifications of mechanical parts of the engine & reprogramming of the ECU:

- Modern diesel engine fuel injection systems operate with very high pressures (up to 2000 bar) → PPO has to be heated prior to fuel injection to reduce the viscosity and the injection pressure has to be adjusted to prevent high wear and damage from the injection system;
- Installation of an overpressure relieve valve into the fuel supply line;
- Identification of PPO and diesel fuel for individual fuel conditioning (diesel = fuel cooling; vegetable oil = fuel heating) in an adapted fuel cycle;
- Automatic setting of the ECU for correct operation of engine parameters and to enable smooth fuel switch over to prevent thermal shock on the fuel equipment, especially at the injection pump(s)/elements (John Deere / VWP, Germany);

- Modification of injection nozzles to cope with higher PPO viscosity and improve fuel atomisation;
- Direct injection engines: readjust injection beam positioning against piston crown to improve combustion process (VWP patent; Germany);
- Indirect injection engines: readjust PPO pre chamber positioning to centralize fuel/oxygen mixture to main combustion centre to improve combustion process (VWP patent; Germany);
- Recalibration of the injection pressures and timings of the multiple injections per combustion to meet emission regulations (e.g. VWP patent, Germany);
- Substantial reprogramming of engine's operation parameters;
- Adapt lube oil specification to control fast ageing of the oil due to acid compounds → use lube oils with high Total Base Number.

It is noted that jatropha oil is still not produced and available on commercial level. Only small quantities of variable quality are being produced. It is still difficult for power plant operators to get larger amounts of high quality jatropha oil on a regular basis. Many countries have started years ago with the research and plantation of jatropha for feeding their domestic power projects and transportation sector with jatropha oil in order to reduce the dependency on crude oil.

Many new power plant projects based on PPO/jatropha oil were already kicked-off worldwide. One of it located in the Galapagos Island of Floreana (2 x 70 kW) which began commercial operation in 2011 and the one on the Island of Isabela with a total capacity of 1000 kW to be implemented in 2012. (M. Hofmann u. a. 2008)

4. Selection of the hybrid system concept

In order to make the sizing of the hybrid system, different concepts were evaluated. The methodology for the evaluation of the different concepts is shown in fig 5. The idea is to evaluate the energy costs of different concepts under different conditions.

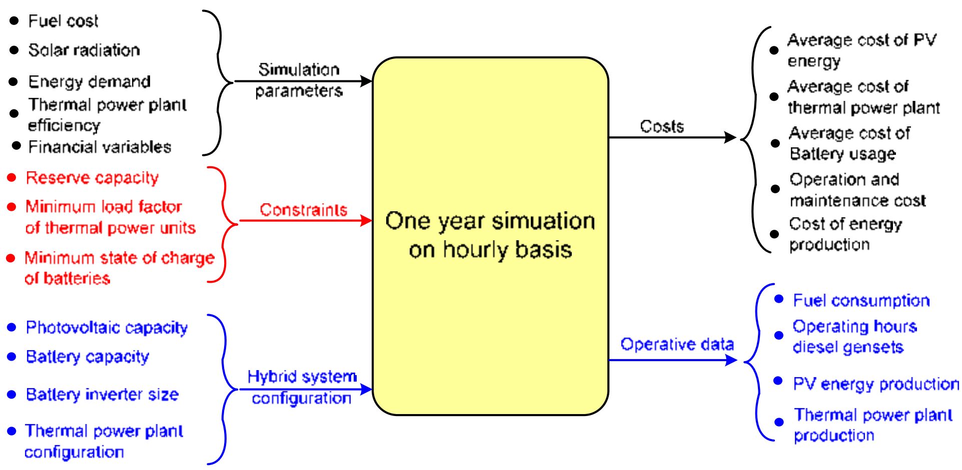

Fig. 5: Evaluation methodology for the different sizing options

The simulation of the different options was performed on the software HOMER. Since HOMER does not consider annual increase on the load, the operating costs were obtained from HOMER for each year with a different load. The simulations were made for each year until 2017. The energy cost calculations and the replacement cost were calculated independently.

4.1 Different options of the hybrid system concept

Four different concepts for the hybrid system are considered:

-PV- Thermal power plant
The PV plant operate in this concept as a negative load and the diesel gensets should cover all the fluctuations by ramping. The PV plant is oversized in order to be able to cope a little bit with the fluctuations by means of limiting power and having some reserve. In this concept the diesel generators must run 20% to 30% below their nominal power to cope with power fluctuations, causing an increase in the maintenance cost specially running with jatropha oil.

-PV-Thermal power plant-small batteries
In this case the batteries are intended to compensate fluctuations of the solar radiations and to avoid ramping operation of the diesel generators. The batteries are sized in such a way that there is always enough time to start another diesel in case of fluctuations of a load or PV power. The normal time to start up and synchronize a diesel is 10 minutes maximum. In this case the PV plant is not oversized and the batteries must cover all the fluctuations. In this case the diesel will operate at the nominal power most of the time reducing the genset maintenance costs.

-PV-Thermal power plant- big batteries (peak shaving).
The objective of this concept is store PV energy during the day in batteries in order to use it at night during peak time. A natural constraint of this concept is the budget available. In this case the batteries are sized to reduce diesel operation at night during peak time (fig 7.). The maximal load time takes from 2 to 3 hours. The start of a third diesel genset during this time is avoided by means of this concept.

-PV-Thermal power plant-big batteries (diesel off).
In order to maximize the fuel savings a concept with the option of a battery inverter forming the grid during the day is proposed. The main advantage of this concept is that it makes possible the system operation in the above mentioned concepts also.

Tab 1. shows the system configuration for the different concepts. These different concepts were simulated in the software HOMER from year 2012 to year 2017 considering a load increase of 8.6% every year. The time step of the simulations was of 1 hour.

Tab. 1: System configurations analyzed

Concept	Diesel capacity	PV	Battery inverter	Battery bank
No batteries	1080 kW	750 kW	-	-
Short term fluctuations	1080 kW	450 kW	300 kW	624 kWh
Peak shaving	1080 kW	1000 kW	400 kW	5000 kWh
Diesel off	1080 kW	1100 kW	500 kW	3400 kWh

4.2 Estimation of energy cost

In order to estimate the energy costs, the maintenance costs, fuel cost and replacement cost were considered. The replacement costs were taken directly from the software HOMER for each year with a different load (load increase) with exception of the replacement costs of the batteries. The fuel costs and maintenance costs were also obtained from HOMER for each year. The battery replacement cost was estimated separately because its lifetime depends highly on the cycling energy and the cycling energy changes year to year because of the load increase.

- Maintenance costs

As rule of thumb it can be generally said that the maintenance costs of diesel is linked to the fuel and lube oil service parts of the diesel engines is roughly doubled due to the requirement of most suppliers of high-speed diesel engines adapted for operation on pure vegetable plant oils to halve service intervals of engines: fuel service parts (e.g. fuel filters, fuel hoses, injection nozzles, respectively injectors, fuel pre-pressure pump) and lube oil service (lube oil change is mostly required after 250 operation hours instead of 500 operation hours with diesel operation). The lube oil filters exchange intervals can usually be kept same as for diesel operation. Frequently checks of the injection pump(s) have to be considered, since material wear might be increased under pure vegetable plant oil engine operation, if the chemical and physical fuel parameters are not correctly set as per the genset supplier's requirements. The exhaust valves shall also be frequently checked to prevent heavy deposits on the valves resulting in not-tight valves (loss of capacity) and burned valves.

PV plant maintenance costs include the annual cleaning of the PV panels and are low in comparison with the maintenance costs of the other components. PV and battery inverters have also low maintenance costs. The maintenance routines of inverters may include replacement of cooling devices, cleaning and yearly inspections. An important cost is the maintenance cost of batteries. The maintenance costs of battery depends a lot on the technology to be employed, and varies also a lot with the specific type of battery to be used. Vented lead acid batteries for example, require a lot of supervision of the electrolyte levels which is not necessary in the case of gel batteries.

- Annual replacement costs
In the case of the diesel generators, the inverters (PV and battery) and the PV panels the annual replacement cost was obtained directly from HOMER. In the case of the batteries, this cost was estimated considering the expected lifetime and some financial variables. A lead acid battery working with a depth of discharge (DOD) limit of 60% can last up to 3600 cycles (BAE batterien). Tab. 2 shows the expected annual replacement cost of batteries for the different options considering a discount rate of 8.67% according to the inflation and reference interests of the central bank of Ecuador[1].

Tab. 2: Expected battery life at 30°C

Concept	Total energy output	Average yearly cycled energy	Expected life	Annual replacement costs
Short term fluctuations	673,920 kWh	175,867 kWh	3.8 Years	37,350 USD
Peak shaving	5'443,200 kWh	505,137 kWh	10.8 Years	83,500 USD
Diesel off	3'628,800 kWh	359,260 Kwh	10.1 Years	56,000 USD

- Fuel costs
The real cost of jatropha oil is a variable difficult to estimate since the supply chain is currently under development. Considering the references from the international markets of palm and soya oil, a price between 1 and 8 USD/Gal is considered in order to evaluate the different options. The base line for the analysis was a fuel price of 5 USD/Gal which is a reference basis comparing with the international price of diesel.

With the total operating cost which include the fuel costs, maintenance and replacement costs the levelized cost of energy (LCE) is calculated in order to compare the different concepts. The levelized cost of energy is the total costs from year 2012 to 2017 divided by the total energy production of the system. The total costs of the system include the inflation rates estimated by the Ecuadorian central bank.

4.3 Comparison of the different alternatives

Fig 6. shows a comparison under different fuel prices. The fuel price is the most critical aspect regarding the economical viability of the system. The concept of a small battery results at the end very expensive and the peak shaving concept is interesting at just for high fuel prices. The temperature is another very important aspect since it affects directly the lifetime of batteries and the annual replacement costs.

Despite the negative effect of the temperature in the lifetime of the batteries, the diesel off option is the best option. Nevertheless it is very interesting option to consider a cooled battery room in order to keep the battery cool in order to enlarge their lifetime.

[1]http://www.bce.fin.ec/

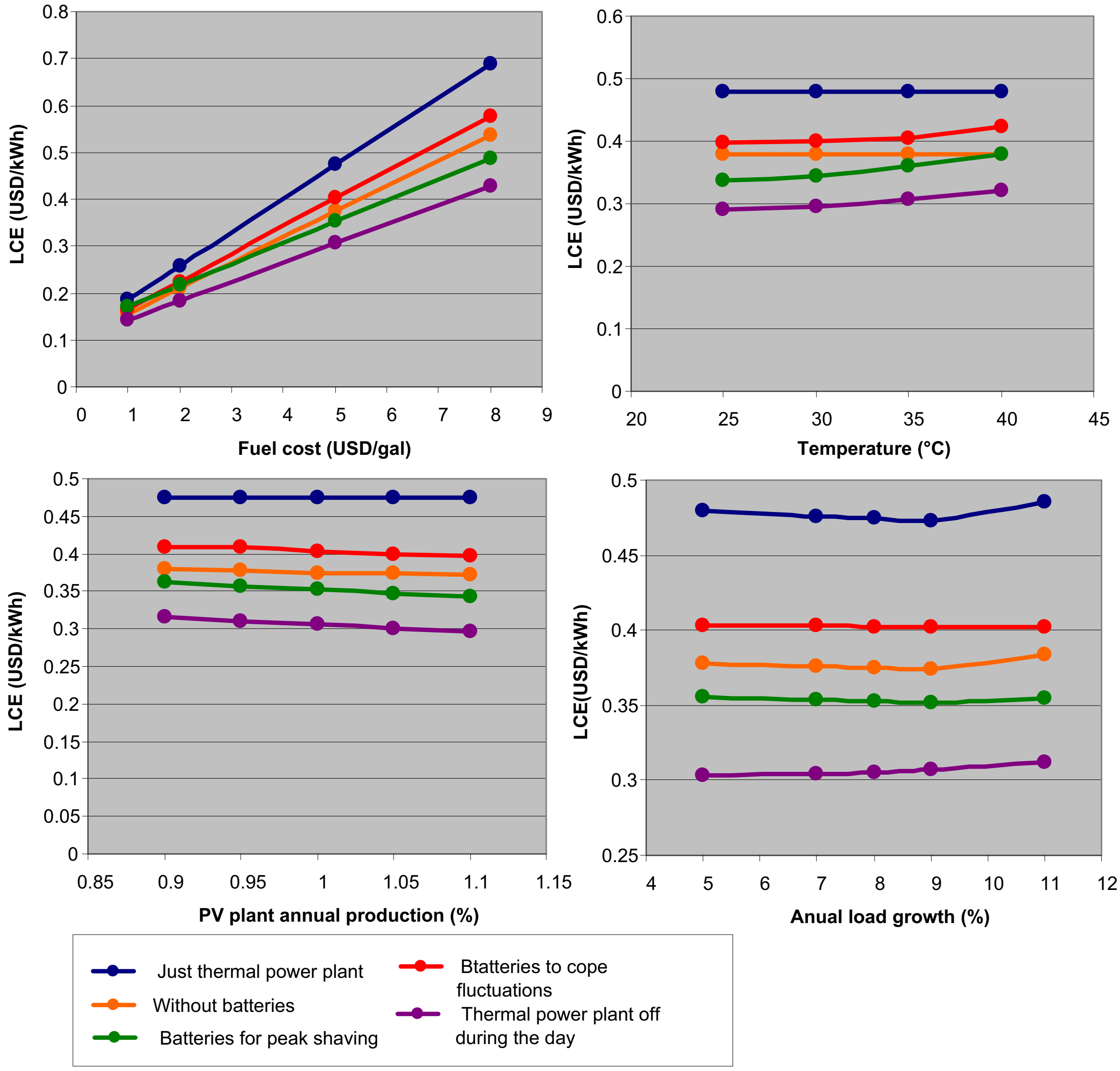

Fig. 6: Comparison of the different options under different conditions

The diesel off concept permits not only the complete stop of the diesel generation during the time of more radiation (fig. 7). It is also possible to avoid the start of a third diesel genset during the peak time. This depends of course on the climatic conditions. It is also important to mention that by means of frequency control it is possible to limit the active power provision of the PV plant. This active power limitation provides also some reserve in case of radiation fluctuations. Fig. 7 presents the expected operation by year 2017.

Another important aspect that has to be taken into account is the temperature of operation of the battery bank. An increase in temperature of operation decreases the lifetime of battery and increases the LCE. Nevertheless the advantages of using a “diesel off” mode remain also under high temperature conditions. It is also important to consider the decreasing price tendency of batteries for the future. This tendency can make other battery technologies better for future expansion of the system.

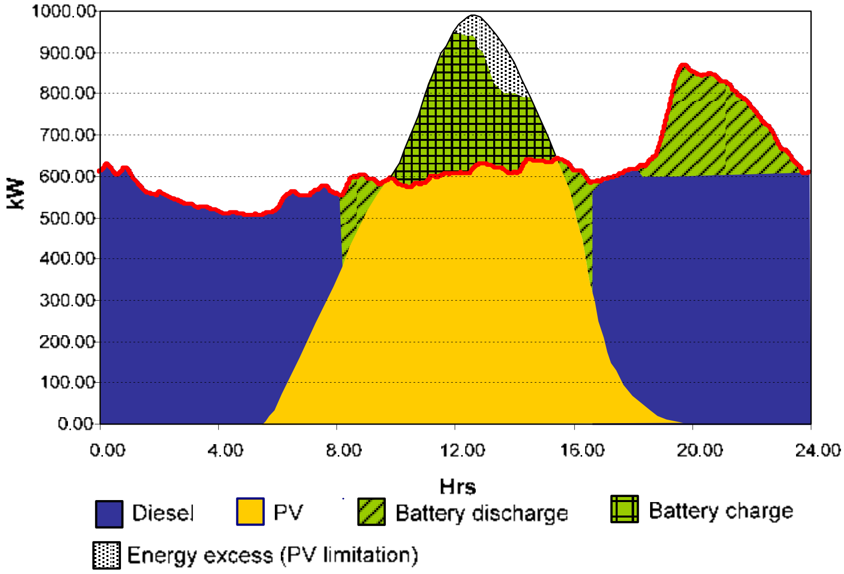

Fig. 7: Comparison of the different options under different conditions

5. Conclusions

From the performed analysis, it can be concluded that the diesel off concept offers the most interesting option for the achievement of a fossil fuel free energy system for the Isabela Island with lower costs. Nevertheless it is very important to take the correct measures in order to make the batteries last as much as possible. The critical factors for the battery are the temperature and the correct management of it.

The diesel off mode also requires the reliable operation of the battery inverter and the diesel generator working in parallel. Both systems must be able to control the voltage and the frequency of the grid in a complete flexible way. The required operation requires that all the units can form the grid in order to enable that all the diesel gensets and the battery inverter could connect and disconnect as required. This kind of operation requires the droop mode operation already studied in (Engler u. a. 2003).

The implementation of a droop concept also facilitates the future expansion of the system without further complicated communication requirements or dispatch algorithms. This is a very important requirement of the system since a high load increase is expected in the next years.

From the control and stability point of view, the implementation of a droop concept permits the automatic regulation an dispatch of the system without any complicated communication requirements. This automatic regulation inherent to electric systems operating in droop mode is also used since a long time in the public grids. Nevertheless it is important to have a supervisory control to perform secondary regulation and also to optimize the use of the different units.

A future development of the system includes intelligent load management by means of the frequency in order to implement a decentralized concept which shifts deferrable loads to the time of maximal renewable generation. This decentralized concept can be also applied for future PV generation in other parts of the electric grid of Isabela.

Considering the price tendency of the fossil fuels to increase, the use of renewable energies and energy storage solutions for such systems will be more feasible in the coming years. Such big scale systems, like the proposed for the Isabela Island require the implementation of concepts like the parallel operation of conventional synchronous generators with battery inverters which can control the grid together in a reliable and stable way. These systems open also the possibility to develop new energy management concepts that involve the consumer. The implementation of this kind of concepts could reduce the operation costs even more and would increase the penetration of renewable also reducing more the environmental impacts in places where the environment preservation is a priority like the Galapagos Island.

6. References

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