Energy Supply in Mini-Grids Regarding Renewable Energies: An Optimization for Petite Martinique

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ABSTRACT

Small islands without grid connection as natural mini-grids are perfect examples for the shift of conventional power generation systems towards renewable energies. Within this work the energy supply system of the Caribbean island Petite Martinique (150 kW peak load, 820 MWh per year) is technological and economic optimized using diesel gensets, photovoltaic, wind power and energy storage systems. The final results show, that a system with a renewable share of almost 85 % is ideal. This system consists of 175 kW PV, one wind turbine (225 kW) and 200 kW / 400 kWh storage capacity saving each year 274,000 liter diesel.

INTRODUCTION

Caribbean islands are highly dependent on fossil fuels for power generation [1]. This leads to relatively high energy costs and high CO_2 emissions per generated kWh [2]. Based on very good natural conditions using renewable energies can be an adequate option to reduce costs and emissions [3, 4].
In this work the energy supply system of the Caribbean island Petite Martinique, Grenada, is analyzed to find the best technical and economic configuration regarding renewable energies. Petite Martinique (PM) has about 1,000 inhabitants living on the island area of 2.4 km^2 without grid-connection to other islands. Thus the results of this analysis can give guidance to operators of other mini-grids on small islands or in remote areas.

At the moment the entire electricity demand of PM is covered by diesel fired generators and the fuel has to be imported. The peak load is 152 kW and the average daily consumption is 2.2 MWh as shown in Fig. 1, which leads to an energy consumption of approximately 800 kWh/year per inhabitant and 819,000 kWh overall [5].

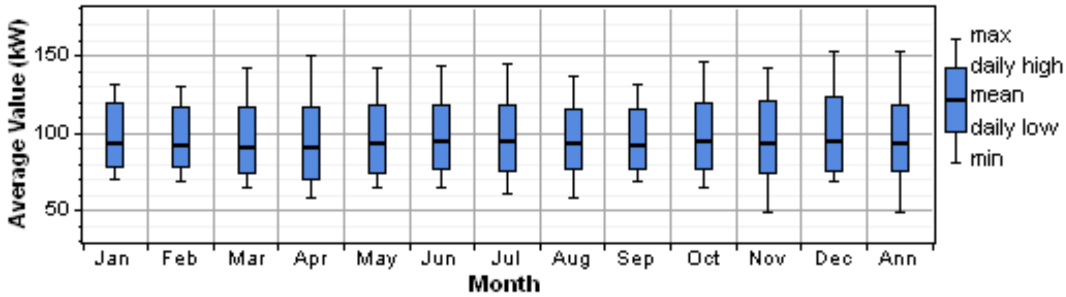

Figure 1: Annual load profile of Petite Martinique.

METHOD AND APPROACH

The first optimization is performed with a simulation tool written for MatLab. It optimizes different power generators and energy storage systems to figure out the most economic supply system under certain conditions. The first constraint is to meet the load each hour under the condition of minimizing the levelized cost of electrictiy (LCOE). The results are shown in continuous steps for different diesel prices. In addition the LCOE of different configurations are shown for one diesel price.

In a second step the technological feasibility according to the grid stability is analyzed with HOMER Energy, developed by the National Renewable Energy Laboratory, U.S. [6]. HOMER Energy also optimizes according to the LCOE as shown in Eq. 1.1 and 1.2. The overall results and a sensitivity analysis should support the local utility to identify the best energy supply system for PM.

$$LCOE = \frac{Capex * CRF(WACC, N) + Opex + Costs_{fuel} * Fuel}{El_{Generated}} \qquad (1.1)$$

$$CRF(WACC, N) = \frac{WACC * (1 + WACC)^N}{(1 + WACC)^N - 1} \qquad (1.2)$$

Equation 1.1: Levelized cost of electricity (LCOE) for power systems. Abbreviations stand for: Capital expenditures (Capex); capital recovery factor (CRF); weighted average cost of capital (WACC); project lifetime (N); operation and maintenance expenditures per year (Opex); cost of diesel per liter ($Costs_{fuel}$); consumed diesel per year (Fuel), generated electricity per year ($El_{Generated}$)

Equation 1.2: Capital recovery factor (CRF) according to weighted average cost of capital (WACC) and project lifetime (N)

RESULTS

The main input data for all calculations and optimizations can be found in Tab.1.

Table 1: Input data for optimizations of the energy supply system of Petite Martinique (data by local utility and suppliers).

	PV	Wind	Battery incl. converter	Diesel gensets
Capex	2,600 USD/kW_p	2,600 USD/kW	1300 USD/kWh_{cap}	0 USD/kW (already inst.)
Opex	30 USD/kW_p*yr	50 USD/kW*yr	5 USD/kWh_{cap}*yr	5 USD/operating hour

Additional input data: WACC: 7.5%, genset efficiency: 25%, full load hours solar PV: 1,800 h/yr, full load hours wind: 2,860 h/yr. Abbreviations stand for: capital expenditures (Capex), operational expenditures (Opex), weighted average cost of capital (WACC).

The PV expenditures are set according to a local tendering. In addition only small wind turbines have been chosen, which are also relatively expensive. As battery system Lithium-Ion batteries are selected. Lead-acid batteries including matching inverters are cheaper than Lithium-Ion batteries, but according to the high ambient temperatures in the Caribbean they are excluded. Their probability of failure significantly increases with higher ambient temperatures and on a small island as PM it is important to have reliable storage systems [7]. Combined with intelligent converters the Lithium-Ion batteries are able to stabilize the grid even under high renewable penetration [8].

Tab. 2 shows the economic optimal energy supply system for a diesel price of 1.20 USD/liter compared to the existing system with diesel gensets only. The levelized costs of electricity of the first optimized system add up to 0.25 USD/kWh, while 80,000 liters diesel per year are consumed. The LCOE are 0.23 USD lower compared to the existing system and around 250,000 liters of diesel are saved every year.

Table 2: Optimized and existing energy supply system for Petite Martinique at diesel price of 1.20 USD/liter.

Configuration	PV [kW]	Wind [kW]	Batteries [kWh]	Capex [USD]	LCOE [USD/kWh]	Diesel cons. [liters/year]
Existing system (diesel only)	0	0	0	0	0.48	330,000
First optimized system	120	260	0	1,000,000	0.25	80,000

As the diesel price is one of the most influencing parameters and very hard to determine for the next 20 years, a sensitivity analysis has been performed. In this analysis the diesel price varies from zero to 6 USD/liter in steps of 0.1 USD for the different optimizations.

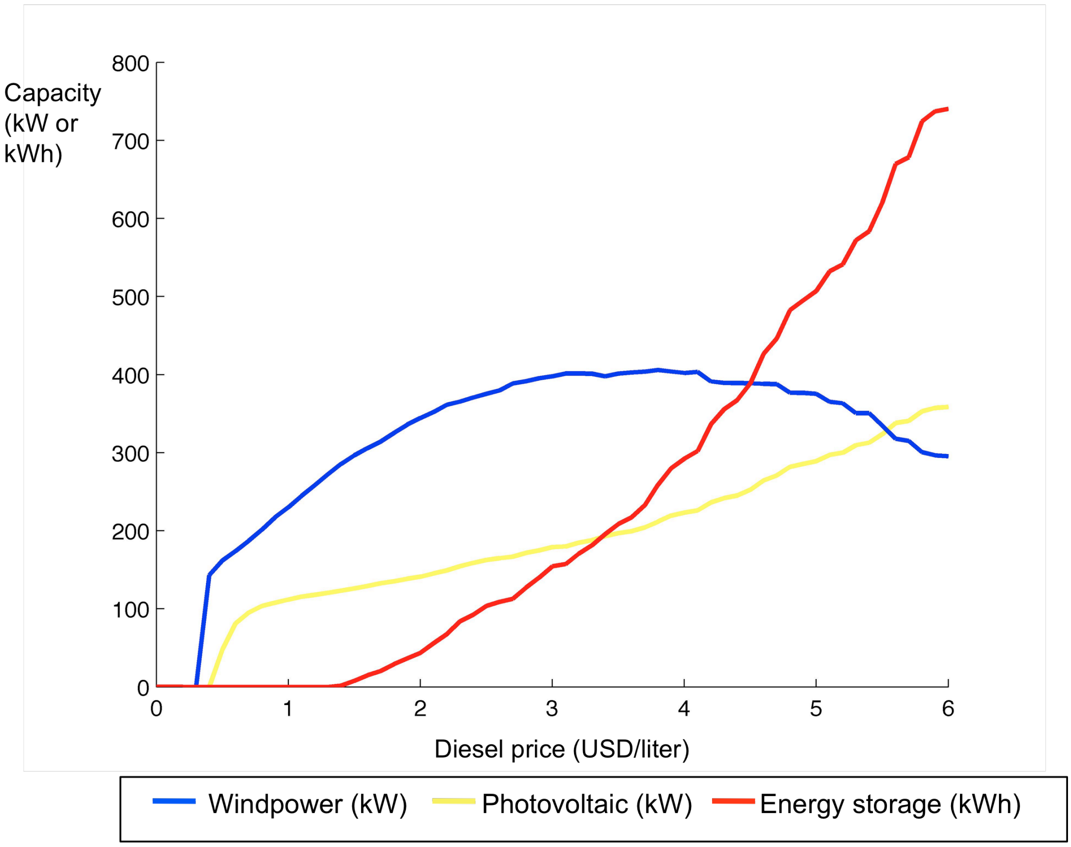

Figure 2: Economic optimized energy supply systems in dependence of the diesel price. This sensitivity analysis depicts the impact of the diesel price on the system configuration.

Fig. 2 shows the results of the sensitivity analysis according to the different diesel prices. Low diesel prices up to 0.30 USD/liter require the existing diesel gensets only, while the installed battery, PV and wind capacity increases with higher diesel prices. Above 3.0 USD/liter the simulation reveals an interesting change. Instead of continuously raising the wind capacity, it is reduced and PV and storage are increasing strongly. This is based on the better synergy of solar power and batteries regarding the load curve at high renewable fractions. Looking at wind power, longer periods of unmet load have to be covered with diesel power generation. At high diesel prices it is more economic to use solar power, which remains similar in the Caribbean almost each day over the year.

Even though it is just beneficial to invest in storage technology at diesel prices higher than 1.4 USD/liter, technological constraints require storage or frequency stabilization systems already at lower diesel prices (equals to lower renewable penetrations) to stabilize the system.

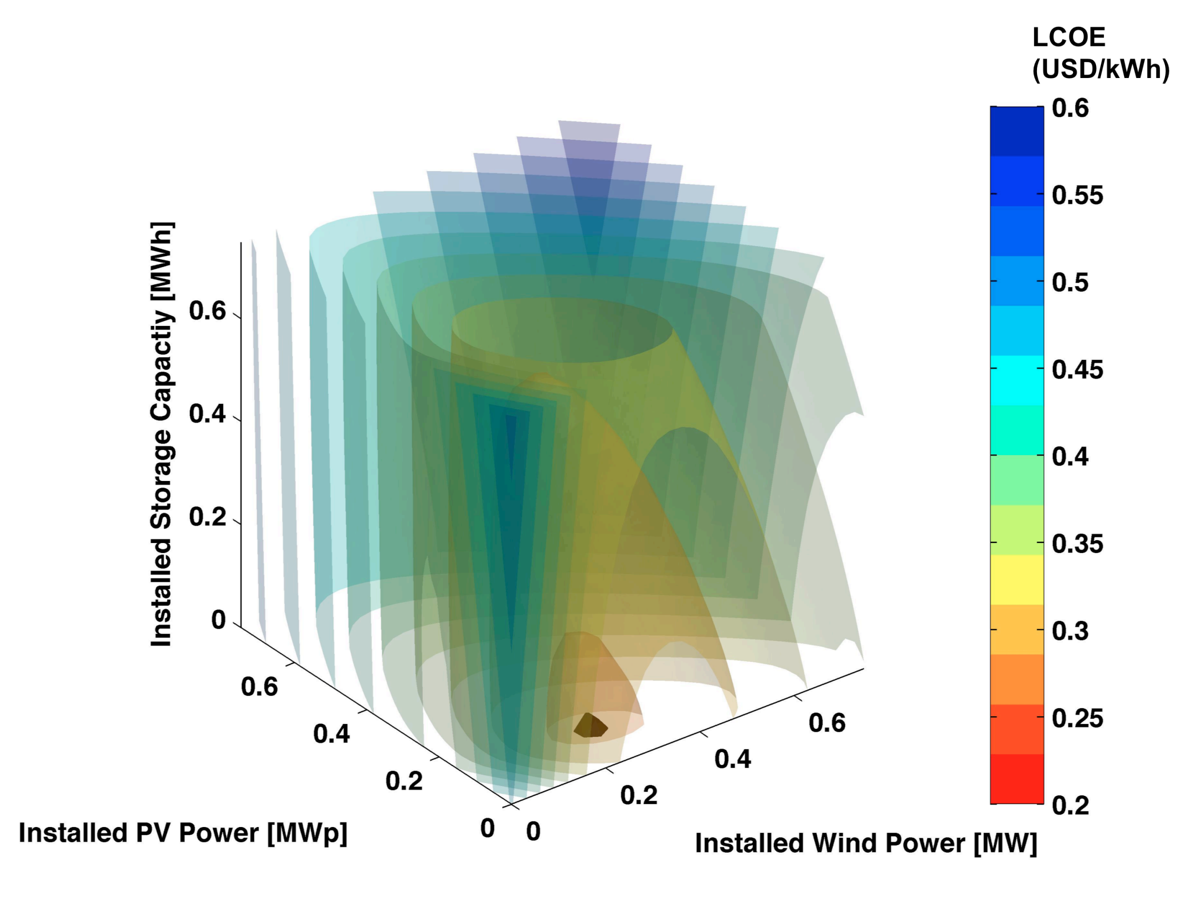

Figure 3: Levelized cost of electricity (LCOE) for different system configurations at the diesel price of 1.2 USD/liter; the black point symbolizes the first optimized system configuration (Tab. 2).

Fig. 3 illustrates the changes in the configuration and their reflectance in the LCOE at the diesel price of 1.20 USD/liter. It can be seen, that the LCOE increase with increased wind or solar power. But they rise slow compared to the dramatical increase of LCOE by reduced renewable energy capacity. In addition an increased storage capacity leads to higher LCOE, but only marginally: plus 200 kWh storage capacity cause 0.01 USD higher LCOE and plus 1,000 kWh cause 0.05 USD additional costs per kWh. Increased storage shifts the ideal system towards more PV and less wind power.

Looking at Fig. 2 and Fig. 3 and taking into account, that the diesel price will probably increase in future, more renewable energy and storage systems should be installed than suggested in Tab. 2. To fulfill the required grid stability and to give a clear

advice to the investor, an additional simulation is performed with HOMER Energy using commercially available technologies as input data.
Based on a technological analysis and in collaboration with local suppliers, the Norwin29 (225 kW) wind turbine [9] and a newly developed Li-Ion battery system (200 kW/ 400 kWh) are chosen. The PV capacity is optimized according to these configurations.

Table 3: Optimized and existing energy supply system for Petite Martinique at diesel price of 1.20 USD/liter.

Configuration	PV [kW]	Wind [kW]	Batteries [kWh]	Capex [USD]	LCOE [USD/kWh]	Diesel cons. [liters/year]	Renewable penetration
Final optimized system	175	225	400	1,560,000	0.30	56,000	83 %

Tab. 3 shows the configuration of the system, which is able to meet the technological constraints according to frequency stabilization, as the battery capacity is higher than the peak load. Thus the battery can fully serve as frequency stabilizer in combination with the inverter. The system is also able to cope with higher fuel costs as predicted in Fig. 2. The combined increase of PV and energy storage follows the suggestion of Fig. 3. In this figure it has been shown, that additional storage makes PV more competitive compared to wind power for PM.
A final sensitivity analysis is performed to see the change in LCOE for the current, the first optimized and the final system according to different diesel prices (Fig. 4).
This clearly shows, that the current system is the least competitive. The first and the final optimization are very close. At a diesel price around 3 USD/liter the final system becomes the most economical. Taking into account, that the final system includes storage and frequency stabilization systems, it is strongly suggested to install this system.
With Capex of 1.56 million USD and Opex of 24,000 USD/year it has a static amortization time of five years. Considering an increasing diesel price, the payback time will be even shorter.

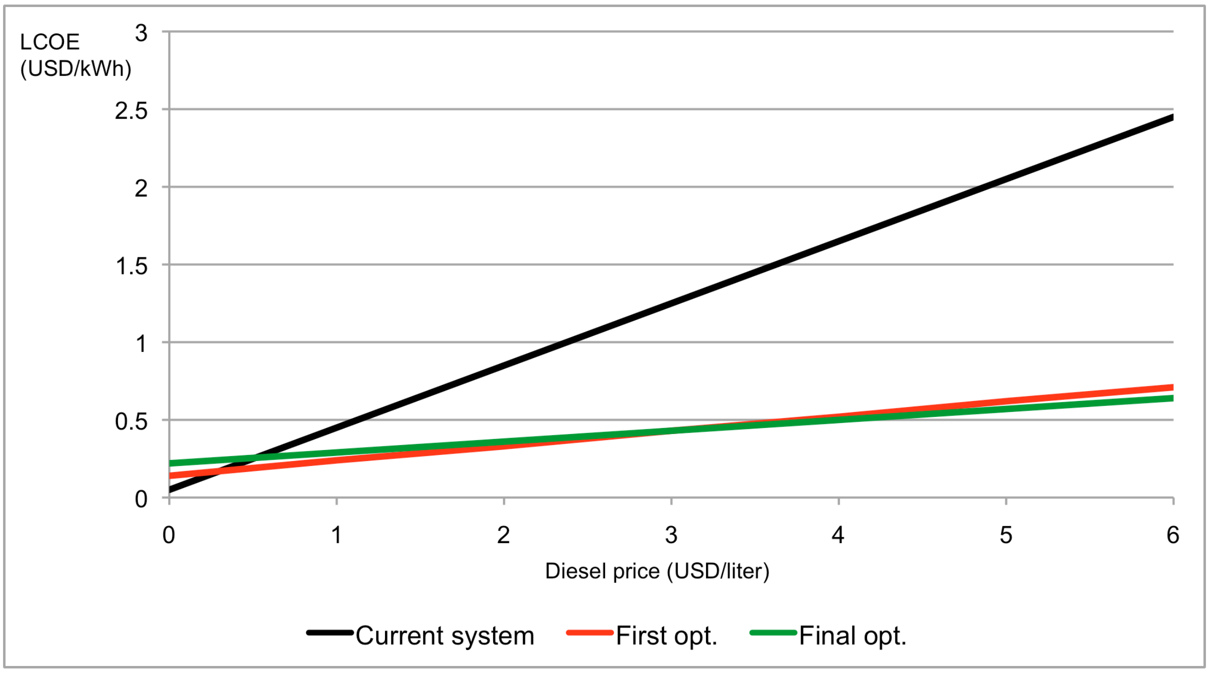

Figure 4: Levelized cost of electricity of the three scenarios according to different diesel prices

CONCLUSIONS

The technically and economic optimized energy supply system for Petite Martinique has a renewable fraction of approximately 85 %, which could be extended to 100% by using bio-fuels. For this scenario the local biomass potential has to be analyzed. Following the suggestions of this research, the local utility should expand the current energy supply system with renewable energies and energy storage systems to reduce costs and emissions. As the optimal system configuration depends strongly on the diesel price, it is difficult to choose the perfect system at the moment. Thus the sensitivity analyses are important to see the development on future prices. The chosen system has proven to be competitive even with increasing diesel prices.

Looking at the significant advantages of the hybrid system compared to the existing power generation by diesel gensets only, other islands and remote areas should take an expansion of their energy supply system with renewable energies under consideration. The MatLab modeling supports the first optimization process to get an idea about the ideal system without taking too much calculation time. HOMER Energy is a valuable simulation tool for a technological and economic optimization. According to this feasibility study, the system can be designed and engineered in detail to finally implement it.

Future research for the MatLab modeling might include deferrable loads, e.g. for seawater desalination, as they are investigated within an additional research work in order to achieve a higher energy output ratio [10].

REFERENCES

[1] Central Intelligence Agency, 2011: Factbook - Maps. http://www.cia.gov/cia/publications/factbook.pdf. February 2011

[2] PetroStrategies, 2010.: Oil transportation. http://www.petrostrategies.org., retrieved in December 2010

[3] Clarke, R., 2006: Overview of Renewable Energy Development in Caribbean SIDS, presented to the High-Level Roundtable on International Cooperation for Sustainable Development in Caribbean Small Island States. Hilton Hotel, Barbados. May 2006

[4] Wright, R. M., 2001: Wind energy development in the Caribbean, Renewable Energy 24, p. 439-444, 2001

[5] Grenlec, 2010: Logsheets Diesel Generators. Handwritten data. January to December 2010

[6] Lambert, E., Gilman, P. and Lilienthal, P., 2006: Micropower system modeling with HOMER. Integration of Alternative Sources of Energy. 2006

[7] EPRI, 2003: EPRI-DOE handbook of energy storage for transmission and distribution applications," tech. rep., EPRI and U.S. Department of Energy

[8] Franzen, E., Strauch, N. and Triebel C., 2010: Switching off the Generator – the Stable Operation of Sustainable Island Grids in the MW Range Using Renewable Energy and Energy Storage, Report younicos AG, Berlin

[9] Blechinger, P., 2011: Energy and Water Supply System for Petite Martinique regarding Renewable Energies A techno-economic optimization. Master thesis, Berlin Institute of Technology, ISBN: 978-3-938720-84-4

[10] Bognar, K., Blechinger, P. and Behrendt, F., 2011: Seawater desalination in micro grids – an integrated planning approach, Energy, Sustainability and Society, SpringerOpen, submitted