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ABSTRACT:
Mobile Telecom antenna towers, or Base Transceiver Stations (BTS) that are located remote from the electrical utility grid are dependent on Off-Grid energy systems. In the past, these energy systems used diesel fuel to generate electricity on site. There are three easy improvements to these systems which greatly reduce or eliminate the creation of CO_2 and the other Greenhouse Gases (GHG) while bringing down the operating expense (OPEX). The paper provides the answers to these three practical questions:

1) How much GHG is actually being generated by Off-Grid BTS tower sites?
2) What can be done to reduce or eliminate the generation of GHG at BTS sites?
3) What are the real financial costs or benefits of this GHG abatement?

BACKGROUND:
The history of generating electricity in parts of the World which are far from electric distribution grids has some common denominators. It is often considered that the difficulties one must overcome and the costs paid just to transport a diesel generator and the fuel to a remote location is painful enough that additional restrictions should not be placed on the energy contractor. Secondly, it has been common to believe that any discussion of carbon footprint or Greenhouse Gas abatement should be focused on the multi-megawatt size coal or diesel fired utility generating plants because the small 16kW remote generator appears to be entirely insignificant by comparison. And perhaps there have also been some feelings that the very apparent benefits of providing the electricity needed for good quality mobile communications and internet access in remote areas far outweighs the long term harmful effects of Greenhouse Gases. The fact that these gases are invisible confounds attempts to increase awareness of the reality.

1) Remote BTS towers are actually a large producer of GHG.

To be clear, we are not discussing the portable generators which are needed for electricity during the workday on a construction project or the emergency back-up generator for a clinic. We need to realize that a BTS must have full power continuously, 24 hours every day. That full duty cycle makes a significant difference in the total GHG generated at the end of any day, month or year.

Over the past decade, the number of remote mobile phone towers along with their diesel generators have steadily increased. What may have been a small amount of GHG generated by this sector ten years ago is no longer insignificant. Africa alone has over 390,000 remote towers. If each BTS tower uses a 16kW generator, the 390,000 remote towers is really a distributed 6.24 GW diesel generation facility running continuously at low efficiency. For comparison, the large coal fired power plants built today are less than 2GW and the majority are smaller than 500MW.

We must also be aware that the generators used at BTS sites are usually built at relatively low cost. It is not affordable to fine tune these small diesel engines for peak efficiency or minimum GHG emissions.

No attempts are made to scrub or otherwise clean up the exhaust. For comparison, the multi-megawatt power plants attract government scrutiny and have strict rules on efficiency and emissions.

2) What can be done to reduce or eliminate the generation of GHG at BTS sites?

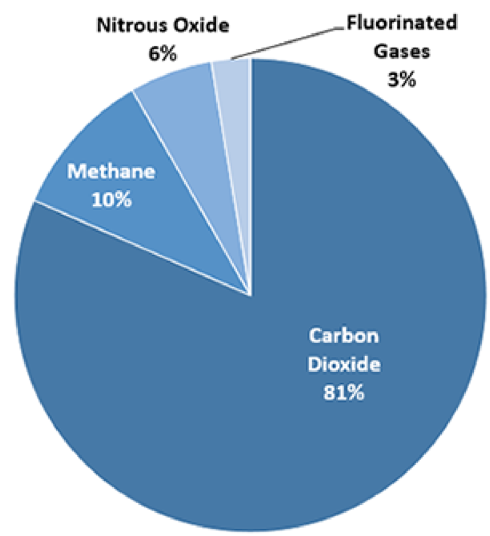
The short answer is simple: Replace the diesel generators with as much solar as will fit on each site. The detailed explanation is not much different. Once installed, solar energy is free. Even the ongoing maintenance is close to zero. The cost is primarily in the Batteries which are required to store energy for the BTS when the sun is not shining. Batteries have a limited number of charge-discharge cycles so they must be replaced after 2 to 10 years. How the batteries are treated by the charger and the load has a major effect on the cycle life and the long term total cost of the energy system.

To establish a baseline, we can determine the exact amount of CO_2 and GHG produced by the typical diesel generator. For this example we will use the average BTS tower load in Sub-Saharan Africa during the period of 2012 to 2018 which was 1.6kW. We also use the popular size diesel generators used which were 16kW. Because the BTS load on these towers is relatively constant, we can calculate the amount of fuel consumed and the CO_2 and GHG created during oxidation.

Every diesel generator, regardless of size, creates exactly 2.639kg of CO_2 per liter of diesel fuel burned. This is a law of chemistry based on the atomic weight of the carbon atom combined with 2 oxygen atoms.

See the pie chart of Greenhouse Gas Emissions at the right. Because CO_2 makes up about 81% of the Greenhouse Gasses generated by burning diesel fuel, we know that every kg of CO_2 represents 1/81% or 1.235 kg of total Greenhouse Gasses. **Therefore, each liter of diesel fuel creates 1.235 x 2.639 or 3.259 kg of GHG**.

The only variable to determine the kg of GHG per kWh of electricity generated is the efficiency of how the generator is operated in the energy system.

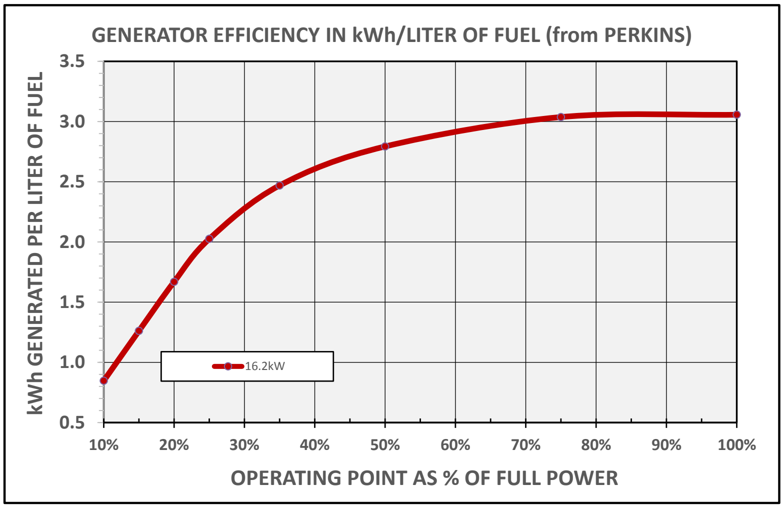


Greenhouse Gases from Diesel Generators

0) DIESEL GENERATOR ONLY – The base case.

Using the specifications of the diesel generators made by Perkins which are typical of all diesel generators, we find that the efficiency for producing electricity is surprisingly low when running below 70% of the full power operating point.

Most BTS Towers use generators that are much larger than required to power the BTS loads. (Above 10kW they are too heavy to steal.) A 16.2kW generator powering a 1.6kW load is running at 10% of the full power and generates only 0.833kWh per liter of fuel consumed.



See the Perkins Generator data in the chart above.

- The Energy required for a 1.6kW BTS load running for 24 hours is 38.4 kWh per day.
- At the generator efficiency of 0.833 kWh / Liter (from the Perkins Efficiency chart above), the daily fuel consumption is 38.4 kWh / 0.833 or 46.08 Liters per day.
- 46.08 Liters per day x 2.639 kg of CO_2 per liter = 121.61 kg of CO_2 per day per site.
- This is 121.61 x 30.42 days per month = 3,699 kg of CO_2 per month per site.
  Expressed in other terms, that is 3.699 metric Tons or 4.077 US Tons of CO_2 per month.

- Because CO_2 is 81% of all GHG, the total GHG per site, per month is 4.567 metric tons, or 5.034 US Tons per month per site.

Knowing the exact amount of GHG produced every month from a standard diesel generator powered BTS site gives us the baseline and the target for reductions. Often the Climate Change field refers to the amount of CO_2 or GHG which has been avoided meaning that it would have been in the atmosphere when using local Electric Utility at the average level of GHG they are claiming. Knowing the actual mix of energy generation fuels on any Electric Utility grid is complex and difficult to prove. In this case however, we know exactly how much CO_2 is generated and therefore the total GHG from diesel, so we have an accurate measure the GHG avoided.

There are three plateaus in technology that provide solutions to reducing or eliminating GHG emissions which greatly improve the base case of a Diesel Generator only:

1) Deep cycle batteries can be added which will allow the generator to run at the 100% rated power point to charge the batteries and then turn off completely for the periods of time while the load runs only from the battery.

2) Solar modules can be added to the system which can eliminate the need for the generator during the daylight hours.

3) Finally, the ultimate energy system uses only solar modules and batteries which are large enough to power the BTS load for a period of time even without sun.

The mission of this paper is to teach how to eliminate or reduce GHG emissions, so each plateau is described in detail. Of course the BTS remote energy systems can be Pure Solar from the beginning which saves a time, trouble and money.

SYSTEM ENERGY FLOW SIMULATION:
The 3 plateaus are described using Energy Flow Simulation Charts. The PV and Genset input with the battery show the fuel consumption. We use the energy flow charts to determine when the generator must run to prevent the Battery State of Charge from going below the worst case Depth of Discharge which would harm the battery. This program takes all the efficiency numbers and losses into consideration.

To understand the resulting charts from the Energy Flow Simulator, use this key:

- The horizontal axis displays one 24 hour day with Noon at the center.
- The left vertical axis is shows the Load, PV and Genset input Power in kW.
- The right vertical axis relates to the Battery Energy levels in kWh.
- <u>The dark Green trace is the critical Battery State of Charge. (The stored energy.)</u>
- The Yellow curve is the maximum solar energy input with local Insolation.
- The Red Line is the constant BTS Load in kW.
- The Light Blue line at the top is the battery maximum capacity when 100% full in kWh.
- The Orange line is the battery at 80% full at the end of Bulk or Constant Current Charge.
- The Black line is the battery energy level at the worst case Depth of Discharge.
- The Brown pulses are the power from the diesel generator when running.

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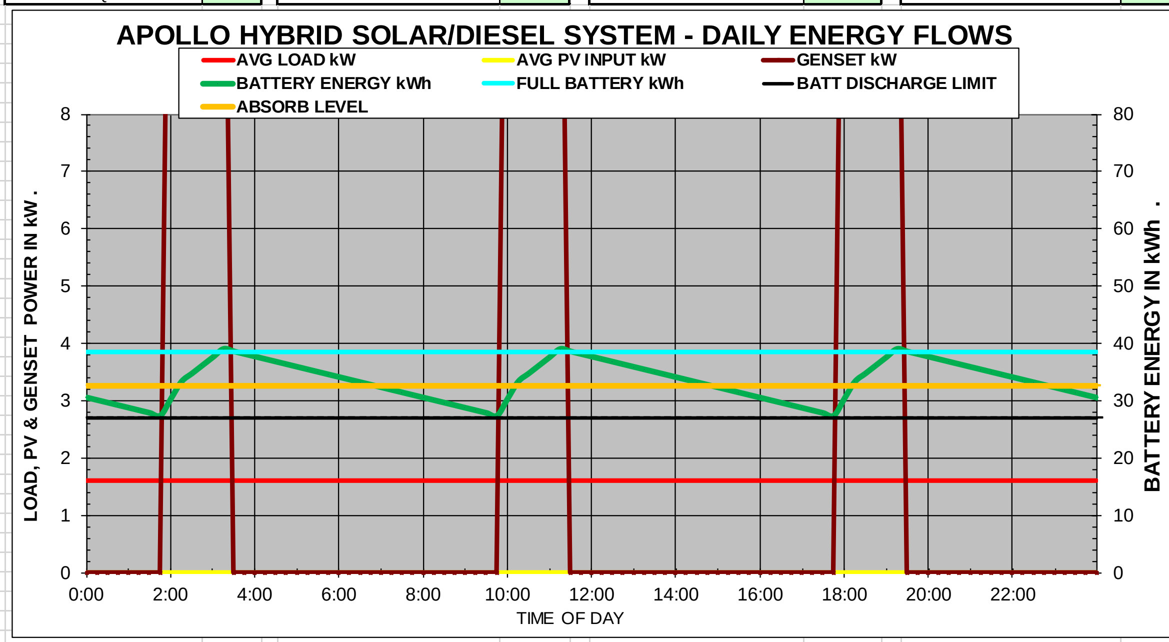
1.60	kW	MODEL:	1	DG + Battery, NO PV	GHG emissions in kg/mo 1724
0		0			

GIVENS		SOLAR ARRAY RESULTS		BATTERY RESULTS		GENSET RESULTS	
TOWER LOAD IN kW	1.60	PV ARRAY IN kW	0.00	MAX ALLOWABLE DoD	30%	GENSET RUN TIME IN hr	4.50
AVG DAILY INSOLUTION	5.85	SQ METERS FOR PV ARRAY	0.0	CAPACITY in Ah at C10	800	RUN TIME AS % OF DAY	18.8%
GENSET SIZE IN kW	16.0	NUM OF T80HV CHG CTLRS	0	CAPACITY REQUIRED IN kWh	38	FUEL USAGE IN LITERS/DAY	17.39
GENSET RUN POINT	100%	PEAK PV CHARGE AMPS	-	MAX BATT CHARGE AMPS	160	FUEL USAGE IN LITERS/MO	529
DG BATT CHARGE AMPS	257	PV ENERGY in kWh/DAY	-	DEEP DISCHARGES / YEAR	1095	TOTAL DG ENERGY kWh/DAY	72.0
ENERGY REQ IN kWh/DAY	47.4	% OF ENERGY FROM SOLAR	0.0%	BATTERY LIFE IN YEARS	1.8	% OF ENERGY FROM DG	151.9%



1) **ADD BATTERIES:** The first plateau "DG+Batt" is shown in the Energy Flow Diagram above:

   The "DG+Batt" systems in the Energy Flow Diagram above are a relatively simple upgrade to existing diesel generator based systems. Because the sites will already have rectifiers in place to convert the AC from the generator into 48 volts DC for the BTS, this is just a task of connecting 48 volt batteries across the DC bus and adjusting the rectifier voltage levels to meet the battery charging specifications. The results of the GHG reduction are a combination of two improvements. First, the generator efficiency can increase from 0.833kWh/liter to about 3.05kWh/liter because it will be running at the 100% power point. Secondly, depending on the size of the battery, the generator can be turned off for a significant number of hours each day.

   The downside issues of the "DG+Batt" plan are not insignificant. First, when the generator is running, it must produce more than twice as much power as the BTS requires because it has to recharge the battery in addition to powering the BTS load. Even though the generator is running at a higher efficiency, it must burn twice the fuel for the recharging function.

   The fuel consumption is higher for another reason. Batteries are not perfect at energy conversion. They lose about 10% of the energy running the load and another 10% when charging. This means that the fuel usage including the price, the delivery costs, and the GHG created will all be about 20% higher than the calculations predict before these losses are considered.

   The most significant cost downside of the "DG+Batt" energy system is the fact that the batteries are used up and must be replaced often. This fact has surprised some tower owners who were enjoying their newfound fuel savings for the first 6 to 9 months only to be surprised that the cost of their second set of batteries wiped out most of the savings. Deep cycle batteries are expensive, heavy and cumbersome to transport and can be difficult to obtain in some parts of the World. The costs to replace them is more than just the cost of the batteries themselves. We can show that a set of batteries for the typical 1.6kW site can be about $5,200. (800Ah at 52 volts sold at $125 per kWh is $5,200.) The fact that they may need replacement every 24 months makes the cost serious. The size and the maximum Depth of Discharge (DoD) determine the cycle life of the battery. Depending on the battery sizing and DoD, the system may put the battery though 3 to 6 charge-discharge cycles every day. Using 3 cycles per day, times 365 days, that is 1,095 deep discharge cycles per year. With the 50% DoD used in some of these systems, the batteries may need replacement in 2 years. The deeper the depth of discharge, the shorter the life.

   The next plateau addresses and solves most of these problems.

2) **ADD SOLAR MODULES:** The second plateau - The Hybrid PV/DG is shown below:

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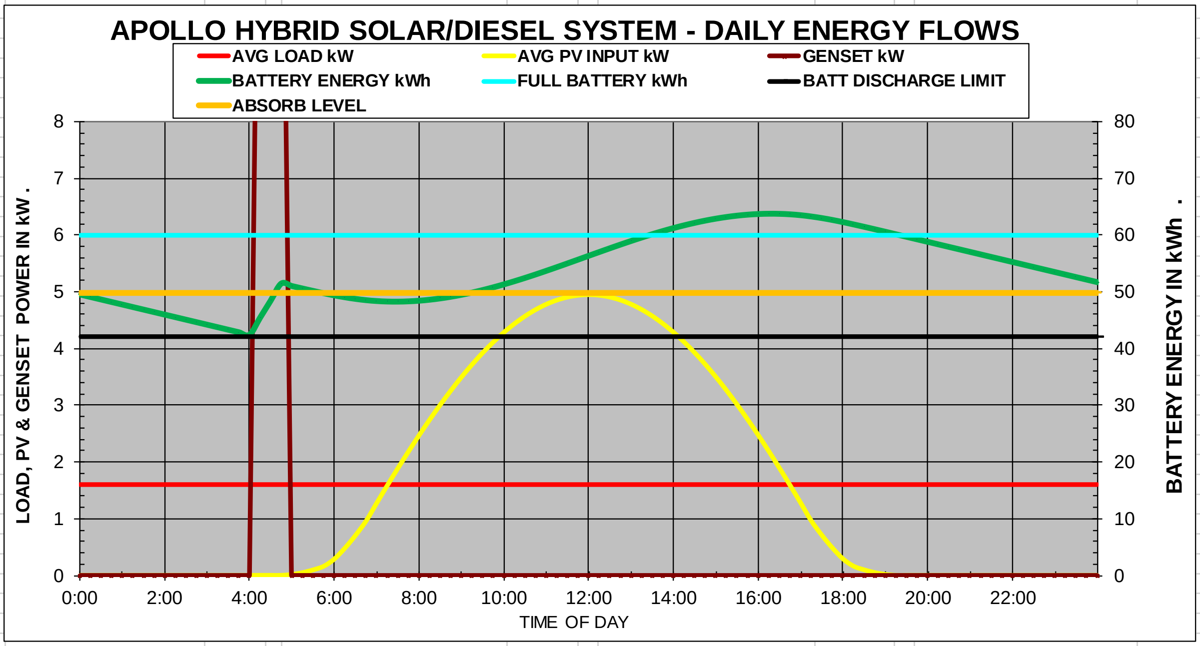
1.60	kW	MODEL:	B	Hybrid 6.3kW PV + DG		GHG emissions in kg/mo	342.6
SENEGAL		GENERIC					
GIVENS		SOLAR ARRAY RESULTS		BATTERY RESULTS		GENSET RESULTS	
TOWER LOAD IN kW	1.60	PV ARRAY IN kW	6.300	MAX ALLOWABLE DoD	30%	GENSET RUN TIME IN hr	0.75
AVG DAILY INSOLUTION	6.01			CAPACITY in Ah at C10	1250	RUN TIME AS % OF DAY	3.1%
GENSET SIZE IN kW	16.0	NUM OF T80HV CHG CTLRS	2	CAPACITY REQUIRED IN kWh	60	FUEL USAGE IN LITERS/DAY	3.46
GENSET RUN POINT	100%	PEAK PV CHARGE AMPS	88.5	MAX BATT CHARGE AMPS	625	FUEL USAGE IN LITERS/MO	105
DG BATT CHARGE AMPS	257	PV ENERGY in kWh/DAY	38.3	DEEP DISCHARGES / YEAR	365	TOTAL DG ENERGY kWh/DAY	12.0
ENERGY REQ IN kWh/DAY	47.4	% OF ENERGY FROM SOLAR	80.8%	BATTERY LIFE IN YEARS	5.4	% OF ENERGY FROM DG	25.3%



Hybrid PV/DG systems shown in the Energy Flow chart above adds Solar or PhotoVoltaic (PV) modules to the existing Diesel Generator and Batteries which is a great step in the right direction. These systems have the same advantages as the previous plateau in terms of generator running point efficiency without the down side of using as much fuel to recharge the battery. The free solar energy during the day is harnessed to both charge the battery and power the load. In a properly designed system, the number of discharges can be limited to one per day, two at the most, so the battery will last for 5 to 7 years and longer if the DoD is limited to 25%.

The hybrid system in the simulation above uses 6.3kW of PV, a 1250Ah battery at 30% Depth of Discharge which has only one 30% discharge per day so it may get over to 6 years of life. The diesel generator is automatically started at 4:00 AM and runs for ¾ of an hour. The sun rising turns the generator off. The fuel consumption is predicted to be 105 liters per month. This plan gets 80.8% of the required energy from solar on average. If there are days of partial darkness, the generator runs longer as needed on those days only.

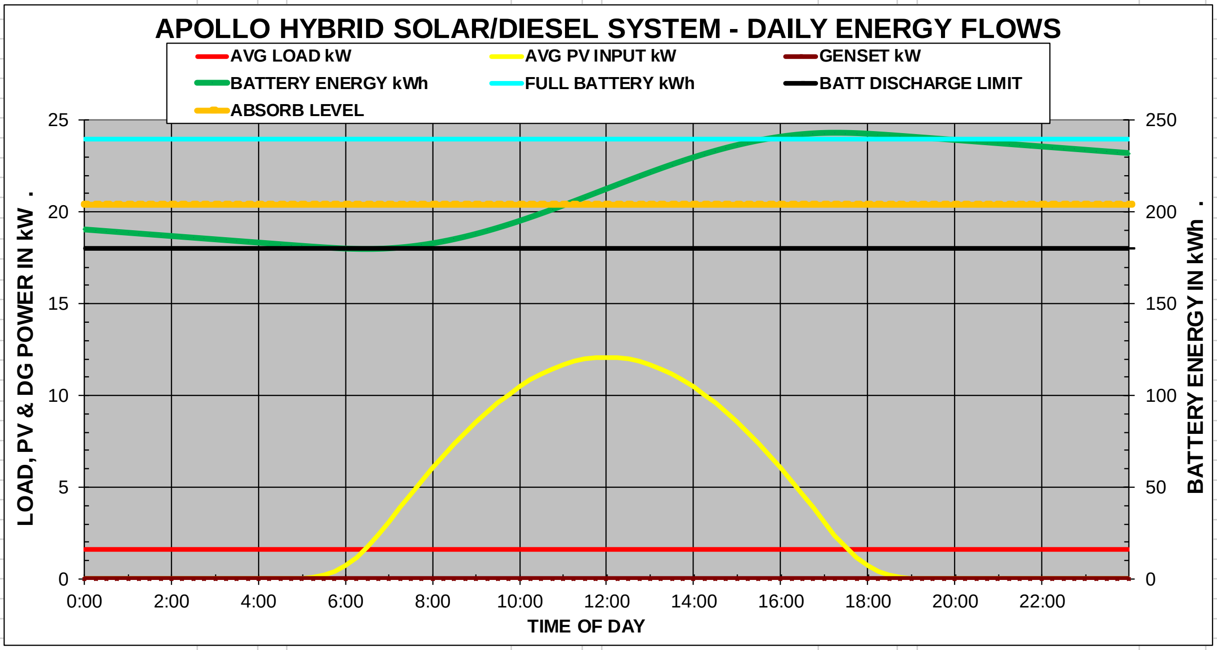
Upgrading to the Hybrid PV/DG configuration from DG+Batt may be easy if the deep cycle batteries are already on the site, have sufficient capacity and are not worn out. The best plan is to install as many solar modules as will fit on the site. For sites with a fence installed at the 15m x15m border or smaller, this can define the amount of solar power. Happily, the energy system can be configured with any percentage of Solar and a good Control System will automatically start the DG to fill in the difference at the appropriate time to keep the batteries charged. The optimum compromise for cost effective operation or sweet spot between CAPEX and OPEX is about 80% solar energy. The 1.6kW BTS in this Hybrid example uses 18 PV modules at 350Watts each.

The critical point is that solar modules do not create any GHG, so the Hybrid PV/DG system for the 1.6kW load site example that was creating 4,568kg of GHG per month using 100% diesel, will create only about 343kg of GHG per month using 80% solar. The cost of the diesel fuel and the run-time related maintenance of the generator is reduced by the same 80%.

The software used to simulate the performance of these remote energy systems yields the average run time of the diesel generator per day along with the fuel consumption and the Greenhouse Gas emissions. The irradiance at any given location is obtained from tables which are compensated for the latitude, the average cloud cover and air quality. The resultant average insolation is used for the hybrid system simulations. When cloudy days limit the solar energy, the diesel generator automatically makes up the difference which averages out over the sunnier months. For Pure Solar systems, the minimum insolation figures must be used which increases the size of the PV arrays required.

3) REMOVE THE GENERATOR – PURE SOLAR This final plateau is shown below:

APOLLO SOLAR - HYBRID PV/DG SIMULATOR - REV 41 - Copyright 2019				8-Apr-19		CONFIDENTIAL	
1.60	kW	MODEL:	5	Pure Solar 17.76kW PV		GHG emissions in kg/mo	0
SENEGAL		GENERIC					
GIVENS		SOLAR ARRAY RESULTS		BATTERY RESULTS		GENSET RESULTS	
TOWER LOAD IN kW	1.60	PV ARRAY IN kW	17.760	MAX ALLOWABLE DoD	25%	GENSET RUN TIME IN hr	0.00
WORST CASE INSOLUTION	5.20	SQ METERS FOR PV ARRAY	103.6	CAPACITY in Ah at C10	5000	RUN TIME AS % OF DAY	0.0%
ARRAY TO LOAD RATIO	11.10	NUM OF T80HV CHG CTLRS	4	CAPACITY REQUIRED IN kWh	240	FUEL USAGE IN LITERS/DAY	-
PV kW PER T80HV	5.0	PEAK PV CHARGE AMPS	187.4	BATTERY TO LOAD RATIO	150	FUEL USAGE IN LITERS/MO	0
DAYS OF PV AUTONOMY	3	PV ENERGY in kWh/DAY	93.4	DEEP DISCHARGES / YEAR	255.5	TOTAL DG ENERGY kWh/DAY	0.0
ENERGY REQ IN kWh/DAY	47.4	% OF ENERGY FROM SOLAR	197.0%	BATTERY LIFE IN YEARS	8.9	% OF ENERGY FROM DG	0.0%



Pure Solar systems shown in the simulation above are the ultimate in remote energy system design. As the name implies, there is no generator and therefore no diesel fuel and therefore no GHG produced. The fuel delivery and theft problems do not exist.

An important benefit of the Pure Solar systems is great reliability. There are no moving parts to require oil, inspection and replacement. And no generators which always need oil changes and other care to make sure they have the best chance of starting every day. Pure Solar sites have proven to demonstrate 100% up time for many years.

In order to provide energy to the BTS during several dark days in a row, the batteries have to be about 3 times larger than a one day Hybrid system battery. The PV modules and the Electronic Cabinet are somewhat more expensive because the PV array must be large enough to recharge the batteries every day, ideally. The 1.6kW BTS load example site when running on Pure Solar will need about 10 times the load. In this example we used 17.76kW of PV modules.

Even though the larger batteries increase the cost of the Pure Solar systems, the fact that no generators or rectifiers are required brings the costs for new Hybrid and Pure Solar systems almost equal.

The only parameter to limit the use of the Pure Solar approach is the size required on the site for the PV Array. The popular 350 watt PV modules measure 1 meter by 2 meters. Wired as 3 modules in series, each 1 kW of PV modules requires essentially 6 square meters of area on the ground. Because many of these systems are installed at less than 20 degrees of latitude, we do not save much space from the trigonometric tilt of the PV array. The PV array is often installed above the electronic cabinet, the batteries and possibly even the generator, so the land can do double duty. The 17.76kW array for the 1.6kW BTS load is going to use 48 PV modules which will need 90 square meters of land area.

With all the advantages of using pure solar, the extra costs for the batteries, modules and even additional land can usually be justified because these sites pay for themselves in about 1 year and after that, the cost of the energy is FREE without additions or unpredictable increases in the price of diesel fuel or maintenance visits. Most significantly, the absolute absence of any GHG means total freedom from any carbon tax or limit in carbon production in the future. This is a multiple win-win because in addition to the tower owner, the ESCO and the MNO, the Planet Earth and all the inhabitants have real benefits.

SUMMARY KPI OF THE RESULTS AT EACH PLATEAU:

APOLLO SOLAR - SYSTEM SUMMARY AND GHG EMISSIONs REPORT	DIESEL GENERATOR	DG + BATTERY	HYBRID PV/DG	PURE SOLAR
Generator Run Time in Hours per day	24	4.50	0.75	0
Diesel Fuel Consumption in Liters per month	1438	529	105	0
Greenhouse Gas emissions in kg per month	4686	1724	343	0
Greenhouse Gas emissions avoided	0	2962	4344	4686
Percentage of energy from solar	0%	0%	78.6%	100%

The Key Performance Indicators of the Diesel Generator Base Case and the 3 plateaus of improvements show the stage by stage steps in minimizing the generator run time, fuel consumption and GHG emissions.

3) –THE FINANCIAL BENEFITS or (COSTS) OF THIS GHG ABATEMENT:

Moving from Diesel Generators to the best choice which is Pure Solar adds the substantial CAPEX for large capacity storage batteries. However, this investment is returned within 1 to 3 years, depending on the local price of the diesel fuel avoided.

The costs of electricity generation in $ per kWh were calculated by Dalberg Analysis for the Dalberg Tower Estimation and Green Potential Model and published in the 2014 GSMA Green Power for Mobile report. For the telecom sites without any grid electricity, the costs were as follows:

- Diesel Generator only (base case) $2.00/kWh
- DG + Battery (Retrofit) $0.85/kWh
- DG + Battery (New) $0.70/kWh
- DG + Battery + Solar (Retrofit) $0.50/kWh
- DG + Battery + Solar (New) $0.45/kWh
- Solar + Battery (New) No DG $0.20/kWh

To compare CAPEX with OPEX calculating the Total Cost of Ownership (TCO) puts both the up-front costs and the ongoing costs on the same chart.

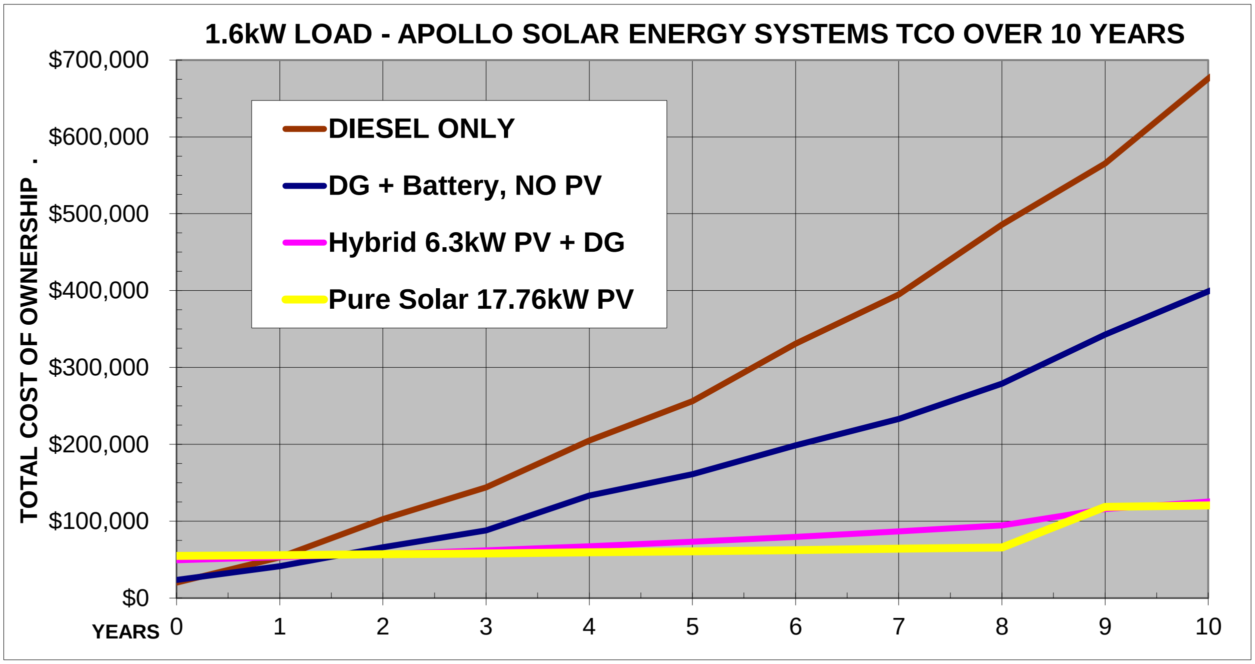
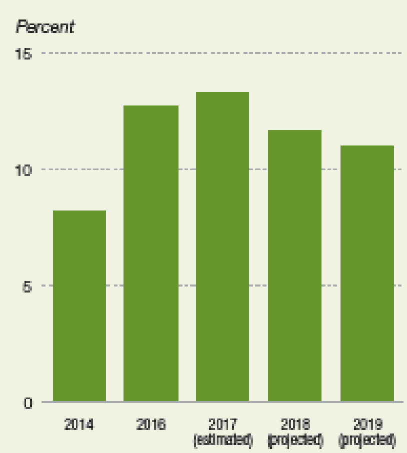


CHART OF TOTAL COST OF OWNERSHIP above shows both the CAPEX and OPEX of base case DG only, and 3 plateaus of improvements: DG+Batt, Hybrid PV/DG and Pure Solar over 10 years.

Although the Diesel Only base case has the lowest CAPEX, each of the improvement plateaus becomes less expensive than the diesel only version in about 1 year. As the TCO Chart shows, after 10 years, the Pure Solar version will cost a total of about $110,000. The Diesel Only version will have cost almost $700,000. The DG+Battery version will cost about $400,000. The Hybrid PV + DG 10 year costs total about $125,000. The Pure Solar plan will cost about $120,000.

The OPEX of the Diesel only and the DG+Batt plans have steep curves on the TCO chart above. The slope is a combination of the Costs of the Diesel Fuel delivered to the sites and the Inflation rate. This chart used US$1.30/Liter for diesel fuel and 11% for inflation. The cost of diesel fuel varies greatly over time and from country to country. We understand that the real inflation rate is over 11% according to the African Development Bank Group. See their chart at the right.

FIGURE 5 West African inflation rate, 2014–19



Source: AfDB statistics.

CARBON TAXES:

Going forward, there is certain to be some form of financial cost to continue using fossil fuels. It is beyond the scope of this paper to describe all the possible carbon 'cap and trade' options, but it is clear that diesel fuel is certain to become more expensive no matter if the carbon taxes are paid at the source or at the borders, or both. If caps are placed on the amount of carbon one can generate, one may not be able to justify the cost of the permits to use diesel fuel at remote towers.

According to the World Bank:

> "Investors and businesses are supported in their response to the TCFD recommendations through the Carbon Pricing Corridor Initiative. The initiative aims to identify the carbon prices needed to achieve the ambitions of the Paris Agreement from a private sector perspective. For the power sector, the initiative found that carbon prices in the range of **US$24–39/t$CO_2$e by 2020 and US$30–100/tCO_2e by 2030** are needed to decarbonize the sector by 2050."
>
> "Half of the ten Organization for Economic Co-operation and Development (OECD) countries with the highest GHG emissions reported the use of internal carbon prices. Internal carbon prices used ranged from **US$5/t$CO_2$e** to over **US$400/tCO_2e** depending on the country, year and sector for which a decision is to be made."

Note that the 1.6kW diesel powered site in our example creates 3.7 tons of CO_2 per month. If the carbon price settles at $24 per ton of CO_2e which could happen in 2020, each site will have to pay $88.80 per month. If the carbon tax is at the top of the World Bank estimations at $400 per ton of CO_2e, the monthly cost per site could be $1,480.