



Case Study

Study of the replacement of HFO and DDO power plants with optimized hybrid PV/LNG power plant for energy transition in Burkina Faso

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Abstract

This article presents the replacement feasibility study in the Burkina Faso's energy mix, the power plants operating on HFO by PV/LNG hybrid power plant and without electrical energy storage. The study is carried out aiming for balance between electricity needs and supply what is being sought there is hybrid PV/LNG power plant electricity kWh cost minimization. The optimal cost of kWh of electricity is obtained by calculating the electricity leveled cost. Simulations results shows that the addition of 300 MW from PV/LNG hybrid power plant in the Burkina Faso's electricity system allows solving electrical power deficit problem with a surplus of 884 MW at day and 389 MW at night, by 2030. On this same horizon, the energy mix cost will drop to below 0.098 \$/kWh. The PV/LNG hybrid system gives a very competitive kWh cost compared to other sources. The PV/LNG hybrid power plant can well replace thermal power plants running on HFO during the energy transition.

Keywords: Energy mix, energetic transition, supply-demand, hybrid power plant, optimization.

Introduction

All human energy activities must face green house gas emissions and the scarcity of fossil and fissile energy resources, which will not be able to meet the increasingly growing demand for electricity indefinitely¹. This is why the recovery of renewable energies and their conversion into electrical energy can be an alternative to meet the electricity needs of future generations and produce a lower impact on the environment^{2,3}.

A serious problem facing the increase in size of renewable energy power plants is the high cost of the initial investment. The cost of producing electricity from renewable energies is still relatively high. Renewable energy associates with conventional energies in hybrid electricity system are necessary for the best optimization of power plants in terms of technical-economic analysis. For the rapid development of hybrid systems, it is necessary that they become more economically attractive^{4,5}. Several criteria are used for the optimization of hybrid systems. The configuration optimization is proposed according to several criteria, including that of the minimum cost of electricity produced^{6,7}. The methods used in power plant optimization procedures are often heuristic methods such as genetic algorithms or software such as Homer, Hybrid², DimHybrid⁸⁻¹³.

This study is taking place in Burkina Faso where electricity is mainly supplied by generators running on HFO and by import¹⁴. Burkina Faso's electricity production is made by photovoltaic

power, hydroelectricity, biomass and above all, from fossil fuels, which are DDO and HFO¹⁴. From an environmental point of view, the choice is oriented towards an energy mix based much more on photovoltaics and other less polluting fossil fuel sources. This is why it is important to study the possibility of integrating hybrid PV/LNG power plant into Burkina Faso electricity production system.

Natural gas is a relatively clean energy source that can replace other more polluting fossil sources in the electricity production. Natural gas is an abundant and inexpensive source of energy. Its use in the energy mix will enable the transition to exclusive use of renewable energies¹⁵. Global natural gas reserves are enormous and the duration of its exploitation is estimated between 80 and 250 years¹⁶. Global natural gas trade was 245.2 million tonnes per year in 2015¹⁷. Natural gas in its liquid form is called liquefied natural gas (LNG). Natural gas liquefaction is achieved when its temperature is lowered to 160°C. Liquefaction of natural gas allows its transport from producing countries to others that use natural gas as fuel for power plants¹⁸. The natural gas liquefaction is growing strongly. In 2016, it represented nearly 32% of total natural gas flows worldwide¹⁹.

The work carried out in this study focuses on PV/LNG hybrid power plant sizing optimization. This hybrid power plant, composed of photovoltaic solar and natural gas-powered generators is an alternative to heavy fuel oil and Diesel

Distillate Oil power plants. Electricity production from PV/LNG hybrid power plant will contribute to stabilizing the electricity grid and reducing green house gas emissions. This involves offering an alternative to highly polluting fuels use in Burkina Faso's electricity production system. In addition, the hybrid power plant will address the electrical grid static and dynamic stability problems.

This work aims to study the possibility to replace heavy fuel oil (HFO) power plant with hybrid PV/LNG power plants, in the Burkina Faso's electricity production system. An analysis will be carried out on the result of comparison between the electricity production costs of the PV/LNG hybrid plant and those of the HFO plant.

The study place presentation: Burkina Faso location and its neighboring countries are represented in Figure-1.



Figure-1: Burkina Faso location and its neighboring countries.

The location of this country is between 9 and 15° north latitude, 2°30' east longitude and 5°30' west longitude. It is limited to the East by Niger, to the North and West by Mali, to the South by Ivory Coast, Ghana, Togo and Benin.

Electricity production in Burkina Faso: Electricity supply in Burkina Faso is done by thermal power plants of 394.1 MW, hydroelectricity of 33 MW, photovoltaic power plants of 60.1 MW and by importing a capacity of 350 MW of electricity from Ghana and Cote d'Ivoire. In 2015, available electrical capacity is 325 MW. In 2020, this capacity increased to 800 MW. In 2025 horizon, 1000 additional localities must be electrified and one (1) million more subscribers²⁰. The national interconnected grid is not capable to provide, at all times the requested power. The electricity grid in ability to meet electricity demand, places it permanently in static instability.

Methodology

In this paper, a PV/LNG hybrid power plant and without storage technical-economic analysis is carried out. What is sought there is to minimize the kWh cost of produced electricity by hybrid

power plant. Electricity production continuity is ensured by LNG generators in sunlight absence.

Modeling solar energy: Global solar irradiation is the sum of direct irradiation and diffuse irradiation.

The direct radiation on a horizontal plane is given by equation (1).

$$S_{DR} = 1370 \times \exp \left[-\frac{T_L}{0.9 + 9.4 \times \sin(h)} \right] \times \sin(h) \quad (1)$$

Where: S_{DR} is direct radiation, T_L is Link trouble factor, h is the sun height.

Equation (2) gives the solar diffuse radiation expression.

$$S_{DifR} = 54.8 \times (T_L - 0.5 - \sqrt{\sin(h)}) \times \sqrt{\sin(h)} \quad (2)$$

Modeling natural gas: In the natural gas classification, there are three categories²¹: natural gas which contains almost 98% of methane, a density of 427 kg/m³ is called light natural, natural gas which contains almost 90% of methane, 7% of ethane and propane, whose density is 445 kg/m³, is designated medium natural gas. Heavy natural gas is which contains almost 88% of methane, 12% of ethane, propane and butane, with a density of 464 kg/m³.

Good quality natural gas has a significant heat capacity due to the presence of a high percentage of methane. The adiabatic temperature of the flame during the combustion of natural gas is proportional to its lower calorific value (LCV), itself proportional to the percentage of methane in the gas.

Liquefied natural gas combustion modeling: The temperature of the natural gas combustion flame can vary between 800 and 1100°C, depending on the methane concentration in the gas. Natural gas containing 50% methane has a flame temperature of 870°C²². In LNG combustion, methane is the most difficult hydrocarbon to oxidize. Relation (3) gives the methane combustion equation.



Where: CH_4 is methane chemical formula, O_2 is oxygen chemical formula, CO_2 is carbon dioxide chemical formula and H_2O is water chemical formula.

The natural gas combustion releases a lot of heat. Combustion begins at around 800°C, in the absence of catalyst and when the radical's concentration becomes sufficiently high for the reaction to begin.

Natural gas generator modeling: The performance of engines running on LNG is described by several parameters, including overall efficiency and specific consumption. Specific consumption is expressed in g/kWh or Nm³/kWh for gas generators^{23,24}. Relation (4) gives the specific consumption.

$$SC = a \times P^2(t) + b \times P(t) + c \quad (4)$$

Where: SC is specific consumption, a , b and c are the generator characteristics, $P(t)$ is the generator output power. Relation (5) expresses the generator overall efficiency²⁴.

$$\eta_G = \frac{3600}{ICP \cdot SC} \quad (5)$$

where: η_G is the generator efficiency, ICP is the natural gas lower calorific value, SC is the generator specific consumption.

Modeling photovoltaic field: A photovoltaic field produces electricity directly by converting the sun's radiation. A photovoltaic field is an assembly of several photovoltaic modules with the aim of producing the desired electrical power. Photovoltaic modules main device is PV cell. Cells are connected in series then in parallel to form a module corresponding to a given electrical power. To know the photovoltaic field electrical output power, PV cell understanding and modeling is necessary²⁵.

The most popular model used to represent PV cell is the single-diode model^{26,27}. It imitates physical photovoltaic cells behavior better than ideal PV cell model²⁸.

Electrical diagram of single-diode equivalent circuit model is shown in Figure-2.

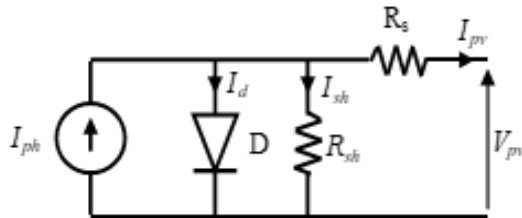


Figure-2: Single-diode model diagram.

The shunt resistor existence, represents construction defect which causes leakage currents within the photovoltaic cell. All high conductivity parallel branches (shunts) release carriers produced by solar irradiation through the PV cell PN junction^{29,30}. Relation (6) gives the single-diode model output current³¹.

$$I_{PV} = I_{ph} - I_s \left[\exp \left(\frac{q(V_{PV} + R_s I_{PV})}{akT} \right) - 1 \right] - \frac{V_{PV} + R_s I_{PV}}{R_{sh}} \quad (6)$$

Where: I_{PV} is PV cell output current, I_{ph} is generated photo-current, I_s is diode saturation current, a is diode ideality factor, V_{PV} is PV cell terminal voltage, k is constant of Boltzmann, q is electron's charge, T is PN junction temperature, R_{sh} is serial resistor, R_{sh} is shunt resistor.

The equation (7) gives the PV cell output power.

$$P_{PV} = I_{PV} V_{PV} \quad (7)$$

Where: P_{PV} is PV cell output power, I_{PV} is the PV cell output current, V_{PV} is the PV cell terminal voltage.

Modeling inverter: The inverter input power is the PV field output power. Inverter output power can be expressed by equation (8)³².

$$P_{Inv,out} = EF_{Inv} P_{Inv,in} \quad (8)$$

Where: $P_{Inv,out}$ is inverter output power, $P_{Inv,in}$ is inverter input power, EF_{Inv} is inverter efficiency.

with:

$$EF_{Inv} = \frac{P_{red}}{P_{red} + P_0 + kP_{red}^2} \quad (9)$$

And

$$P = \frac{P_{Inv,out}}{P_n} \quad (10)$$

Where: EF_{Inv} is inverter efficiency, P_{red} is the inverter reduced power, P_0 and k are coefficients provided by manufacturer.

Technical-economic study: In this process, the initial investment, maintenance and operation cost, renewal cost and residual value of the hybrid power plant are considered in the calculation of hybrid power plant electricity production cost³³.

He is wanted here, the cost equation minimization. This equation is a function of generating elements size, while respecting the hybrid power plant energy constraints. The electricity kWh cost produced by the hybrid power plant is determined by LCOE (Levelized Cost Of Electricity)^{34,35}.

Hybrid power plant LCOE is determined by calculating the net present value of generating elements. This consists of reducing to their present value all expenditures during the project lifetime. Relation (11) gives LCOE expression.

$$LCOE = \frac{I_0 + \sum_{d=1}^n \frac{A_d}{(1+i)^d}}{\sum_{d=1}^n \frac{M_{elect}}{(1+i)^d}} \quad (11)$$

Where: $LCOE$ is the levelized cost of electricity, I_0 is the investment cost, d is the project lifetime, A_d is the expenditures during the project lifetime, M_{elect} is the produced electricity during 1 year, I is interest rate, n is operational lifetime.

Results and Discussion

The project lifetime in this study is 25 years. Costs are calculated for a power plant of 150 MW power, using only LNG as fuel, 150 MW power plant using only HFO, 150 MW photovoltaic plant and 300 MW PV/LNG hybrid plant.

Costs of power plants produced electricity: Table-1 gives the electricity production costs of the power plant using only HFO and the weight of each component in the electricity kWh cost.

Table-1: HFO power plant electricity costs.

Cost components	Cost (\$/kWh)	Weight (%)
Investment cost	0.02039	12
Interest and other charges	0.00663	4
Fuel cost	0.13281	80
Lubricant cost	0.00335	2
Operating cost	0.00269	2
kWh cost	0.17566	

The electricity kWh cost produced by the power plant using only HFO is 0.17566 \$. The fuel cost is 0.13281 \$/kWh, or 80% of the kWh cost, followed by the investment cost which amounts to 0.02039 \$/kWh, or 12% of the kWh cost. The observation is that the fuel cost occupies the largest share in the electricity kWh cost. This is explained by the fact that the purchasing and transporting fuel costs considerably increases the electricity kWh cost and makes it less competitive. In addition, all equipment's are imported, which increases the investment cost. Table-2 gives the produced electricity costs by the LNG power plant and the weight of each component in the electricity kWh cost.

Table-2: Electricity costs of LNG power plants

Cost components	Cost (\$/kWh)	Weight (%)
Investment cost	0.02140	17
Interest and other charges	0.00696	5
Fuel cost	0.09484	73
Lubricant cost	0.00336	3
Operating cost	0.00269	2
kWh cost	0.12927	

The electricity kWh cost with LNG power plant is 0.12927 \$. The natural gas cost is 0.09484 \$/kWh, or 73% of the kWh cost, followed by the investment cost of 0.02140 \$/kWh, or 17% of kWh cost. Fuel cost is the largest part of electricity kWh cost. The purchasing and fuel transporting costs considerably increase the electricity kWh cost and makes it less competitive. In addition, all equipment's are imported, which increases the investment cost.

However, the cost of electricity produced from LNG (0.09484 \$/kWh) is lower than the cost electricity produced from HFO (0.13281 \$/kWh). The investment costs in both being approximatively the same, the electricity production from LNG turns out to be the best suited.

For the 100% photovoltaic power plant, costs are calculated for 150 MW of PV plant. Table-3 gives the produced electricity costs by the PV plant and the weight of each component in the electricity kWh cost.

Table-3: Photovoltaic power plant electricity costs.

Cost components	Cost (\$/kWh)	Weight (%)
Investment cost	0.067188	81
Interest and other charges	0.014637	18
Fuel cost	0	0
Lubricant cost	0	0
Operating cost	0.00075	1
kWh cost	0.08257	

The produced electricity kWh cost is 0.08257 \$. The investment cost is 0.067188 \$/kWh, or 81% of the electricity kilowatt-hour cost. Subsequently, other financial charges is estimated at 0.014637 \$/kWh, or 18% of the kWh cost. The investment cost constitutes the main cost in the electricity kWh cost with photovoltaic power plant. Fuel and lubricant costs are zero and operating costs are very low (0.00075 \$/kWh), or 1% of the electricity kWh cost.

For the hybrid electricity production system, combining 150 MW PV generator and 150 MW LNG generator, the costs are calculated for PV/LNG hybrid power plant. The electricity production costs details and the weight of each component in the kWh cost are given in Table-4.

The composition of the cost per kWh in the case of hybrid PV/LNG power plant, the fuel cost is 0.075077 \$/kWh, or 63% of the kWh production cost, followed by the investment cost of 0.03095 \$/kWh, or 26% of the kWh production cost. Building cost of power plant using liquefied natural gas is very high. In

the case of such power plant, regasification device must be integrated, which generates an additional cost.

Table-4: Electricity costs of the PV/LNG hybrid plant.

Cost components	Cost (\$/kWh)	Weight (%)
Investment cost	0.031	26
Interest and other charges	0.008	7
Fuel cost	0.075	63
Lubricant cost	0.003	2
Operating cost	0.002	2
kWh cost	0.119	

Comparison of electricity production costs: Table-5 gives the produced electricity kWh cost of HFO, LNG plant, PV power plant and PV/LNG hybrid plant.

Fuel expenses in the case of a hybrid PV/LNG power plant (0.11949\$/kWh) are low compared to those of HFO power plant (0.17566\$/kWh) and power plant running only on liquefied natural gas (0.12927\$).

Analysis of the hybrid PV/LNG power plant impact on the energy mix: PV/LNG hybrid power plant electricity impact on the energy mix is analyzed. The gaps between electricity supply and demand analysis makes it possible to determine whether the national interconnected grid (NIG) is in a situation of energy surplus or deficit. Table-6 gives the gaps between available power and demand for electrical power from 2022 to 2030.

A deficit in daytime and night time supply is observed in 2022. In 2023, a deficit of 52 MW observed at night and a surplus of 103 MW in daytime. From 2024, electricity supply exceeds demand. In 2030, electricity surpluses will be 619 MW during the day and 124 MW at night.

The PV/LNG hybrid power plant operationalization is planned for 2023. Table 7 gives the gaps between electricity supply and demand after the PV/LNG hybrid power plant commissioning.

Table-5: Comparison of power plant electricity costs.

Cost components	Cost (\$/kWh)			
	HFO power plant	GNL power plant	PV power plant	PV/LNG hybrid power plant
Investment cost	0.02039	0.02140	0.067188	0.03095
Interest and other financial charges	0.00663	0.00696	0.014637	0.00854
Fuel cost	0.13281	0.09484	0	0.075077
Lubricant cost	0.00335	0.00336	0	0.002656
Operating cost	0.00269	0.00269	0.00075	0.002249
kWh cost	0.17566	0.12927	0.08257	0.11949

Table-6: Gap between electricity supply and demand without the hybrid power plant.

Year	2022	2023	2024	2025	2026	2027	2028	2029	2030
Day gap (MW)	-113	103	395	621	592	743	795	706	619
Night gap (MW)	-134	-52	70	228	199	248	300	211	124

Table-7: Gap between electricity supply and demand with the hybrid power plant.

Year	2022	2023	2024	2025	2026	2027	2028	2029	2030
Daygap(MW)	37	253	595	841	847	943	1 045	961	884
Night gap(MW)	16	98	270	448	454	448	550	466	389

According to the results of Table-7, a clear improvement in Burkina Faso's energy mix and a clear reduction in the electricity deficit is observed from 2023. The national interconnected grid (NIG) goes from an energy deficit situation during the day in 2022, to supply and demand balance situation, or even an energy surplus in 2023. From 2024, the energy surplus increases until 2030, despite the increase in demand.

An additional electrical power of 300 MW from the hybrid power plant from 2023 in Burkina Faso's electricity system makes it possible to cope with the power deficit at day and at night with a power surplus of 253 MW and 98 MW respectively. In 2030, this surplus would reach 884 MW at day and 389 MW at night.

The positive evolution of power gaps between electricity supply and demand also leads to changes in the country's energy mix cost. In terms of costs, the Burkina Faso's energy mix cost evolution from 2022 to 2030 is illustrated in the graph of Figure-3.

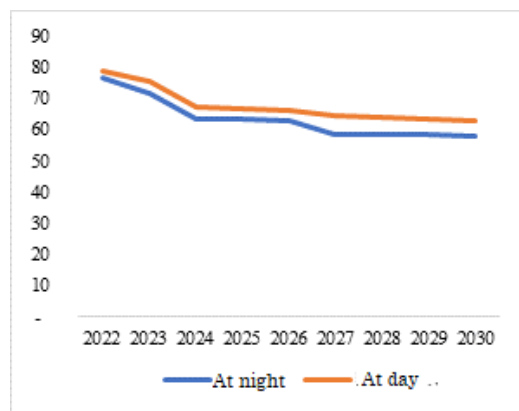


Figure-3: Energy mix cost evolution.

In Figure-3, the observation is that the energy mix cost has been falling steadily since the PV/LNG hybrid power plant electricity injection. This drop in the producing electricity kWh cost continues until it falls below 0.098 \$/kWh. At this cost, the energy mix cost becomes as competitive as the importing electrical energy kWh cost from neighboring countries and the photovoltaic power plant kWh cost.

Conclusion

This research objective is to study the possibility of replacing power plants running on HFO by PV/LNG hybrid power plant, in the Burkina Faso's interconnected electricity grid. The produced electricity from HFO, LNG, PV and PV/LNG hybrid power plant, costs were analyzed.

On a technical level, this model has natural gas thermal production of 150 MW which makes it possible to stabilize the electrical grid, thus compensating for the intermittency of

photovoltaic solar production. Thermal production is stable and allows electrical power to be ramped up quickly with more controllable and quantifiable output. Solar PV production brings the advantage of its easy operation and its very advantageous electricity production cost. In this thermal production absence, it would be essential to install expensive and less reliable batteries in order to stabilize the electrical grid.

On an economic and financial level, for an electricity production of 300 MW in hybrid mode, the kWh cost of 0.1195 \$, is well below the producing electricity cost with HFO (0.1659 \$). The fuel and the initial investment costs for power plants are the most significant. Relative to Megawatt-hours produced number, the charges collapse so as to bring us to a production cost that is more competitive than the other two production sources taken individually.

The hybrid PV/LNG system gives a competitive kWh cost compared to other sources. Given that the objectives assigned to actors in the electricity sector, in the national economic and social development plan, as well as in planning documents, are to provide quality electrical energy in sufficient quantity and at lower cost, this electricity production system can replace thermal power plants operating on DDO and HFO, during the energy transition.

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