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Comparative Study of Electricity Production Cost of Energy Mix of Burkina Faso

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ABSTRACT

This paper presents the feasibility study of replacing HFO power plants with LNG power plant, taking into account the balance of electricity supply and demand in the energy mix of Burkina Faso. The study consisted of calculating and comparing the optimal electricity production costs of each production mode and verifying the competitiveness of electricity production cost using LNG compared to HFO. The simulations results showed that LNG cost being less expensive than HFO cost, the production cost per kWh of electricity using LNG is very competitive compared to the production cost per kWh of electricity using HFO. Power plants running on LNG can replace HFO plants in electricity production in Burkina Faso. Switching to natural gas will optimize Burkina Faso's energy mix and ensure energy security at a compatible cost with household income. This will gradually reduce the country's dependence on imported electrical energy.

KEYWORDS: *LNG, HFO, electricity, Energy Mix, kilowatt-hour cost*

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I. INTRODUCTION

Limited greenhouse gas emissions and depletion of fossil resources are leading the world to seek alternative energy sources for a sustainable and cleaner future in the energy sector [1]. Many countries also implement policies and fiscal pressure to reduce environmental risks and greenhouse gas emissions [2], [3]. In West Africa, the huge electricity supply gap, coupled with the high cost of fuel available in many African countries, provides opportunity for natural gas. Natural gas is currently inexpensive, abundant and relatively clean energy source with great promise as fuel can facilitate the energy transition towards economy based on renewable energies over the coming decades [4].

Natural gas is usually classified into three categories: light natural gas, containing almost 98% methane, with a density of 427 kg/m^3, medium natural gas, containing almost 90% methane, has 7% of ethane and propane. Its density rises to 445 kg/m^3 and heavy natural gas, containing nearly 88% methane, has 12% ethane, propane and butane. It thus reaches a density of 464 kg/m^3 [5].

Liquefied natural gas (LNG) refers to natural gas transformed into liquid form. This state is reached when the gas is cooled to a temperature of approximately -160°C at atmospheric pressure. Liquefaction makes it possible to condense natural gas into LNG, reducing its volume by a factor of nearly 600 for the same calorific value. Industrially, LNG is produced in large quantities in cryogenic plants. Natural gas liquefaction is primarily used as a means of transporting natural gas from producing to consuming countries [6]. Around 13.4% of natural gas produced worldwide in 2022 is transported using this method [7]. This method is growing strongly on a global scale and accounted for nearly 32% of total natural gas flows worldwide in 2016 [8].

There are huge known reserves of natural gas around the world. It is estimated that there is global natural gas reserve whose exploitation can last from 80 to 250 years [9]. In 2015, global trade in natural gas accounted for 245.2 million metric tons per year [10].

Several countries in sub-Saharan Africa are large producers of natural gas. Mozambique and Tanzania recently discovered more than 250 trillion cubic feet of gas reserves. These two countries have already taken steps to meet the demand for domestic natural gas. National natural gas prices in many African countries are very competitive. In Mozambique, these prices vary between 1.21 $/MMBtu and 8.4 $/MMBtu, for industrial customers. These same prices are applied in Ghana and Nigeria for energy production. Equatorial Guinea and Angola also export liquefied natural gas (LNG) [11].

However, the production of electricity from natural gas requires comparative analysis, both technical and economic, for the different existing methods of electricity production, in particular for electricity production using Heavy Fuel-Oil (HFO).

In West Africa, the Azito thermal power plant in Ivory Coast was commissioned in 1999 with a first gas turbine with 150 MW power, as part of the first phase [12]. In the second phase, a second turbine of 150 MW power was added, then in the third phase, in 2016, it was converted into a combined cycle power plant with a capacity of 420 MW. In 2019, a new upgrade increased this capacity to 453 MW. In order to increase the nominal electricity production capacity of Côte d'Ivoire, Azito Energie S.A. will produce an additional 250 MW of electricity and will reach total capacity of approximately 706 MW, or nearly 30% of the country nominal power [13]. In Togo, the Electric Energy Company of Togo (EECT), through the ContourGlobal company, installed a power plant with power of 100 MW running on natural gas, which is transported through the Pipeline of the West African Gas Pipeline Company, to supply the power plant generators. The power station generators operate on natural gas [14]. Switching to natural gas optimizes Togo's energy mix and provides a serious option for reducing its relatively high operating costs, due to heavy fuel oil use. In order to meet the growing demand for electricity, Togo plans to install a second thermal power plant, whose engines will run on liquefied natural gas. In Central Africa, Equatorial Guinea, Cameroon and Congo are the countries that have started implementing notable projects for natural gas use in the region [15]. Equatorial Guinea has undertaken to develop its gas resources by converting certain thermal power plants to gas. In 2012, the government approved the project to expand the Turbogas power plant in Malabo, increasing its capacity from 70 MW to 154 MW. In the same dynamic, it was decided, in 2015, to convert two of the three turbines of Bata thermal power station (24MW) to liquefied natural gas instead of the exclusive fuel oil use and increase its capacities to 100 MW.

In 2010, Cameroon initiated the project to build the country's first gas power plant in Kribi, with a capacity of 216 MW. In 2015, the electricity production and distribution operator, inaugurated a gas power plant with a capacity production of 50 MW. In 2011, Congo inaugurated a 300 MW gas power plant near Pointe-Noire, the economic capital. It is the largest production unit in the country.

In Burkina Faso, where the study takes place, energy policy has for a long time, been based on thermal power plants development and electricity importation from neighboring countries, notably the Côte-d'ivoire and Ghana [16]. Nowadays, national electricity production is ensured from fossil sources including Diesel Distillate Oil (DDO) and Heavy Fuel-Oil (HFO), photovoltaic solar, hydroelectric and biomass [16]. From environmental considerations point of view and political option, the choice is moving more and more towards an energy mix with a particular emphasis on photovoltaic and possibly other less polluting production sources.

It is important to analyze natural gas potential in the electricity production mix by 2030 and to identify the critical aspects, as well as the costs associated with this approach. This scenario shows that a significant increase in natural gas contribution in the energy mix of the electricity sector by 2030 is compatible with environmental objectives. This will make it possible to compensate the dismantling power plants operating on DDO and HFO.

This study focuses on electricity production from thermal power plants using liquefied natural gas (LNG) as an alternative solution to thermal power plant using heavy fuel oil. Thermal production of electricity using liquefied natural gas will contribute to electrical grid stabilization and to reduction of greenhouse gas emissions. This involves proposing an alternative to the use of very polluting HFO in the electricity production system and dealing with the problem of electrical grid stability.

The main objective of this work is the feasibility study, in terms of costs, of replacing power plants running on Heavy Fuel-Oil (HFO) with others on Liquefied Natural Gas (LNG), taking into account the The balance of elctricity supply and demand in the energy mix of Burkina Faso, located in West Africa.

II. PRESENTATION OF THE STUDY PLACE

This study concerns the electrical energy supply in Burkina Faso.

2.1. Geographical location of Burkina Faso

Burkina Faso is a landlocked country, located in the heart of West Africa, between 9 and 15° north latitude, 2°30' east longitude and 5°30' west longitude. It covers 274,000 km^2 area and borders six countries: Niger to the east, Mali to the north and west, Ivory Coast, Ghana, Togo and Benin to the south. The location of Burkina Faso is given on the map in Figure 1.

Figure 1 Location of Burkina Faso

2.2. Electricity production in Burkina Faso

The entire energy mix of Burkina Faso consists of 394.1 MW of thermal power, 33 MW of hydroelectricity, 60.1 MW of photovoltaic solar, to which is added an import capacity of 200 MW with Ghana and 150 MW with Côte d'Ivoire, for a total available of 837.2 MW. Figure 2 provides an overview of the electrical map and interconnection lines with neighboring countries.

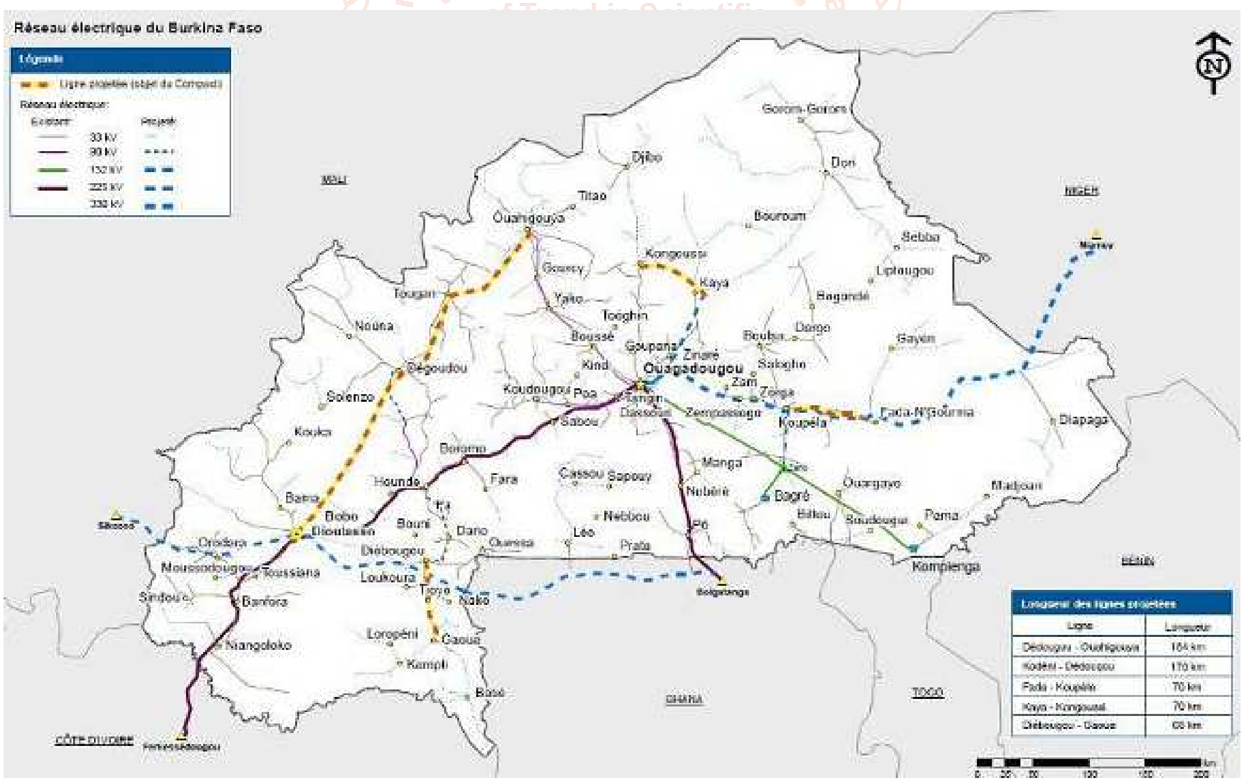

Figure 2 Electric map of Burkina Faso and interconnection lines.

Available electrical capacity increased from 325 MW in 2015 to 800 MW in 2020.

Burkina Faso currently imports nearly 60% of its electricity consumption, mainly from Ghana and Ivory Coast. In 2025, the planned access rate is 70% nationally and 50% in rural areas, representing installed power of 1,500 MW. This horizon, 1000 additional localities must be electrified, 1 million more subscribers [17].

Burkina Faso's national interconnected grid is not capable of providing the requested power at all times. This electrical grid inability to provide the requested power puts it in static insecurity. Figure 3 shows a graph of forecasting demand evolution of the national interconnected grid (NIG), from 2018 to 2030.

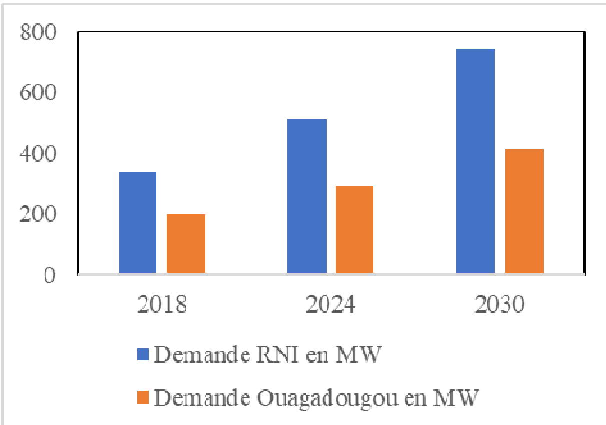

Figure 3 Evolution of the NIG demand forecast.

III. MATERIAL AND METHOD

The aim is to find, among the methods of producing electricity from thermal with Heavy Fuel-Oil and thermal with Liquefied Natural Gas, the best production mode, which balances supply and demand in electricity, for the energy mix of Burkina Faso. The choice will be made by comparing the optimal electricity production cost per kWh for each production mode.

The generating elements power of each production mode is calculated taking into account the balance between electricity supply and demand over the project lifetime [18]. Once the generating elements power of each mode of production has been determined, the levelized cost of the electricity is calculated. For the comparison to be objective, six cost items are taken into account: the investment cost, the fuel cost, the operating cost, the interests lubrificant cost and renewal cost. The lifetime used in the kWh cost calculations is 25 years.

3.1. Natural gas combustion modeling

Natural gas is essentially made up of more than 90% methane [19]. The methane combustion reaction is given by equation (1).

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \qquad (1)$$

CH_4 is the chemical symbol for methane, O_2 is the chemical symbol for oxygen, CO_2 is the chemical symbol for carbon dioxide, H_2O is the chemical symbol for water.

This reaction is strongly exothermic. In the absence of catalyst it begins around 800°C, when the concentration of radicals becomes sufficiently high to initiate the reaction. Carbon dioxide (CO_2) is not the only product of the reaction. Incomplete oxidation or decomposition of CO_2 can result in the formation of carbon monoxide (CO).

3.2. Techno-economic analysis

In the process of technical-economic analysis, investment, maintenance, operation and renewal costs, as well as the residual value of power plants generating elements are considered in the calculation of electricity kilowatt hour (kWh) cost [20]. It is proposed here, the minimization of a cost equation expressed as a function of the optimal size of each generating element of the power plants, while respecting the energy constraints of each power plant [21], [22].

The generating elements powers of FHO and LNG power plants are determined so as to ensure the balance between electricity supply and demand. In addition, for each power plant component, five types of cost must be taken into account: investment cost, interest and financial costs, fuel cost, lubricant cost and operating costs [23].

Depending on whether the expenses are current (operating, maintenance costs, etc.) or non-current (replacement costs, etc.), the discount factor for expenses is expressed according respectively to equations (2) and (3) [24].

$$PW(i,a,d) = \frac{\left(\frac{1+i}{1+a}\right)\left[\left(\frac{1+i}{1+a}\right)^{d} - 1\right]}{\left(\frac{1+i}{1+a}\right) - 1} \qquad (2)$$

$$PW(i,\overline{a},d) = \frac{\left(\frac{1+i}{1+\overline{a}}\right)\left[\left(\frac{1+i}{1+\overline{a}}\right)^{d} - 1\right]}{\left(\frac{1+i}{1+\overline{a}}\right) - 1} \qquad (3)$$

a is the discount rate, i is the inflation rate and d is the duration of the project.

The discount rate for non-current expenses is given by relation (4).

$$\overline{a} = \frac{(1+a)^{nj}}{(1+i)^{nj-1}} - 1 \qquad (4)$$

nj is the lifetime of component j.

The investment cost is linked to the system purchasing cost, as well as the system installing cost. The investment cost of HFO or LNG thermal power plants is given by equation (5).

$$C_{I-Th} = \beta D_{max} a_1 x_1^{-b_1} \qquad (5)$$

C_{I-Th} is the investment cost of a thermal power plant, a_1 is the acquisition coefficient 1 of the thermal generators, b_1 is the acquisition coefficient 2 of the thermal generators, x_1 is the peak power of the thermal generators, D_{max} is the maximum load of each thermal generator, β is the charging rate of each thermal generator.

The maintenance cost is given as a percentage of the initial cost of each component for a period of one year. Relation (6) gives the equation for the maintenance cost of an HFO or LNG thermal power plant.

$$C_{M-Th} = N(a_0 + b_0 x_1) PW_{Th}(i,a,d) \sum_{t=1}^{24} X_t \quad (6)$$

C_{M-Th} is the maintenance cost of a thermal power plant, N is the number of days of operation of thermal generators per year, a_0 is the maintenance coefficient 1 of thermal generators, b_0 is the maintenance coefficient 2 of thermal generators, x_1 is the peak power of the thermal generators, $PW_{Th}(i,a,d)$ is the discount factor of the investment cost of the thermal generators, X_t is the number of thermal generators in operation at time t.

The operating cost of the HFO or LNG thermal power plant is given by relation (7).

$$C_{Op-Th} = C_0 x_1 N(a_2\beta + b_2) PW_{Th}(i,a,d) x_1 \sum_{t=1}^{24} X_t \quad (7)$$

C_{Op-Th} is the operating cost of a thermal power plant, C_0 is the cost of Nm^3 of natural gas or HFO, x_1 is the peak power of the thermal generators, N is the number of operating days of the thermal generators per year, a_2 and b_2 are the consumption parameters of each thermal generator, β is the charging rate of the thermal generators, X_t is the number of thermal generators in operation every hour of the day, $PW_{th}(i,a,d)$ is the update of the investment cost of the thermal power station.

Each element of the power plant has a lifetime. It must be replaced periodically throughout the operation of the plant [25]. The cost of replacing the elements of the HFO or LNG thermal power plant is given by relation (8).

$$C_{R-Th} = PW_{Th}(i,\bar{a},d) x_1 \frac{D_{max}}{\beta} x_1^{-b_1} \quad (8)$$

C_{R-Th} is the replacement cost of a thermal power plant, $PW_{Th}(i,\bar{a},d)$ is the discount rate adjusted for the replacement of thermal generators, D_{max} is the maximum load of each generator, β is the charging rate of the thermal generators, x_1 is the peak power of the thermal generators, b_1 is the acquisition coefficient 2 of the thermal generators, a_1 is the acquisition coefficient 1 of the thermal generators.

The discounted residual value of the thermal generators is given by relation (9).

$$V_{R-GTh} = S(a,d) \frac{nr_{GTh}}{n_{GTh}} \frac{D_{max}}{\beta} a_1 x_1^{-b_1} \quad (9)$$

nr_{GTh} is the remaining life of the thermal generators, n_{GTh} is the total life of the thermal generators, $S(a,d)$ is the discount factor of the residual values of the thermal generators.

The objective function F(x) for each mode of electricity production is expressed according to relation (10).

$$F(x) = C_I + C_M + C_{Ex} + C_R + V_R \quad (10)$$

C_I is the investment cost, C_M is the maintenance cost, C_{Ex} is the operating cost, C_R is the replacement cost, V_R is the residual value of the generating elements.

The kWh cost of electricity produced by each mode of production is calculated by determining the Levelized Cost of Energy (LCOE). The calculation of the levelized cost of electricity for electricity installations is done by applying formula (11).

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_{t,el}}{(1+i)^t}} \quad (11)$$

$LCOE$ is the levelized cost of electricity per kWh, I_0 is the sum of investment expenditure, A_t is the total annual costs for year t, $M_{t,el}$ is the electricity produced during the year considered, i is the real interest rate, n is the economic and operational lifetime, t is the considered year ($1, 2, ..., n$).

IV. RESULTS

In this work, it is a question of studying the feasibility in terms of costs, of replacing power plants operating on Heavy Fuel-Oil (HFO) by others on Liquefied Natural Gas (LNG), taking into account the balance between supply and demand for electricity, in the energy mix of Burkina Faso, located in West Africa. The study is carried out for a project life of 25 years.

4.1. Electricity production costs of power plants

For a thermal power plant using only HFO as fuel, the costs are calculated for a guaranteed power at the injection point of 300 MW and for electrical energy of 11721404173 MWh, over the project lifetime. Table 1 gives the value of expenses and their proportion in electricity kWh cost.

Table 1 Electricity producion costs with HFO

Cost Component	Total cost ($)	Value ($/kWh)	Weight in kWh cost (%)
Investment cost	236789832	0.020	12
financial charges	77002433	0.006	4
Fuel cost	1542342228	0.132	80
Lubricant cost	38962188	0.003	2
Operating expense	31257379	0.0026	2
kWh cost		0.164	100

The simulations gave $0.164 per kWh of electricity produced by the HFO power plant. The share of lubricant cost and operating expenses, respectively $38962188 and $31257379 are the lowest, around 2% of kWh cost. Interest and other financial charges are $77002433, or 4% of kWh cost. In the electricity kWh cost, that of the fuel ($1542342228) occupies the largest share, more than 80%, followed by the investment cost ($236789832), for nearly 13% of the kWh cost.

For the thermal power plant using only LNG as fuel, the costs are calculated for a guaranteed power at the injection point of 300 MW and for electrical energy of 11721404173 MWh over the project lifetime. The simulation results are shown in Table 2.

Table 2 Electricity production costs with LNG

Cost Component	Total cost ($)	Value ($/kWh)	Weight in kWh cost (%)
Investment cost	248629324	0.021	17
financial charges	80852554	0.0069	5
Fuel cost	1101525611	0.093	73
Lubricant cost	38962188	0.0033	3
Operating expense	31257379	0.0026	2
kWh cost		0.128	100

The simulations gave $0.128 per kWh of electricty produced by LNG power plant. Interest and other financial charges ($80852554) represent 5% of the kWh cost, the lubricant cost is $38962188 or 3% and operating expenses, $3,1257,379, represent 2% of the kWh cost. In the electricity kWh cost ($0.128), that of fuel ($1101525611), occupies the largest share ($1101525611), or 73%, followed by investment cost ($248629324), which makes 17% of kWh cost.

4.2. Power plants costs comparison

Table 3 gives the costs of each expenditure item in the electricity production cost from HFO and LNG thermal power plants.

Table 3 Electricity costs with HFO and LNG

Cost Component	Costs ($)	
	HFO	LNG
Investment cost	236789832	248629324
financial charges	77002433	80852554
Fuel cost	1542342228	1101525611
Lubricant cost	38962188	38962188
Operating expense	31257379	31257379

In producing electricity cost with HFO and with LNG, the cost of HFO ($1542342228) is higher than that of LNG ($1101525611). The fuel cost is the highest compared to other expense items. Additionally, the HFO cost is higher than the LNG cost by $440816617, or gap of 28%.

The lubricant cost ($38962188) and operating expenses ($31257379) are the same in both cases. The investment cost for HFO power plant ($236789832) is lower than the investment cost for LNG power plant ($248629324), with a gap of 4.761%. Financial costs and interest in the case of HFO power plant ($77002433) are lower than those of LNG power plant ($80852554). That's a gap of 4.761%.

With the expenses incurred to produce electrical energy of 11721404173 MWh, by each HFO or LNG power plant, the production cost per kWh of electricity from the HFO plant and the LNG plant. Table 4 gives the share of each expenditure item in the cost of producing one kWh of electricity from the HFO and LNG thermal power plant.

Table 4 Share of each expenditure in kWh cost

Cost Component	Costs ($/kWh)	
	HFO	LNG
Investment cost	0.0202	0.0212
financial charges	0.0065	0.0068
Fuel cost	0.131	0.093
Lubricant cost	0.0033	0.0033
Operating expense	0.0026	0.0026
Coût du kWh	0.164	0.128

The production cost per kWh of electricity from the HFO plant and the LNG plant is \$0.164 and \$0.128, respectively.

Despite higher investment cost and interests, LNG electricity production is less expensive than HFO electricity production. This is due to each type of fuel cost. LNG costs almost 1.5 times less than HFO. This makes it possible to have production cost per kWh of electricity from LNG more competitive than production cost per kWh of electricity with HFO.

V. CONCLUSION

The objective of this work is the feasibility study, in terms of costs, of replacing power plants running on Heavy Fuel Oil (HFO) with others running on Liquefied Natural Gas (LNG), taking into account the balance of supply and the demand for electricity, in the energy mix of Burkina Faso, located in West Africa. The study consisted of calculating and comparing the optimal electricity production costs of each production mode, and verifying the competitiveness of electricity production cost using LNG or HFO. The study is carried out for 25 years project lifetime. The simulation results showed that despite higher LNG plant investment cost of (\$248629324) than HFO plant investment cost (\$236789832), the LNG cost (\$1101525611) being cheaper than HFO cost (\$1542342228), the production cost per kWh of electricity (\$0.128) using LNG is very competitive compared to production cost per kWh of electricity (\$0.164) using HFO. Power plants running on LNG can replace HFO plants in electricity production in Burkina Faso. Switching to natural gas will optimize Burkina Faso's energy mix and ensure energy security at compatible cost with household income. This will gradually reduce the country's dependence on imported electrical energy.

The replacement of heavy fuel oil generator with one running in LNG enabled a significant reduction in CO_2 emissions.

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