# A TECHNICAL AND ENVIRONMENTAL APPROACH OF THE UTILIZATION OF THE DIESEL INSTEAD OF THE NATURAL GAS IN THERMOELECTRICAL POWER PLANTS IN BRAZIL

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***Abstract.*** This work analyses the Thermodynamic and Ecological Performance of a thermoelectrical power plant with nominal power of 310 MW in combined cycle. In the worldwide scenery, combined cycle power plants have become more and more known, due to the stage of development of the technology as well as to its high efficiency and low levels of atmospherical emissions when compared with conventional thermodynamic cycles. In Brazil, unfortunately, the diesel oil has been utilized in thermoelectric power plants, for the natural gas has not met the demand, in face of the problems in the contract with Bolivia. The study of the operation of these thermoelectric power plants with a second combustible, as the diesel, for instance, becomes more necessary, seen that the levels of thermal efficiency and of emissions undergo considerable alterations. This work aims to analyze the thermal and ecological efficiency of this thermoelectrical power plant, through a comparison between the natural gas and the diesel. And analysis of the First Law of Thermodynamics is made and the ecological efficiency of the plant being studied for the two combustibles is determined. From the results obtained, it is inferred that the utilization of the natural associated to the use of the technology of the combined cycle presents better energetic and ecological efficiency when compared to the diesel.

*Keywords: Thermoelectrical Power Plant, Natural Gas, Diesel, Ecological Efficiency, Diagram of Sankey*

## 1. INTRODUCTION

In the Brazilian System, it is important the exploitation of the hydroelectric potential since it is economically feasible, with a thermoelectric generation adequate complement. The thermal generation is fundamental in the energetic area to minimize new rationing risks and improve the system electrical liability as the thermals have no hydrological hazard and help the transmission system. In other countries, thermal generation is the prevailing system, with practically no rationing risk, while in Brazil the prevailing system is still the hydroelectric one, offering approximately one rationing every 20 years (Villela, 2007a).

The changes in the thermoelectric market traditional structure have been induced by the increasing environment restrictions to the use of charcoal, especially in the industrialized countries, which present a natural gas transportation solid infra-structure. The chief gas natural advantage, compared to charcoal, relies on the smaller carbon dioxide emission intensity. The natural gas arises as an interesting alternative to the petroleum products, for it is an energetic that produces lower environment impact, burns easily and may be canalized and safely conducted to the final consumer.

Economically, the thermoelectric power plant most efficient option is the combined cycle (CC), which consists in the association of steam turbines, using natural gas as fuel. In terms of emission, the utilization of steam gas in cycle combined with natural gas is the most adequate because it presents greater thermodynamic efficient and consequently lower fuel consumption.

In this context, this work presents the thermoelectric environment implications in Brazil, comparing natural to diesel utilization.

## 2. POWER PLANTS DESCRIPTION

To analyze the engineering system design and enhance gas turbine performance, on power plant was selected to perform the experiments in this study. The Figure 1 show the gas turbine system associated to the recovering kettle and steam turbine, from which a corresponding functional diagram can be made. The system proposed will utilize, for comparison purposes, natural gas or diesel as fuel. Under the atmospheric conditions, the air penetrates the compressor and is compressed until it reaches the combustion pressure. Next, it is sent to the combustion chamber, where it is pauselessly burned under constant pressure and the gases from the combustion expand in the gas turbine producing electricity. The gases with high temperature are then sent to the heat recovering, producing more electrical energy. The most adequate type of fuel for this system is the natural gas, which has high energetic density and optimum combustion efficiency (Villela and Silveira, 2006).

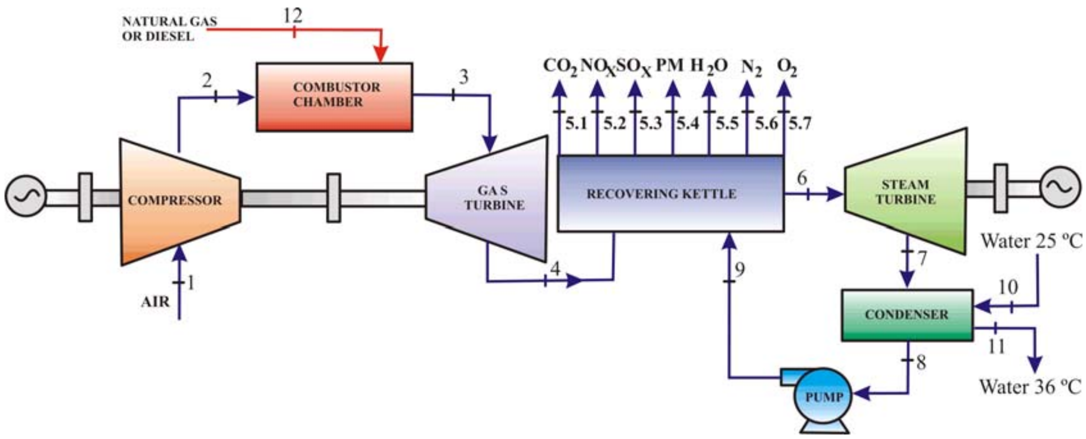


Figure 1. Gas Turbine System Associated to the Recovering Kettle and Steam Turbine

## 3. GENERAL RELATIONS

In this system the following considerations are adopted: it works in permanent regime; all components operate with no heat loss, the principles of ideal gas are applied to the air and to the combustion products, a complete combustion is considered. In this case two decision variables are taken in account: temperature ($T_5$) of the exhaustion gases in the turbine and pressure relation of the selected gas turbine Pr = $P_3/P_4$. These variables were chosen because of the influence on the thermodynamic performance of the system and also according to the criterion of selection utilized in the determination of the gas turbine. Thus, considered $P_1$ and $P_5$ are the ambient pressure (101.325 KPa) and represent the pressure loss percentage in the dos gases in heat recovery and in the combustion chamber respectively (Valero, 1994; Silveira and Tuna, 2003).

The temperature ($T_3$) of the gas turbine inlet and the value de $\lambda_G$ are defined by the following equations (Cohen and Rogers, 1989; Silveira and Tuna, 2003).

$$T_3 = \frac{T_4}{\left\{1 - \eta_{ISO_{GT}} \cdot \left[1 - (Pr)^{\frac{(1-\lambda_G)}{\lambda_G}}\right]\right\}} \tag{1}$$

$$\lambda_G(T) = \frac{1}{1 - \frac{R_G}{Cp_G(T)}} \tag{2}$$

The temperature $T_2$ (considering $T_1$ equal the 25 ºC), and value $\lambda_{air}$ , are defined by (Silveira and Tuna, 2003):

$$T_2 = T_1 \cdot \left\{1 + \frac{1}{\eta_{ISO_c}}\left[\left(\frac{P_2}{P_1}\right)^{(\lambda air - 1)/\lambda air} - 1\right]\right\} \tag{3}$$

$$\lambda_{air}(T) = \frac{1}{1 - \frac{R_{air}}{Cp_{air}(T)}} \tag{4}$$

The enthalpys of air and gases in points 2, 3 are defined respectively by (Si-Doek et al. 1996):

$$h_2 = Cp_{air}(T_2).(T_2 - T_0) \tag{5}$$

$$h_3 = Cp_G(T_3).(T_3 - T_0) \tag{6}$$

The air flow rate is calculated from the association of the mass conservation principle with the First Law of Thermodynamics:

$$\dot{m}_{air} = \dot{m}_G - \dot{m}_{fuel} \quad (7)$$

The pump and compressor works are obtained from (Moran and Shapiro, 2004):

$$\dot{W}_p = \frac{\dot{m}_S .(h_9 - h_8)}{\eta_p} \quad (8)$$

$$\dot{W}_C = \dot{m}_{air} \int_{T_1}^{T_2} Cp_{air(T)} dT \quad (9)$$

Table 1. Fixed parameters (Silveira and Tuna, 2003; Dincer et al. 2004)

| | | | |
|---|---|---|---|
| Rair | 0.287 | $\Delta P_{HR}$ | 0.05 |
| $R_G$ | 0.290 | $\eta_{ISOC}$ | 0.90 |
| CpD (kJ/kg K) | 1.193 | $\eta_{ISOGT}$ | 0.85 |
| CpGN (kJ/kg K) | 1.209 | $\eta_p$ | 0.90 |
| LHV – NG (kJ/kg) | 47966 | $\eta_{ST}$ | 0.98 |
| LHV – D (kJ/kg) | 44574 | $\eta_C$ | 0.86 |
| $T_{env}$ (° C) | 25 | $T_o$ | 25 ° C |
| $\Delta P_{CC}$ | 0.05 | $P_o$ (kPa) | 101.325 |

The gas turbine thermal efficiency is estimated by (Moran and Shapiro, 2004; GTW Handbook, 2003):

$$\eta_{GT} = \frac{1}{\text{Heat rate}} \quad (10)$$

The power ($\dot{W}_{ST}$) and the electricity produced ($Ep_{ST}$) by the steam turbine are defined by (Sue and Chuang, 2004; Moran and Shapiro, 2004):

$$\dot{W}_{ST} = \dot{m}_S .(h_8 - h_7) \quad (11)$$

$$Ep_{ST} = \dot{W}_{ST} . \eta_{ST} \quad (12)$$

The power ($Ep_{GT}$) of steam turbine and the total power produced by the system are given by (Sue and Chuang, 2004; Moran and Shapiro, 2004):

$$\dot{W}_{GT} = Ep_{GT} \quad (13)$$

$$Ep_{total} = Ep_{GT} + Ep_{ST} \quad (14)$$

Thus the power supplied by the fuel ($E_{fuel}$) and the plant global efficiency ($\eta_{gl}$) are obtained by (Sue and Chuang, 2004; Moran and Shapiro, 2004):

$$E_{fuel} = \dot{m}_g .LHV \quad (15)$$

$$\eta_{gl} = \frac{Ep_{GT} + Ep_{ST} - \dot{W}_p}{E_{fuel}} \quad (16)$$

The first law analysis is used to deal with the energy analysis of variable mass processes, in which the energy losses and the corresponding energy efficiencies for each of the component are calculated.

Figure 3 shows the energetic losses of the thermoelectrical power plants are analyzed, by means of a graphic representation of the diagram of Sankey for the natural gas utilized for performance and efficiency evaluation of system (Villela, 2007b)

The turbine exhaust temperature is 176,7 ºC and the gas turbine power are same for both fuels (natural gas, diesel) (Barclay, 1995; Santana, 1999). In this cycle the efficiency of the plant with the use of the natural gas is 1.3% higher than diesel. This difference is mainly attributed to the different fuels and combustion features and is not discussed herein.

## 4. DIESEL AND NATURAL GAS

### 4.1. Diesel

Petroleum subproduct, basically composed of hydrocarbons, diesel oil is a compound formed mainly by carbon atoms and low concentration Sulphur and nitrogen. It is flammable, moderately toxic, volatile, clear, suspension matter free and with strong and particular scent (Gas is the way, 2004).

According to Petrobras, the enterprise produces 85% of the diesel oil and the rest of the market is supplied with imported product. In Brazil, the diesel oil consumption is imputed to the transportation field, which represents 80% of that market. 94% of this oil is destined to the transportation branch. The Brazilian diesel, compared to the American and the European ones, exhibits high Sulphur content in its composition. Searching for a better motor performance and the atmospheric emission reduction, Petrobras implanted the Diesel Oil Quality Evolution Program, in which approximately US$ 1.2 billion will be invested. Besides the Sulphur compound emission reduction, the diesel oil quality evolution provides a better motor performance, scent and smoke decrease. Since January, 1998, the maximum Sulphur percentage allowed for the national diesel is 0.5% (Carvalho and Lacava, 2003).

In general, the diesel generator unitary power, compared to the one of the big thermopower or hydropower plants, is not that big. It is necessary, however, to consider that the number of units installed is significant and that, together, they represent a significant fraction of the total installed power in Brazil. Only the diesel plants nowadays authorized to supply electrical energy to the network respond for 26.6% of the total installed power in Brazilian thermopowers. Normally, this potential remains idle due to the diesel oil cost and its use is reasonable only in special situations like eventual interruptions in the network supply and peak consumption hours, when the power demand is high, and in localities far away from the electrical network. The power nowadays installed in the Brazilian thermopower industrial estate is around 10.4 GW: the diesel plants supply 2.8 GW of this total. It can be pointed out, in the diesel plants universe, the units of the State of Amazonas: these represent 30.7% of the total power installed in diesel generator in Brazil. Mato Grosso (22.1%), Bahia (10.7%) and Rondonia (9.5%) come next. Hydroelectricity is the most consumed energetic, responsible for 43.4% of the total. Next come the ones that use diesel oil (13.1%), sugar cane products (including ethylic alcohol, 8.2%) and firewood (6.2%). Petroleum subproducts, together, respond for 28.5% of the total Brazilian energy consumption. Among these the diesel oil is pointed out, second energetic in the Brazilian matrix (it is the most utilized subproduct), responsible for almost half of subproducts consumed.

### 4.2. Natural Gas

It is a scentless, flammable and suffocating gas when inhaled in high concentrations, and because it is gaseous, does not need to be vaporized, as, for instance, the fuel oil, to burn, thus resulting from it a pollutant emission reduced clean combustion. Natural gas is a mixture of light hydrocarbons, which at surrounding temperature and atmospheric pressure, remains in gaseous state. It is found underground in the nature, accumulated in porous rocks, generally accompanied by petroleum, making up a reservoir (Salomon, 2003).

According to Comgas, the largest gas distributing company of the state of São Paulo, the natural gas volumetric composition may be:

$CH_4$ (methane): 89.3%
$C_2H_6$ (ethane): 8%
$C_3H_8$ (propane): 0.8%
$C_4H_{10}$ and $C_5H_{12}$ (butane and pentane): 0.1%
$CO_2$ (carbon dioxide): 0.5%
$N_2$ (nitrogen): 1.3%

In one $Nm^3$ of natural gas at CNTP (Normal Temperature and Pressure Conditions) its mass is approximately 720 grams. At CNTP the $m^3$ is denoted by the symbol $Nm^3$ (N means normal). The maximum total Sulphur in one $Nm^3$ of natural gas will be 20 mg, corresponding to 0.0028% of the fuel mass (Carvalho and Lacava, 2003).

Regulation 41, April 15, 1998, emitted by the Petroleum National Agency, grouped natural gas in three families, according to the calorific power range. The Brazilian natural gas belongs to the (M) medium group, with the following specifications (Villela, 2007a):

- calorific power higher than 20ºC and 1 atm: 8800 – 10200 kcal/$Nm^3$
- air relative density at 20ºC: 0.55 – 0.69
- total Sulphur: maximum 80 mg/$Nm^3$
- $H_2S$: maximum 20 mg/$Nm^3$
- $CO_2$: 2% at maximum volume
- $O_2$: 0.5% at maximum volume
- inert: 4% at maximum volume
- water dew point at 1 atm: maximum-45ºC
- free of dust, condensed water, injecting scents, gums, gum-forming elements, condensable hydrocarbons; flavor compounds, methanol or other solid and liquid elements.

Brazil is the largest importer of Bolivian gas, importing between 900 million cubic feet per day (MMcf/d) and 1 Bcf/d in 2006, more than two-thirds of Bolivia's total natural gas exports. In 1999, Bolivia began exporting to Brazil under a 20-year, take-or-pay contract through the Gasbol pipeline. The 2,000-mile Gasbol connects Santa Cruz, Bolivia to Porto Alegre, Brazil, via Sao Paulo. The system has a maximum capacity of 1 Bcf/d. Gasbol also has a 170-mile, 100-MMcf/d extension that connects to a gas-fired power plant in Cuibana, Brazil. The agreement between the two countries is a take-or-pay contract, meaning that Brazil often must pay for natural gas that it does not actually use. There have been times in the past when, due to dampened economic growth, Brazil has not been able to use the entire volume. With the nationalization of hydrocarbons, Bolivia and Brazil entered into discussions regarding the price paid for transported gas. In February 2007, Bolivia and Brazil reached agreement for new prices on transported gas: gas destined for Cuiaba saw prices rise 285 percent to $4.20 MMBtu; and Brazil agreed to pay international prices for liquid components (ethane, butane, propane, natural gas liquids, and natural gas gasoline) received in the Gasbol pipeline. (EIA, 2008)

## 5. METHODOLOGY FOR ECOLOGICAL EFFICIENCY CALCULATION

The higher concentrations allowed for the substances present in the air are considered as reference, and these values are shown in Table 2 (Who, 2003).

Table 2. Air quality patterns (Who, 2003)

| Gas denomination | Concentration in 1 hour ($\mu g/m^3$) |
|---|---|
| $NO_x$ | 200 |
| $SO_x$ | 125 |

According to the CONAMA (Environment National Council) Resolution nº 3, June 28, 1990, the value allowed for the particulated matter (MP) concentration is 150 $\mu g/m^3$, but in some countries carbon taxes have been implanted, penalizing those who release high $CO_2$ concentrations, stimulating its reduction and settling its maximum emission limit. Based on these patterns and considering the $CO_2$ emission maximum concentration, 10000 mg/$m^3$, the coefficients for the $(CO_2)_e$ Equivalent Carbon Dioxide) hypothetical pollutant concentration calculation is determined (Cardu and Baica, 1999a). For the calculation of this coefficient, the $CO_2$ maximum concentration value allowed is divided by the corresponding air quality patterns for $NO_x$, $SO_2$ and MP in hour. Thus, the expression for the $(CO_2)$ is:

$$(CO_2)_e = (CO_2) + 80(SO_2) + 50(NO_x) + 67(PM) \qquad (1)$$

In equation (1), $(SO_2)_e = 80\ (SO_2)$ is the sulphuric dioxide equivalent in $(CO_2)$, $(NO_x)_e = 50\ (NO_x)$ is the nitrogen oxide equivalent in $(CO_2)$ and the particulated matter equivalent in $(CO_2)$ is $(PM)_e = 67\ (PM)$. The best fuel from the ecological standpoint is the one which presents a minimum amount of $(CO2)_e$ Equivalent Carbon Dioxide obtained from its burning. In order to quantify this environmental impact the "pollutant indicator" ($\Pi g$) is defined as it follows (Cardu and Baica, 1999a):

$$\Pi g = \frac{(CO_2)_e}{Qi} \qquad (2)$$

where $(CO_2)_e$ in kg/kg (kg per kg of fuel), Qi in MJ/kg is the PCI (fuel lower calorific power) and Πg in kg/MJ is the pollution indicator and kg refers to $(CO_2)_e$ mass.

### 5.1. Ecological Efficiency

Ecologic efficiency is defined as an indicator which allows the evaluation of the thermopower plant gaseous emission environment impact, by comparing the hypothetically integrated pollutant emissions ($CO_2$ equivalent emissions) to the existing air quality patterns. The ecological efficiency ($\varepsilon$) evaluates the environmental impacts caused by thermopower plant emissions, considering the combustion of 1 kg of fuel, and not the amount of gases released by generated power unit (Cardu and Baica, 1999a, 1999b). The conversion efficiency is also considered a determinant factor on the specific emissions, expressed by a fraction number. According to Cardu and Baica (2001), the ecologic efficiency is calculated by:

$$\varepsilon = \left[ \frac{0{,}204}{\eta + \Pi_g} \ln\left(135 - \Pi_g\right) \right]^{0{,}5} \tag{1}$$

where $\varepsilon$ integrates the aspects that define the intensity of the environment impact of thermopower plant in one coefficient: the fuel composition, combustion technology in the pollution indicator and conversion efficiency. Value $\varepsilon$ is directly proportional to thermopower plant efficiency ($\eta$) inversely proportional to ($\Pi_g$), pollutant indicator value, and also alternates between 0 and 1, similarly to thermopower efficiency. Ecological point of view, $\varepsilon = 0$ is considered to be an unsatisfactory situation, but $\varepsilon = 1$ indicates the ideal situation.

Table 3 shows the characteristics of the two fuels utilized: natural gas and diesel and their respective ecological efficiencies. It is verified, under the ecological standpoint, that the natural gas use is better than the use of the diesel, presenting ecological efficiency of 0.914.

Table 3. Fuels characteristics in thermopower plants (technology CC)

| Fuels | Technology | $\eta$ | **$(CO_2)_e$ (kg/kg)** | **$\Pi_g$ (kg/MJ)** | **$Q_i$ (MJ /kg/)** | $\varepsilon$ |
|---|---|---|---|---|---|---|
| Natural Gas | CC | 51 | 3.01 | 0.063 | 48.088 | 0.944 |
| Diesel | CC | 51 | 3.21 | 0.101 | 40.765 | 0.914 |

## 6. COMPARISON BETWEEN NATURAL GAS AND DIESEL AS FUELS

According to Carvalho and Lacava (2003), the $CO_2$, $NO_x$ and Particulate Matter (PM) ($SO_2$) generated from the diesel and natural gas combustion, respectively, are determined. Thus, considering $NO_2$ in the combustion products from these fuels, we have the following equations for normalized $\alpha$ air excess:

**- diesel**

$$1C_{12}H_{26} + 18{,}5\alpha O2 + 69{,}56\alpha N_2 \rightarrow 12CO_2 + 13H_2O + 139{,}12\alpha N_2 \tag{2}$$

**- natural gas**

$$0{,}893CH_4 + 0{,}08C_2H_6 + 0{,}008C_3H_8 + 0{,}0005C_4H_{10} + 0{,}0005C_5H_{12} + 0{,}005CO_2 + 0{,}013N_2 + 2{,}118\alpha O_2 + 7{,}965\alpha N_2 \rightarrow 1{,}087CO_2 + 2{,}064H_2O + 7{,}965\alpha N_2 + 2{,}118(\alpha - 1)O_2 \tag{3}$$

By using the natural gas and diesel combustion equations (1 and 2), it is possible to compare the atmospheric emissions between natural gas and diesel. The results show that:

- a diesel thermoelectric power plant generates 3.1059 kg of $CO_2$ /kg of diesel and for a natural gas thermoelectric power plant the $CO_2$ generated (in dry base, corrected to 12% of oxygen) is 2.7038 kg of $CO_2$/kg of natural gas.
- for the $NO_x$, a diesel plant generates2.4 kg of $NO_x/m^3$ of diesel. On the other hand, a thermoelectric power plant using natural gas generates 2270 kg of $NO_x$ per million of fuel cubic meter.
- for the diesel, the particulate matter emission factor is 1.2 kg per fuel cubic meter and for the natural gas this factor is 240 kg of particulate matter per fuel cubic meter The $SO_2$ emission factor in the diesel is 17.04 kg/$m^3$ for each 1% of Sulphur in its composition; however, the natural gas shows a very low Sulphur percentage and this implies in a very low $SO_2$ emission factor.

The results are presented in Table 4. In this table a great advantage in terms of atmospheric emissions when using natural gas in relation to diesel as fuel is noticed.

Table 4. Comparison of the results of pollutant emissions between a natural gas and a diesel thermoelectrical power plant.

| **Pollutant emissions (kg/kg of fuel)** | **diesel** | **natural gas** | **diesel/natural gas** |
|---|---|---|---|
| $(CO_2)_e$ | 3.21 | 3.01 | 1.1 |
| Particulated matter | $13890.10^{-7}$ | $3039.10^{-7}$ | 4.6 times |
| $SO_2$ | $9861.10^{-6}$ | ------- | ------- |
| $NO_x$ | $2778.10^{-6}$ | $856.10^{-6}$ | 3.3 times |
| $CO_2$ | 3.1059 | 2.7038 | 1.2 times |
| Total (kg/kg of fuel) | 3.1187 | 2.7070 | 1.2 times |
| Ecological Efficiency (%) (cycle of 54% yield) | 91.4 | 94.4 | ------- |

## 7. CONCLUSION

This work shows that it is possible to evaluate the environmental impact on thermoelectrical power plants utilizing the ecological efficiency parameter. Thus, it can be concluded that:

- for the air quality standards adopted in this study, it can be noticed that the use of the natural gas as a high technology, as well as the use of the combined cycle (CC), represents an excellent option on the ecological standpoint.

-the emission levels of a thermoelectrical power plant using natural gas and a thermal plant using diesel are, respectively, $3039.10^{-7}$ and $13890.10^{-7}$ kg/kg of fuel for the particulated matter; 0.00 and $9861.10^{-6}$ kg/kg of fuel for the $SO_2$, 2.7038 and 3.1059 kg/kg of fuel for the $CO_2$, $856.10^{-6}$ and $2778.10^{-6}$ kg/kg for the $NO_x$. The total emission for a diesel thermoelectrical power plant in comparison with a natural gas plant is, respectively, 1.2 times, based in kg/kg of fuel. In terms of ecological efficiency, the characteristics of a thermoelectrical power plant utilizing natural gas and one using diesel are, respectively, 94.4% and 91.4%.

The study shows that the use of natural gas as fuel is better than the diesel, presenting ecological efficiency higher values, but with a second combustible, as the diesel.

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