TECHNICAL AND ECONOMIC STUDY OF THE ENERGY TRANSITION FROM NATURAL GAS TO GREEN HYDROGEN IN THERMAL POWER PLANTS

Laince Pierre Moulebe*
Department of Electrical Engineering
Laboratory of Complex Cyber-Physical Systems (LCCPS) of ENSAM, Hassan II University
150 Bd du Nil, Casablanca 20670, Morocco, mpierrelaince12@gmail.com
https://orcid.org/0000-0001-7149-5694

Abdelwahed Touati
Department of Electrical Engineering
Laboratory of Complex Cyber-Physical Systems (LCCPS) of ENSAM, Hassan II University
150 Bd du Nil, Casablanca 20670, Morocco, touati2010@hotmail.com
https://orcid.org/0000-0001-9589-0090

Eric Obar Akpoviroro
Department of Electrical Engineering
Laboratory of Complex Cyber-Physical Systems (LCCPS) of ENSAM, Hassan II University
150 du Nil, Casablanca 20670, Morocco, akposobar@yahoo.com
https://orcid.org/0000-0002-4776-4708

Oumayma Belbsir
Department of Electrical Engineering
Laboratory of Complex Cyber-Physical Systems (LCCPS) of ENSAM, Hassan II University
150 Bd du Nil, Casablanca 20670, Morocco, belbsiroumaima123@gmail.com

Nabila Rabbah
Department of Electrical Engineering
Laboratory of Complex Cyber-Physical Systems (LCCPS) of ENSAM, Hassan II University
150 Bd du Nil, Casablanca 20670, Morocco, nabila_rabbah@yahoo.fr
https://orcid.org/0000-0002-2221-4830

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Highlight
Decarbonization of gas-fired power plants by using green hydrogen as fuel.

Abstract
This research article contributes to the challenge of global warming by presenting the approach of the use of green hydrogen to reduce greenhouse gases. It shows that CO_2 emissions can be significantly reduced in thermal power plants by replacing natural gas with green hydrogen as a fuel. This work presents the techno-economic study of the energy transition of a 12 MW thermal power plant based on green hydrogen. The presented study is based on the energy consumption of Nigeria, 73% of which is covered by natural gas thermal power plants. The obtained results show that the cost of this transition is ca. 17 million dollars (USD) for a reduction of 114 tCO_2 per plant with a return on investment between 4-5 years. In addition, through modeling and numerical simulation, this article shows that estimated return on investment can be shortened by using the thermal power resulting from the turbine, through industrial use.

Keywords
Green hydrogen; thermal power plan; combustion.

Introduction
Our planet is facing numerous phenomena that threaten it today. One of the most devastating is a global warming [1]. Indeed, in the face of the effects of global warming, the actions taken on a daily basis do not have a considerable impact in the short term. Especially that such short-term damages are already visible,

i.e. the melting of glaciers, which causes rising waters and involves floods or fires that have repeated over the past two years due to high temperatures [2,3].

The fight against global warming involves the implementation of several technologies allowing the reduction of greenhouse gases (GHG) in the medium term. Faced with the effects observed in the world, the long-term solutions do not have considerable profitability these days, hence the solutions put in place must tackle the sectors having the greatest impact on GHG emissions. Among the most polluting sectors is energy supply, which relies still on power plants and particularly on thermal power plants, which occupy the second place after nuclear power [4] (Figure 1). The amount of GHG from thermal power plants is believed to be considerable over the next years [5] as shown in Figure 2.

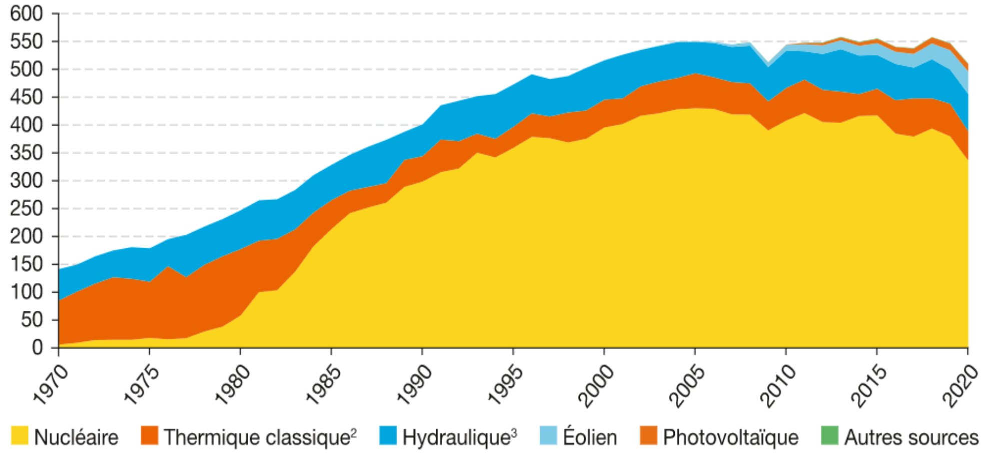

Figure 1. Net-electricity generation. *Source: [4].*

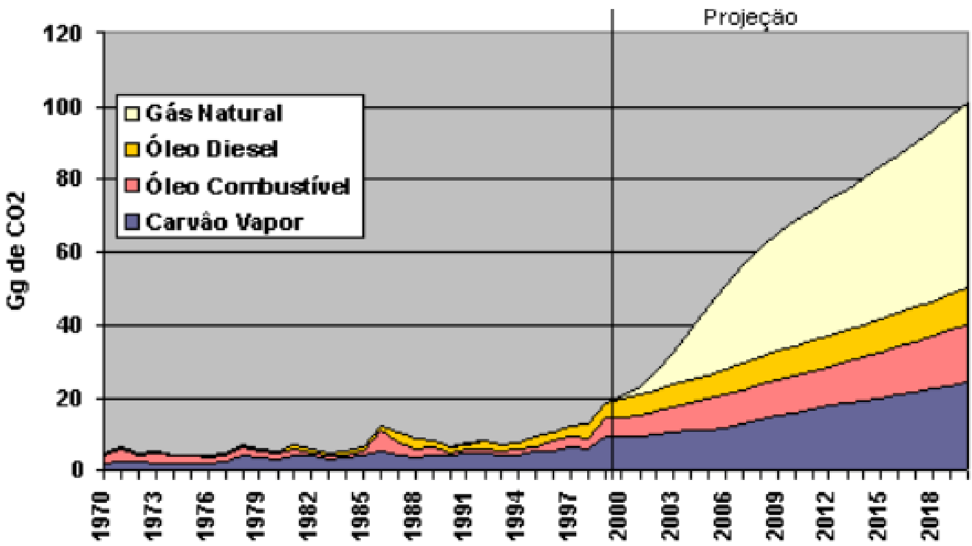

Figure 2. Annual emissions of CO_2 from thermal generation of electricity in public power plants. *Source: [5].*

In 2019, global CO_2 emissions from fossil fuels accounted for 33 gigatons, of which 41% came from the electricity generation sector. The remaining 69% comes mainly from the transport sector and industry including the tertiary one. According to the IPCC 2018 special file "Global warming of 1.5°C", we have 580 gigatons of CO_2 in our carbon budget and with this value the terrestrial globe has a 50% chance of keeping global warming at 1.5°C compared to pre-industrial levels. However, if humanity continues on the current emissions trajectory, there are only 15 years left before the budget is exceeded.

Although actions to fight global warming undertaken today will have a positive impact in the years to come, it is important to invest in research and development (R&D) concerning these sectors, which on other hand can have more significant impact in the short-term perspective. Among the solutions in progress for several years are those focused on the decarbonization of large and small-scale electricity production systems by replacing it be electricity from renewable energy such as photovoltaics or wind turbines. However, knowing that electricity production systems generate 41% of GHG [6], this article is particularly focused on the study of the reduction of CO_2 resulting from the production of electricity by thermal power plants using natural gas as fuel.

In this article, the technical and economic aspects concerning the integration of green hydrogen in the production of electricity of thermal power plants were analyzed. There are several articles that deal with the production of electricity from green hydrogen on a small, medium and large scale [7,8] . The integration of hydrogen in thermal power plants is a part of the fight against global warming especially the burning the hydrogen does not contribute to the CO_2 emission directly. In 2020, approximately 1.6TW of gas turbine was installed in the world, of which the production of electricity represented 22%. According to the literature, the most common and effective approach for the decarbonization of thermal power plants is to change the combustion gas, which is mostly natural gas or methane [6].

The article mainly deals with centralized production, which involves the production at medium and large scale [7,9], corresponding to the use of green hydrogen for mini generators [8]. In case of Nigeria, it represents the use of electricity by 40% of the population, i.e. 89,692,840 inhabitants who spend ca. 14 billion USD per year, i.e., equivalent to 40 million liters of fuel [10,11] or alternatively the use of hydrogen as fuel in thermal power stations [6,12]. The ability of a gas turbine to run on high hydrogen fuel requires a combustion system that can handle the specific nature of that fuel and General Electric (GE) has diffusion combustion systems in service for turbines Aeroderivative and Heavy-Duty gas engines capable of burning hydrogen. These include the Single Annular Combustor (SAC) for Aeroderivative gas turbines and the Quiet Single-Nozzle Combustor (MNQC) for heavy-duty gas turbines. Today, GE is able to quote hydrogen levels up to ~90 - 100% (by volume) for applications with the MNQC combustor or single nozzle combustor. The type of combustion system to be implemented in existing thermal power plants for 90-100% hydrogen combustion is not part of the study of this article. The work carried out in this article, with Nigeria as a case study, shows that thermal power plants and the use of generators have a considerable impact on GHG emissions and in particular on CO_2. Through research, it is shown that the carbon tax cost of operating thermal power plants covers the cost of transitioning from a CO_2 emitting turbine to a zero-carbon gas turbine with hydrogen as flue gas. This article also shows that Nigeria spends 14 billion dollars for generators using 43 million liters of fuel per year or 113 000t of CO_2

Methods

The scenario is based on Nigeria energy system. Through statistical calculations, the electricity production from thermal power plants is presented and the calculation of the cost linked to GHG emissions was performed. Subsequently, through bibliographic research the price of switching from a 12MW thermal power plant running on natural gas to operating with green hydrogen as fuel was found. All of these results made it possible to present the return on investment (ROI) linked to the decarbonization of thermal power plants of this power. The return on investment (ROI) is obtained by calculating the cost of the annual carbon tax, knowing that it is worth 11,493 USD/day, or 3.6 million USD/year for an emission of 114 931 200 g CO_2/ day, equivalent to 18 million USD over 5 years, which is compared to the cost of the transition of a thermal power plant from natural gas to hydrogen, which is 17 million USD. With the aim of reducing the number of years of the ROI, numerical modeling was carried out on MATLAB Simulink in order to observe the different powers which emerge from it, mainly thermal energy.

Results and discussion

Study sample

This part presents an assessment of the number of thermal power stations in Nigeria. All the data presented in this part were used to analyze and to present the economic and environmental aspects. This study showed the impact in terms of GHG emissions, the cost of these solutions as well as the cost of the carbon tax that can be applied.

According to Table 1, it can be seen that the production of electricity from natural gas in thermal power plants accounts for 73% of national production in Nigeria [13,14].

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Table 1. Distribution of power generation plants. Source: *[12].*

Type	Power (MW)	Percentage (%)
Gas-fired	11.972	73%
Hydro plants Providing	2.062	13%
Solar, wind, and other sources such as diesel and Heavy Fuel Oil (HFO)	2.35	14%
Total	16.384	100%

Table 2. GHG emissions per kWh electrical energy generated by actual best available technology for each energy vector. *Source: [15].*

Generation technology	Source	g CO2/ kWh$_e$	Ref.
Coal	Combustion	900	49
Gas	Combustion	400	49
Nuclear	Uranium enrichment	4	49
Wind	Construction	10-30	49
Photovoltaic	Construction	100-200	49
Hydro		18	6

According to this distribution (Table 1) and according to Table 2 presenting the amount of CO_2 emitted by the various electricity production technologies, estimation of all GHG from thermal power plants in Nigeria was made. The estimation of the amount of CO_2 from thermal power plants in Nigeria per day in these power plants can be obtained through the following equations.

(1) $$GES_{co2} = E_{cth} \times GHG \times 24 = 114\,931\,200\ gCO_2$$

(2) $$P_c = T_c \times GES$$

(3) $$GES = C_a \times FE \times PRG$$

(4) $$P_c = 114\,931\,200 \times 49 \times 10^{-6} \times 100 = 11\,493\ USD/day$$

where:
E_{cth} - 11972 kWh
GHG - 400 gCO_2/Wh$_c$
(PRG) = 1 - the global warming potential
(T_c) - carbon tax taken at 100 USD / tCO_2
(FE) - the emission factor
(GES) - GHG emission
(C_a) – consumption
(P_c) - carbon price
(E_{cth}) - power production by gas fire.

In this case study, the value of GES_{co2} is estimated at 114 931 200 gCO_2, which corresponds to 11,493 USD to be paid per day considering a carbon tax evaluated at 100 USD [16]. Through these data, it can be concluded that the interpolation concerning the carbon tax applied to these installations generates a significant cost of 3.6 million USD/year.

In order to perform a numerical simulation of the production of energy equivalent to 12 MW in a thermal power plant based on green hydrogen, several bibliographic searches were carried out. Thanks to this, it was found that the first electricity-hydrogen-electricity project on an industrial scale in the world was carried out in France [17]. It was based on the conversion of a thermal power plant producing heat and electricity of 12 MW with natural gas into a power plant using green hydrogen as combustion gas between 80 and 100%. The budget for this

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implementation was 16.9 million USD. Therefore, by analogy it can be assumed that the conversion of a 12 MW thermal power plant from natural gas to hydrogen as the flue gas would require approximately 17 million USD. From where, through the estimate on the study sample, it can be deduced that after 5 years the country will spend on carbon tax the price necessary for the decarbonization of all of their natural gas thermal power stations.

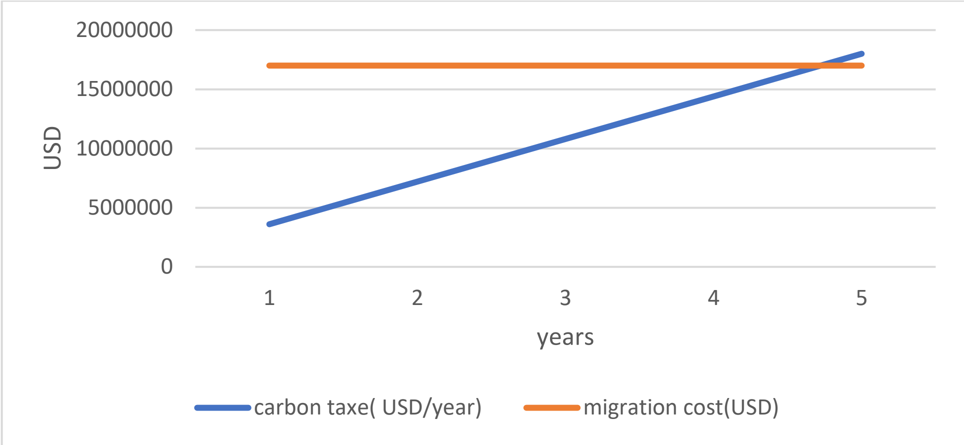

Figure 3. Evolution of the costs of the two technologies. *Source: Author.*

According to the interpolation presented on Figure 3, it can be deduced that in 5 years, Nigeria will spend 18 million USD for the carbon tax. This amount is higher than the cost necessary for the conversion of thermal power plants working on natural gas into the one using green hydrogen as a combustion gas.

Modeling, simulation and evaluation of the cost of a 12 MW thermal power plant running on green hydrogen.

During the process of generating electricity in a thermal power plant operating with green hydrogen as the fuel gas, a large amount of thermal energy is normally generated. In various research works, this phenomenon is represented by cogeneration techniques [18–20]. It is therefore important to analyze the productivity of a gas turbine with hydrogen fuel produced from wind or solar energy. For this purpose the SGT-400 [21] turbine was considered and various parameters resulting from several modeling oriented in the same framework were taken into account as well [22–24]. It is important to note that the ability of a gas turbine to operate with a fuel with a high hydrogen content requires a combustion system able to manage the specific nature of this fuel [25]. General Electric (GE) has diffusion combustion systems in service for Aeroderivative and Heavy-Duty gas turbines capable of burning hydrogen. This also leads to very high flame temperatures as well as high NOx emissions. The proposed system contains the Single Annular Combustor (SAC) for Aeroderivative gas turbines and the Quiet Single-Nozzle Combustor (MNQC) for heavy-duty gas turbines up to ~90 –100% (by volume) for applications with MNQC combustor or single nozzle combustor.

This modeling does not consider the characteristics of the combustion system and the modeling makes it possible to observe and to analyze the thermal parameters of the gas in order to have a possibility of implementing this thermal energy. As presented in [22,26], the gas turbine mainly consists of the compressor, the burner, and the turbine.

Modeling in the compressor

(5)
$$P_c = P_c^{in} \times PR$$

(6)
$$T_c = T_c^{in}\left[1 + \frac{\frac{P_c}{P_c^{in}}^{\frac{\gamma-1}{\gamma}} - 1}{\eta_c}\right]$$
[24]

(7) $$W_c = \dot{m}_a \times C_p^a (T_c - T_a)$$ [24]

(8) $$\rho_a^C = \frac{P_c}{\mathrm{T}_c \times C_p \times \frac{\gamma - 1}{\gamma}}$$ [27]

where:
P_c^{in} - Compressor inlet pressure
P_a- Ambient air pressure
P_c- Compressor outlet pressure
P_c- Compressor outlet pressure (bars)
T_c^{in}- Compressor inlet temperature
T_a - Ambient temperature
T_c - Compressor outlet temperature
S_{out} – Entropy
hs - Specific enthalpy
W_c- Compressor thermal power
ρ_a^C- Compressor density
η_c - Compressor efficiency
C_p^a - Thermal capacity
$\dot{m}_c$ and $\dot{m}_a$ - respectively represent the flow of air leaving and entering in the compressor
τ_c - The time of the passage of the air in the compressor according to the speed and the length of the latter
W_c - Heat flux during compression (w)
$\dot{m}_a$ - Mass flow (kg/s) of incoming air
C_p^a - Heat capacity of ambient air entering the compressor($\frac{j}{kg \times K}$)
ρ_a^C - Density of outgoing air of the compressor.

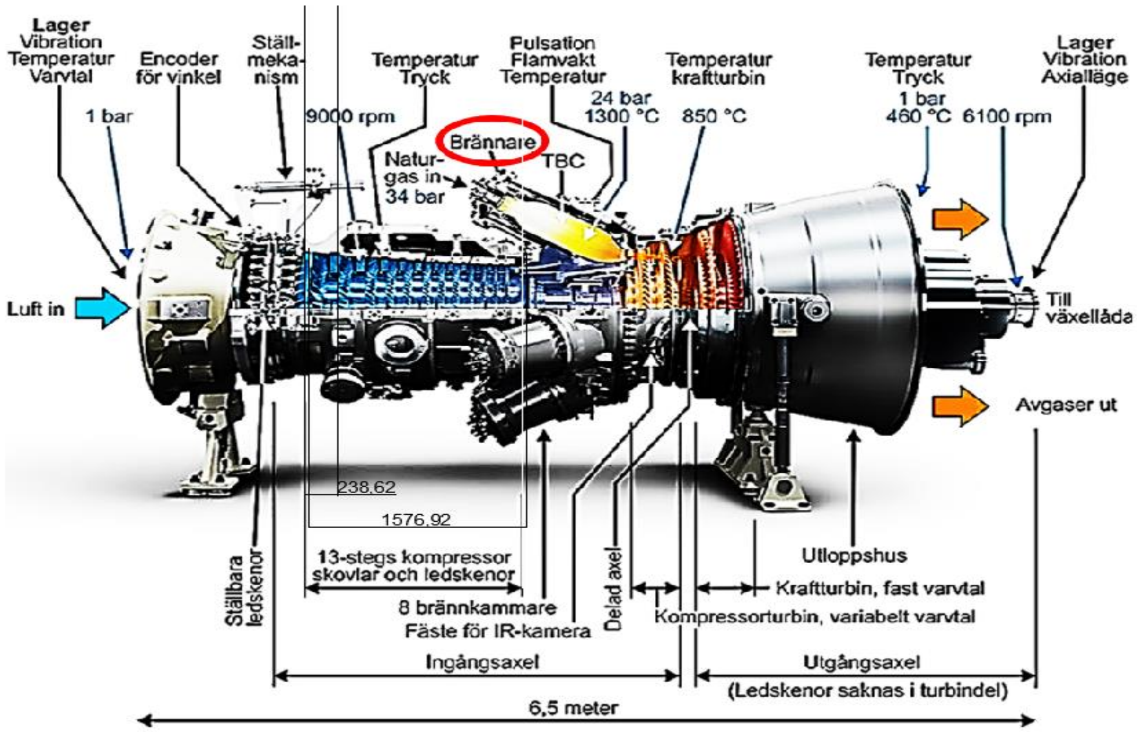

Figure 4. Industrial gas turbine SGT-750. *Source: [18].*

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Using data given in Figure 4, the length of each main compartment intervening in the process including the approximate time of each phase can be estimated.

Modeling in the burner (combustion chamber)

(9) $$P_b = P_c \times (1 - dP)$$ [24]

(10) $$W_b = \dot{m}_{a/h} \times C_p^{hot}(T_b - T_c)$$ [24]

(11) $$\dot{m}_{a/h} = \dot{m}_a + ff$$ [24]

(12) $$ff = \frac{W_b}{FCV}$$ [24]

(13) $$T_b = \left[\frac{T_c + q_t \times \frac{Q_b \times \eta_f}{c_p}}{1 + q_t}\right]$$ [28]

where:
ff - Fuel flow (kg/s)
FCV - Value of the heat of combustion of hydrogen (141000 KJ/Kg)
W_b - thermal power in the burner (Kw)
$\dot{m}_{a/h}$ - flow rate of the air-hydrogen mixture entering the burner.

Turbine modeling

(14) $$\eta_t = \left[\frac{1 - \frac{T_t}{T_b}}{1 - \frac{P_t}{P_b}^{\frac{\gamma-1}{\gamma}}}\right]$$

According to the literature [27], P_T^m is the mechanical transmission power of the SGT-400 turbine estimated at 13.40MW.

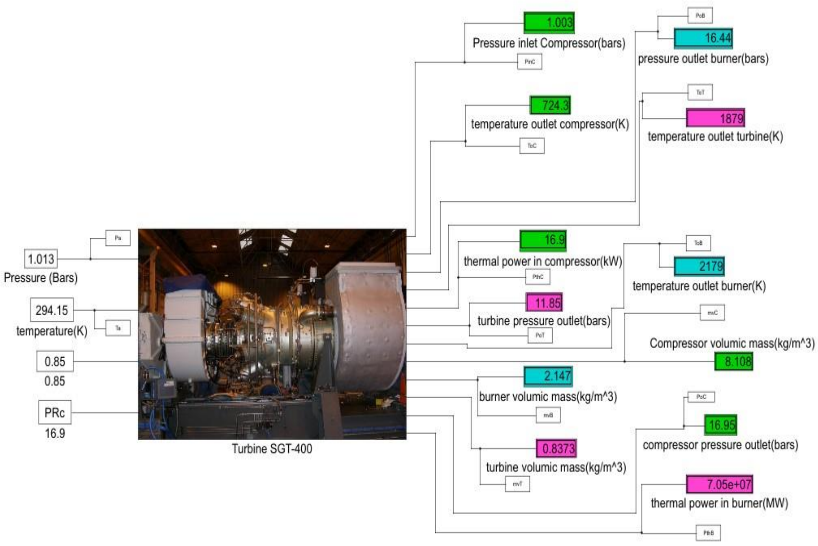

Figure 5: Extract of the modeled system. *Source: Author.*

Table 3. Specifications Adopted for The Simulation. *Source: Author.*

Components	Rating values
FE	49
T_c(USD)	100
PRG	1
η_c	0.86
Pa(Bars)	1.013
Ta(K)	294.15
FCV	141000
C_p^a (J/kg·K)	1010
C_p^{hot} (J/kg·K)	1230
GHG (gCO_2/Wh_c)	400
Pa (bars)	1.013
Ta (K)	294.15
Flux (kg/s)	38.9
dP	2%
V (m/s)	100
γ	1.4
PRc	16.8
PmecT (kW)	13.4
Lc (m)	1.6
η_b	36.8
$\dot{m}_b$ (kg/s)	39.4
$\dot{m}_c$ (kg/s)	38.9

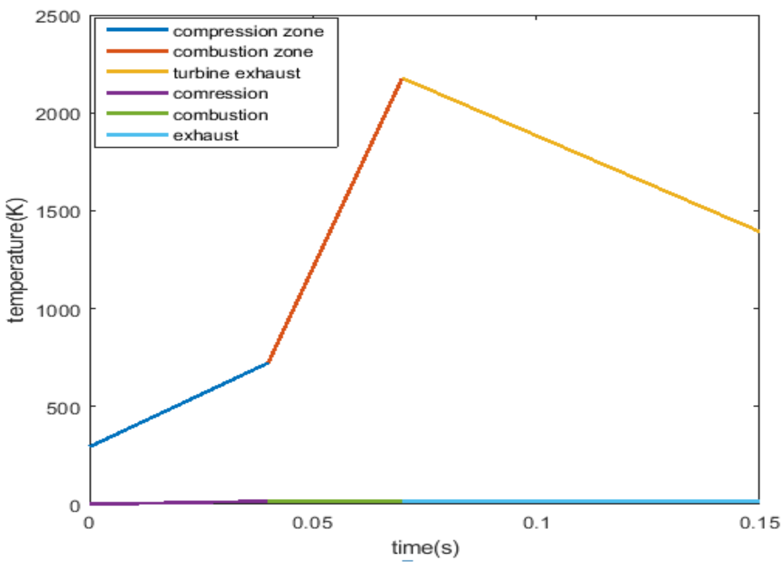

Figure 6. Temperature variation. *Source: Author.*

Figures 6 and 7 show the evolution of temperature and pressure respectively in the modeled system according to the data in Table 3 below.

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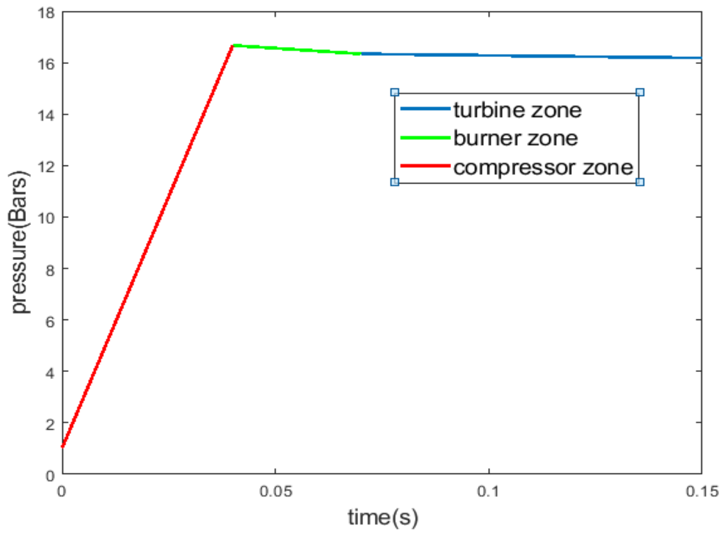

Figure 7. Pressure variation. *Source: Author.*

Impact

This article presents a techno-economic study on decarbonization through the use of the green hydrogen energy vector. Faced with the global challenge of reducing the rate of GHG emissions, several R&D projects are emerging. With this in mind, R&D presents several points of considerable progress in clean electricity production and clean storage systems like the construction of solar and wind power plants. Concerning this, R&D has been making other efforts for several years for the integration into the industrial world of green hydrogen, which is considered to be the energy vector capable of changing and revolutionizing the energy trend. Indeed, green hydrogen is currently being used in many sectors such as transport, refinery industries, power plants and energy storage, the configuration and traditional implementation of which causes an emission of considerable quantities of GHG. Knowing that the primary objective of R&D today is the reduction of GHG emissions, mainly CO_2, and that achieving of this objective requires acting on the systems and sectors most polluting on a global scale, this study focuses on the electricity production sector, which represents 41% of the CO_2 emission rate in the world. The study is particularly oriented towards thermal power plants running on natural gas. This article shows that the energy transition of thermal power plants from natural gas to green hydrogen as fuel is an effective way to fight against CO_2 emissions. Through a techno-economic study based on the case of Nigeria, it was shown that the transition from a 12MW natural gas plant to green hydrogen requires approximately 17 million USD investment. In comparison to a carbon tax estimated at 100 USD/tCO_2, it can be noted that the return on investment is possible after 4 years because the quantity of carbon emitted is estimated at 114 931 200 gCO_2, which corresponds to a tax of 11.493 USD/day, or 3.6 million USD/year and over 5 years the carbon tax expenditure will account for 18 million USD. In addition, the study shows that the country spends 40 million liters of fuel per day for the use of generators knowing that one liter of fuel emits 2.67 kg of CO_2. On the other hand, in order to analyze certain data of a gas turbine at the time of combustion, a numerical modeling accompanied by a production simulation was made. The results show that the amount of thermal energy coming out of the turbine part can be enhanced for industrial use. Applied internationally, the result on the environmental plan will be considerable but also on the financial plan because after valorization of the thermal energy coming out of the turbine the return of investment could be close to 3 years.

Conclusion

With the aim of expanding and promoting solutions to fight and reduce CO_2 emissions into the atmosphere, this article presents a techno-economic study of the migration of natural gas thermal power plants to green hydrogen as fuel. Indeed, this work has shown that power plants contribute significantly to CO_2 emissions reduction, particularly in the case of thermal power plants. The economic study shows that it cost about 17 million dollars for the transition from Natural Gas to Green Hydrogen of a 12 MW thermal power plant for a return on investment over 4.5 years without considering the tri-generation that can be applied to the view of the thermal power released by the turbine. According to the simulation, the inlet of a temperature of 294.15K after passing through the burner is achieved, whereas temperature goes to 2100K, at the outlet after driving the turbine and the outgoing gas has a temperature of 1879K for a thermal power of around 16 MW. This result

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shows that the thermal power obtained can be used in the wood industry for drying, or in the industry of the circular economy by recycling plastic so as to act doubly on the protection of the environment and improve the overall efficiency of the combined system.

Conflict of interest

There are no conflicts to declare.

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