Assessment of Economic and Environmental Impacts of using Green Hydrogen Gas for Generating Electricity in the KSA

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Abstract: - The energy sector in the Kingdom of Saudi Arabia (KSA) faces serious challenges regarding its current energy mix and energy policies. These challenges are even more complex in the sphere of electricity generation. Where on one side, these challenges are attributed to the fast-growing domestic demand for electricity. While on the other side, KSA depends extensively on traditional fossil fuels for generating electricity and hence facing high rates of carbon dioxide (CO2) emissions. To address these challenges, the Kingdom's 2030 vision opted for economic diversification and decarbonization by encouraging the transition towards using green hydrogen gas for electricity generation as a clean energy source. This attempt has been associated with measures addressing rationalization of the demand side for electricity. The objective of this paper is to explore the economic and environmental viability of using green hydrogen gas for generating electricity in KSA. Working toward this objective, an economic assessment has been applied to five hypothetical cases or scenarios to identify the most cost-effective (least expensive) to run the turbine generator at net zero CO2 emission. In addition, an assessment of the environmental impact has been applied to the same five hypothetical cases or scenarios to identify the most environmentally friendly i.e., help effectively to reduce or minimize the CO2 emissions. The findings of this assessment reject the economic viability of the transition towards using green hydrogen gas for electricity generation in the KSA, where the calculations of the five cases registered an inverse relation between the NPV and the use of green hydrogen gas in electricity generation. These findings confirm the environmental variability of this transition, where the calculations of the five cases registered a positive relation between decarburization and the use of green hydrogen gas in electricity generation. Based on these findings, the economic ramifications and viability of this transition require a thorough investigation addressing economic and non-economic aspects.

Key-Words: - Green hydrogen gas; Carbon dioxide CO2; KSA; Electricity generation; Economic impact; impact Environmental.

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1 Introduction

The energy sector in the KSA faces serious challenges. One of which is that domestic energy consumption relies exclusively on fossil fuels i.e., oil and natural gas. This consumption rose above international standards, particularly the electricity demand, which showed strong rates of growth. This is mainly due to the fast-growing population, improvements in the standards of living, ambitious economic and industrial development programs, and subsidy regimes that encourage wasteful consumption, [1], [2]. If this trend of domestic energy consumption (mainly oil and natural gas) continues, the KSA might become a net energy importer in the coming future.

This issue has even been made worse by growing concerns over the adverse environmental implications associated with the extensive use and reliance on fossil fuels in generating electricity. Prominent evidence for that, 57% to 59.6% of the electricity in the KSA is generated by combusting natural gas (methane) in gas turbine generators, which become a significant source of carbon dioxide (CO2) emissions. According to the International

Energy Agency (IEA), these emissions have grown from 151 metric tons in 1990 to 495 metric tons in 2019, [3]. CO2 accounts for 80% of the total greenhouse gases (GHG) emitted in the KSA. Therefore, in the year 2020, the KSA ranked as the 10th top emitter of CO2 worldwide with approx. 1.6% of the world's share, [4].

There are two options available for reducing these emissions either by utilizing hydrogen gas as a primary fuel or by mixing it in different ratios with natural gas, [5].

Realizing the urgent need to address ahead of adverse economic and environmental impacts of the heavy dependence on hydrocarbons in the electricity sector, policymakers in the KSA launched long-run reform policies and programs for the diversification and sustainability of energy consumption and supplies. These policies and programs considered the reform of the electricity sector as a top policy priorities. This is articulated in the Kingdom's promising vision for 2030, one pillar of which is diversifying the energy mix and reducing dependence on fossil fuel sources, along with taking advantage of available opportunities–especially those related to the expansion of the capacity for renewable energy generation. Another pillar of this vision is the commitment to cut the Kingdom's CO2 emission to the level of net zero by 2060, which means achieving a kind of balance between the GHGs released into the atmosphere and captured from it, [6].

In the quest for addressing the economic and environmental challenges of using fossil fuels, the transition to hydrogen gas in electricity generation in the KSA is seen as a key player and a more promising option. Unlike natural gas, hydrogen gas has the benefit of zero-emission when combusted. Whereas, the combustion of emission from hydrogen is only water if used as a primary fuel in the power generation from gas turbines-generators, or it will significantly reduce the CO2 emission depending on the mixing ratio, [7]. On the other hand, the trade-off is that hydrogen gas has lower energy capacity (1/3 of methane) by volume and higher prices than natural gas, which is expected to increase the fuel cost for running the gas turbine-generators in the power plants, if not linked to CO2 capture.

This study focuses on the GE 7F Series simple cycle gas turbine generator, currently in service at the Saudi Electric Company Riyadh power plant number 12 (PP12). The study utilizes the GE 7F Series simple cycle gas turbine-generator manufacturer General Electric and provides information for two main objectives:

The **first objective** is to conduct an economic assessment. In this respect, an attempt is made to evaluate and compare the cost of operating the gas turbine generator at net-zero emission considering the cases (scenarios) shown in Table 1.

In the light of the above cases or scenarios, the study attempts to answer the question:

Which one of the respective cases is most cost-effective (least expensive) to run the turbine generator at net zero CO2 emission?

The **second objective** is to conduct an assessment of the environmental impact in the case of using hydrogen gas for electricity generation. The major concern in this respect is CO2 emissions into the atmosphere if hydrogen is used along with natural gas to run the gas turbine generators. Again, the above cases or scenarios (25%, 50%, 75%, and 100%) are going to be employed for the assessment. From this perspective, the study attempts to answer the question: Which one of the respective cases is most environmentally friendly i.e., help effectively to reduce or minimize the CO2 emissions?

Table 1. Five scenarios for the economic and environmental assessment

Scenario	Natural Gas Used (%)	Hydrogen Gas Used (%)
Case-1	100	0
Case-2	75	25
Case-3	50	50
Case-4	25	75
Case-5	0	100

To answer these two questions, the study suggested the following hypotheses:

Hypothesis 1 (H1):

The transition towards using green hydrogen gas for electricity generation in the KSA is an economically viable option.

Hypothesis 2 (H2):

The transition towards using green hydrogen gas for electricity generation in the KSA is an environmentally friendly option i.e., reduces the CO2 emissions effectively.

The rest of this paper is composed of the following sections: Section 2 is devoted to reviewing the relevant literature on the theme of this study, while section 3 describes the methodology and data used for conducting the economic and environmental assessments. The findings of the five hypothetical cases (scenarios) and their presented in Section 4. Finally, Section 5 concludes and recommendations regarding the nexus economic-environmental impacts arising from the transition to green hydrogen gas in generating electricity in the KSA.

2 Literature Review

Globally, energy consumption skyrocketed during the last several decades. One way to address this rising demand for energy without harming the environment is via the use of renewable energy sources. In this context, green hydrogen gas gained momentum as an efficient fuel and clean energy carrier worldwide. Nevertheless, there is discourse over the production methodologies and end-use applications of green hydrogen gas. Whereas the economic and environmental viability of these production methodologies and the end-use applications remain debated. For example, conventional production methods, like steam methane reforming, primarily derive hydrogen from natural gas, leading to substantial CO2 emissions. While, the electrolysis, especially when powered by renewables, presents a cleaner alternative, producing hydrogen with minimal CO2 emissions, [8].

Hydrogen gas can be used as a fuel to generate power, heat, or electricity. Currently, the primary use of hydrogen gas is in fertilizer production, petroleum refining, and methanol production. There are four main types of hydrogen: brown, grey, blue, and green hydrogen. This classification of hydrogen is based on the raw material and production route as shown in Figure 1. Needless to say, green hydrogen is the most environmentally friendly among the other types for the production of fuel and electricity from emission-free sources. Powered by a renewable energy source, such as wind or solar power, electrolysis, the splitting of water into hydrogen and oxygen, is mainly implemented to produce green hydrogen, [9].

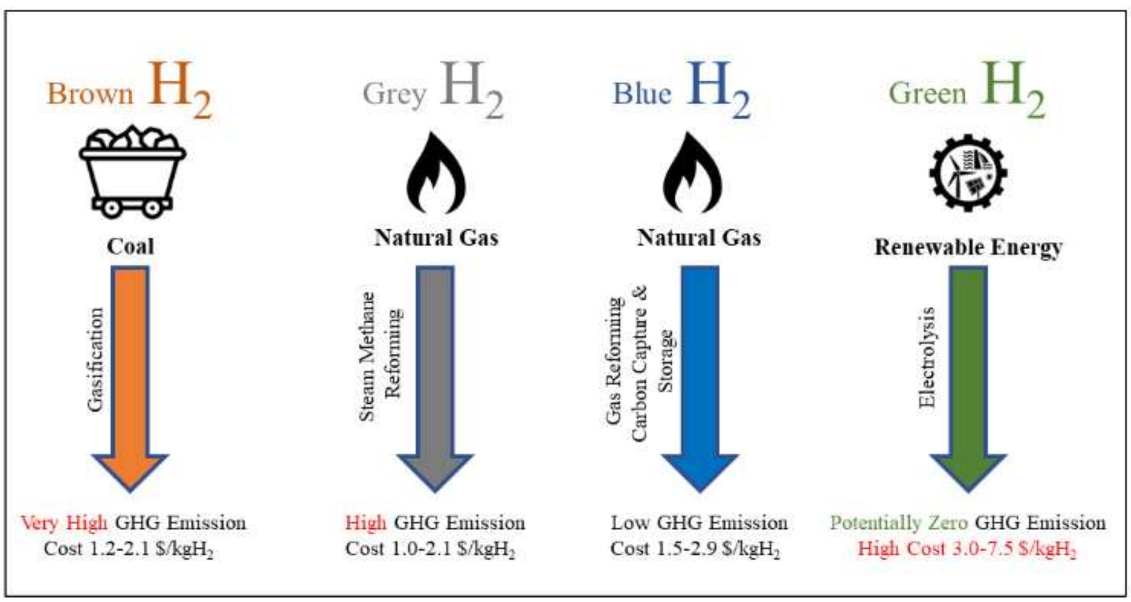

Fig. 1: Types of Hydrogen, [9]

It is necessary to mention that the so-called carbon capture, utilization, and storage CCUS technologies play a major role in the sustainability of energy systems around the globe. However, several factors justify the slow adoption of CCUS technology worldwide. High cost is a primary factor since CCUS applications do not all have the exact cost. The cost can vary significantly by CO2 source, from a range of 15-25 US$/t CO2 for industrial processes producing highly concentrated CO2 to 40-120 US$/t CO2 for processes with low-concentration gas streams, such as cement production and power generation. Capturing CO2 from the air is currently the most expensive approach but could play a unique role in carbon removal. Some CO2 capture technologies are commercially available now, while others are still in development, contributing to the extensive range in costs, [10].

The KSA is marching forward with its plan to diversify its energy mix to meet the Kingdom’s demand for energy and reduce liquid burning at power plants. Recently, the Saudi giant national oil company (Aramco) has been investing in utilizing the Kingdom's unconventional gas resource. There are unconventional gas processing plant projects under construction like south Ghawar, Hawaya Unayza ($ 1.8 billion), and Jafurah ($ 110 billion), [11], [12].

Having the world's cheapest solar power potential, the KSA has the intention to accelerate the use of renewable energy by the Kingdom's vision 2030. Therefore, in August 2020, the KSA announced a $5 billion project of a green hydrogen plant powered by 4 gigawatts (GW) from renewable energy sources, which is the world's biggest hydrogen project announced so far. Saudi Arabia's ACWA Power and Air Products own this plant jointly. The target of this partnership is to produce 650 tons of green hydrogen gas by the year 2025 and export it to the world market, [13]. Moreover, the KSA is willing to invest in developing CCUS facilities around the country as part of its contribution and commitment to address the drivers of global climate change, [14].

The current installed power generation capacity in the KSA is 85 GW. This includes five types of power generation units: Gas Turbine Generator (GTG), Combined Cycle Generator (CCG), Steam Turbine Generator (STG), Diesel Generator (DG), and Renewable Energy (RE). Figure 2 illustrates the electricity generation stations by type and location in the Kingdom. Figure 3 shows that 60.1% of the total installed generation units are GTG and almost 17.8% are STGs. While CCG forms, 17.5%, and almost 3.8% are DGs. The remaining is RE with less than 0.7%, [15].

Fig. 2: Electricity generation stations: types and locations, [5]

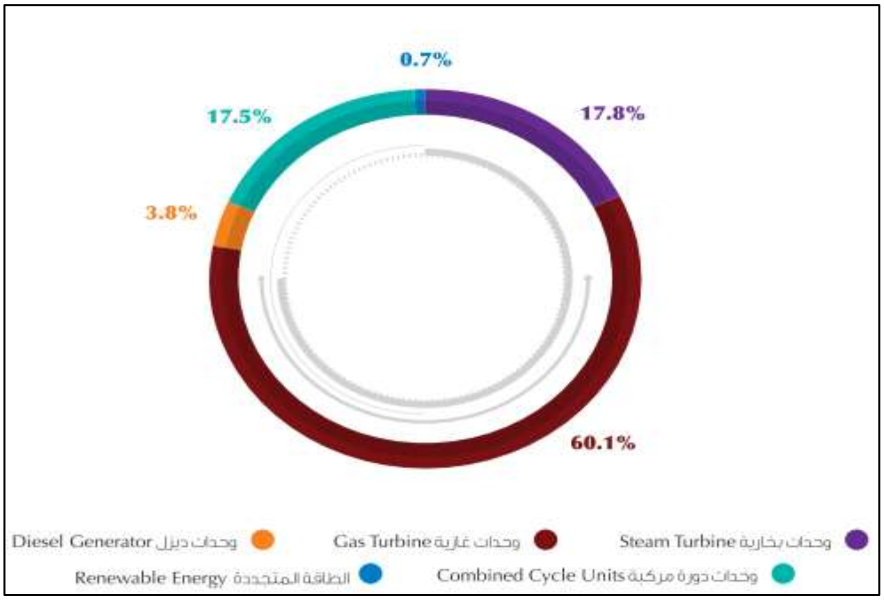

Fig. 3: Percentage distribution of the total installed generation units, [15]

Gas turbines are fuel-flexible power generation units, yet they currently use mainly natural gas. Gas turbine technologies are under continuous upgrade and improvements. Currently, the available turbines in the market are compatible with using fuels with high shares of hydrogen even up to 100%. High mixing rates are necessary for gas turbines to be feasible in a low-carbon future energy system, [16]. As a key partner, General Electric (GE) has been involved in the KSA power sector for nearly eight decades. GE power generation technology is installed in nearly 40 Saudi Electricity Company (SEC) sites, and more than half (> 50%) of the total Kingdom's electricity generation is generated from over 500 GE-manufactured turbines, [17]. In 2012, GE won over a US$300 million contract to supply Riyadh Power Plant number 12 (PP12) with eight F-Class gas turbine generators, [18]. According to GE, gas turbines are fuel-flexible. They can be modified to run on green hydrogen or similar fuels as a new unit or be upgraded even after a long service on traditional/conventional fuels, like natural gas. The F-Class gas turbine can run fuels with a high volume percent of hydrogen up to 100%.

Hydrogen production and adoption will enable Saudi Arabia to be less reliant on domestic oil and will be a source of income for global buyers. The Kingdom has an excellent opportunity to invest in the production of green hydrogen gas as it has the lowest cost of solar photovoltaic (PV) generation globally, at 0.0162 U.S. dollars per kilowatt-hour (US$/kWh). However, the adoption of green hydrogen gas as an energy source is still in its early stages. Beyond and above, the development of using green hydrogen gas in electricity generation is dependent on aspects related substantially to cost reduction. The recent drop in renewable costs significantly improved green hydrogen production in the upcoming years. The Levelized cost of green hydrogen (produced from renewable energy sources) will drop to a range of 0.8-1.6 US$ per kilogram (US$/kg) in 2050 from 2.5-4.5 US$/kg in 2019.

As renewable prices drop, green hydrogen will become more feasible and attractive. Other factors, such as the prices of conventional hydrocarbon energy sources such as oil and natural gas, will contribute to the speed of hydrogen adoption. Since conventional energy sources are available, the hydrogen adoption rate will decrease if conventional energy sources remain in a low-price regime. On the other hand, the global environmental protection policies and climate mitigation measures will impact conventional energy sources' costs by further elevating the cost of conventional energy sources, leading to an improved future outlook for green hydrogen gas, [19], [20], [21].

The opportunity to improve the efficiency of domestic energy use and maximize the potential of oil exports is enormous. Therefore, the KSA plans to convert half of its power sector to gas and the other half to renewables, [22]. Hence, the Kingdom will continue to use natural gas as fuel to generate at least fifty percent of its power demand, and green hydrogen will be available and produced in the Kingdom. The KSA intends to increase the electricity generation capacity to 120 GW by 2032 in response to the rapidly growing domestic demand for electricity, [5].

Finally, the transition to green hydrogen gas for electricity generation as a new source of energy supply in the GCC region in general and in the KSA in particular is still in the infancy stage. Therefore, different aspects and potentials of this issue are still not yet covered by the previous studies. Among those aspects and potentials - to the best of our knowledge - no study has been conducted on the assessment of economic and environmental impacts of using green hydrogen gas for generating electricity in the KSA. Therefore, the purpose of this study is to provide academics and policy-makers in the KSA with scientifically sound findings on the economic and environmental viability arising from the switch to green hydrogen as a vector for generating cost-effective and clean energy along with the challenges and barriers in this respect.

3 Methodology

The methodology for reviewing hydrogen energy policies typically involves several steps. While the specific approach may vary depending on the context and objectives of the review, here is a general outline of the methodology Figure 4, gives a visual representation of the adopted methodology.

3.1 Economic Evaluation

The Economic evaluation is illustrated in Figure 4. The annual amount of fuel required to operate the turbine and the corresponding CO2 emission is first estimated based on the gas turbine specification for each case defined in the study objectives (section 1). The annual fuel gas cost and CO2 capturing cost are estimated. The sum of the annual fuel and CO2 capturing costs is the annual cost for running the turbine at net zero CO2 emission. After that, all the cost values are used to measure the cost of running the turbine at net-zero After that, all the cost values are used to measure the cost of running the turbine at net-zero emission throughout the 30 years by computing its net present value (NPV). This NPV will be calculated for each case and then a comparison is done.

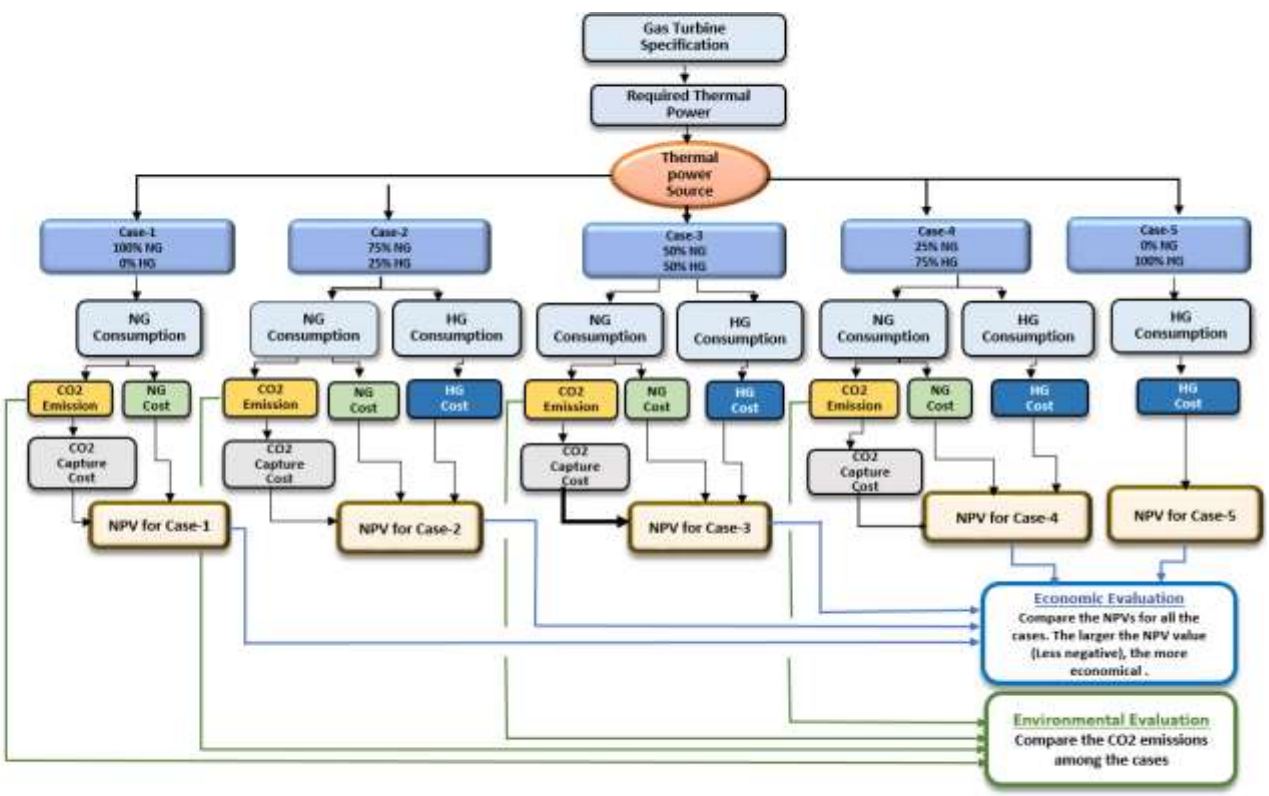

Fig. 4: Economic and environmental evaluation chart

3.2 Environmental Evaluation

The environmental evaluation is illustrated in Figure 4. The annual amount of fuel required to operate the turbine and the corresponding CO2 emission is first estimated based on the gas turbine specification for each case defined in the study objectives. The annual CO2 emissions are then compared for each case. The emission for each case is compared with the base case to evaluate the impact of using hydrogen gas to fuel the gas turbine.

3.3 Data

Natural gas and electricity costs are to be considered based on Saudi Minister Council Decision Number 95, Dated 17/03/1437, which is still in effect today. The green hydrogen gas prices are based on the international market prices, ranging from 4.5 US$/kg H2 in 2019 to an expected 0.8 US$/kg H2 in 2050, according to King Abdullah Petroleum Studies and Research Center, [23], [24].

The required amount of Natural gas and hydrogen gas to run the study focused on the GE 7F Series gas turbine generator computed/collected from the turbine specification sheet and the online calculator from the turbine manufacturer (general electric). Accordingly, the carbon dioxide emissions will be generated using the simple complete combustion formula, [24].

The following is the list of the assumptions used for this study:

- The turbine is considered a simple cycle turbine.
- No modification is required on the turbine as it is designed to run on up to 100% hydrogen.
- Therefore, the capital and operating expense of the turbine remain unchanged except for the fuel cost, which is investigated in this study.
- The turbine is assumed to operate at full load 8760 hours per year (hr/yr).
- The turbine is assumed to be run on its maximum load, generating 239 MW power, which requires 2.12 × 109 Btu/hr.
- The natural gas composition is assumed to be 100% Methane (CH4).
- The natural gas low heating value (LHV) is considered to be 20,267 Btu/lb (983 Btu/Scf).
- The hydrogen gas low heating value (LHV) is considered to be 51,585 Btu/lb (290 Btu/Scf).

At the start of the study, the green hydrogen gas cost was 2.5 $/kg, and it will reduce as expected to 0.8 $/kg in 2050. Therefore, the reduction rate is assumed to be 0.05862 $/k.

3.4 Annual Fuel Consumption

The annual fuel consumption is estimated using the following equations:

$$(LHV_{H2} \times H_2) + (LHV_{NG} \times NG) = 2.12 \times 10^9 \qquad (1)$$

$Where$:
LHV_{H2}: $Low\ heat\ value\ of\ Hydrogen = 51585\ \left(\frac{Btu}{lb}\right)$
H_2: $Hydrogen\ consumption\ \left(\frac{lb}{hr}\right)$

LHV_{NG}: $Low\ heating\ value\ of\ Natural\ Gas = 20267\ (\frac{Btu}{lb})$

$NG = Natural\ gas\ Consumption\ (\frac{lb}{hr})$

$Reauired\ heat\ to\ run\ the\ turbine = 2.12 \times 10^9$
Based on the study cases defined in section 1.1, the hydrogen consumption can be calculated as below:

$$H_2 = \frac{2.12 \times 10^9 \times R}{LHV_{H2}} \qquad (2)$$

$where$:
R: Fraction of heat produced by Hydrogen to run the turbine =0 for Cae#1,0.25 for case#2,0.5 for case#3, 0.75 for case#4 and,1 for case#5.

Based on the study cases defined in section 1.1, the natural gas consumption can be calculated as below:

$$NG = \frac{2.12 \times 10^9 \times (1 - R)}{LHV_{NG}} \qquad (3)$$

The annual natural gas consumption is estimated as follows:

$$ANGcon = 8760 \times NG \qquad (4)$$

$where$:
$ANGcon$
: $Annual\ natural\ gas\ conumption\ (\frac{lb}{year})$

The annual hydrogen consumption can be then estimated as follows:

$$AHcon = 8760 \times H_2 \tag{5}$$

3.5 Annual Fuel Cost

The fuel gas (natural gas, hydrogen, or mix) annual cost is estimated for each case defined in Table 1 using the following equation:

$$AFC_X = ANGcon_x \times NG_{Cost} + AHcon_x \times H_{cost} \tag{6}$$

$where$:
$AFC_X: Annual\ Fuel\ Cost\ for\ case\ x$ (\$)
$x: case\ number\ defined\ in\ section$ 1.1
$NG_{Cost}:\ Cost\ of\ natural\ gas.\left(\frac{\$}{lb}\right).$
$H_{cost}: cost\ of\ hydrogen\ \left(\frac{\$}{lb}\right).$

3.6 Annual Carbon Dioxide (CO_2) Emission

For ease of study cases defined in Table1, the annual CO2 emission can be estimated as follows:

$$ACDE_x = ANGcon_x \times 2.75 \tag{7}$$

3.7 Annual Carbon Dioxide (CO_2) Capture Cost

The annual CO2 capture cost from the air is estimated using the following equation:

$$ACCC_x = \frac{ACDE_x}{2200} \times 80 \tag{8}$$

$where$:
$ACCC_x = Annual\ CO_2\ Capture\ Cost\ \left(\frac{\$}{year}\right)$
$2200\ is\ used\ t\ convert\ ACDE_x\ from\ \left(\frac{lb}{yer}\right)\ to\ \left(\frac{ton}{year}\right)\ and, 80\ is\ the\ average\ CO_2 capture\ cost\ in\ \left(\frac{\$}{ton}\right)$, [10].

3.8 Net Present Value

The NPV is calculated using the following equation:

$$NPV_x = \sum_{t=1}^{29} \frac{(AFC_{x,t} + ACCC_{x,t})}{(1+i)^t} \tag{9}$$

$where$:
$NPV_x: the\ net\ present\ value\ for\ case\ x\ defined\ in\ Table 1.$
$t: number\ of\ years.$
$i: discount\ rate\ (assumed\ 3\%).$
$Note: AFC_{x,t}\ \&\ ACCC_{x,t}\ values\ are\ in\ negative\ (Cost).$

4 Empirical Results

4.1 Economic Evaluation

The NPV is calculated for the five cases defined in section Table 1. The results are illustrated in Figure 5.

From the figure, it is clear that the more hydrogen is introduced to operate the turbine the higher the expenses as the NPV value becomes smaller. Although the use of hydrogen reduces the CO2 emissions and corresponding capture cost it increases the net zero emission operating expenses due to the current relatively high prices of green hydrogen gas (1.1 \$/lb).

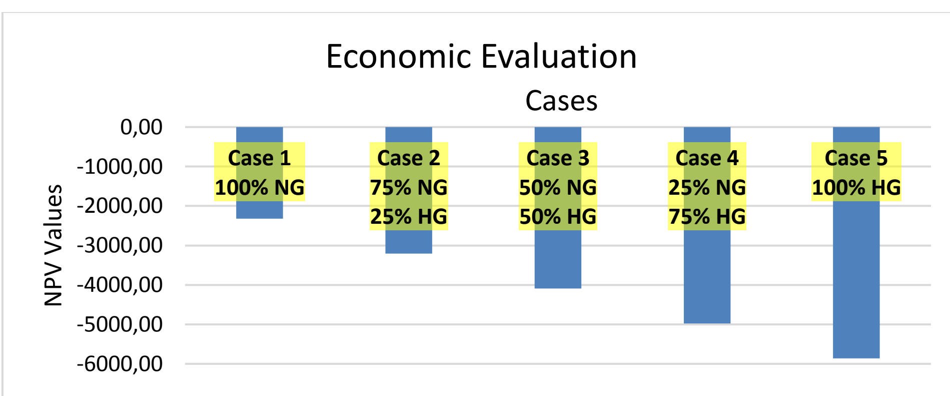

Fig. 5: Economic Evaluation- NPV Values

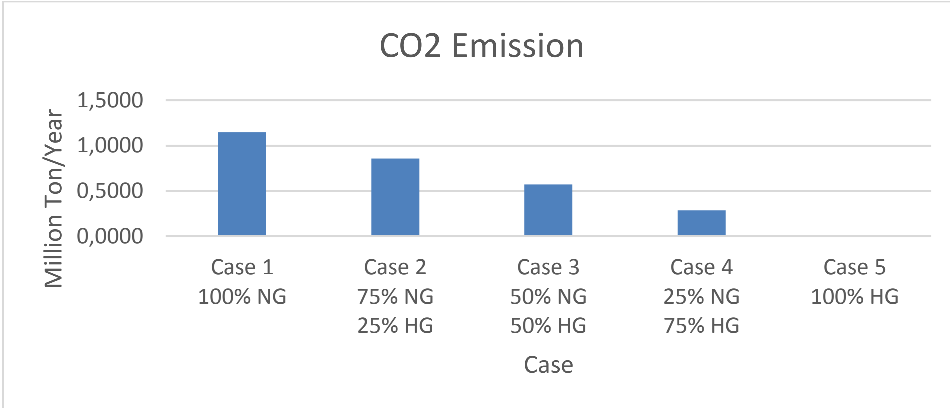

Fig. 6: Environmental Evaluation- CO_2 Emissions

In conclusion, with the current hydrogen prices, using 100% Natural gas in conjunction with CO2 capture (Case-1) is the best economic choice as it results in the largest NPV value among all the cases as of now, [25].

As the world is moving towards hydrogen gas as an energy source, global green hydrogen production from renewable energy will increase and hydrogen prices will reduce. The economic evaluation result in this study is expected to change in the future due to the future reduction in hydrogen gas prices.

Refer to Attachment-1 for NPV detail calculation for all cases. Worldwide, the decarburization policies of numerous governments, along with the decreasing costs of producing renewable energy, are reinforcing the argument for hydrogen as a viable energy carrier and fuel source. Hydrogen energy offers opportunities for reducing carbon emissions clean hydrogen produced with renewable or nuclear energy, or fossil fuels using carbon capture, can help to decarbonize a range of sectors, including electricity to reduce emissions**,** [24], [25].

4.2 Environmental Evaluation

The CO2 annual emission is calculated for the five cases defined in Table 1. The results are illustrated in Figure 6.

It is clear from the above figure that the introduction of hydrogen gas into the turbine fuel has a significant impact on reducing CO2 emission. With 100% natural gas in Case-1, the annual CO2 emission is 1.1 million tons per year while it is reduced by 25% in Case-2 and by 50% in Case-3 to zero emission in Case- 5 with 100% hydrogen fuel, [26], [27].

Introducing Hydrogen gas into the turbine generator fuel helps to make the turbine operation friendlier to the environment by significantly reducing the CO2 emissions or even eliminating the emissions, which ultimately reduces the air pollution and improves the quality of the air.

5 Conclusions and Recommendations

This work analyzes the economic and environmental impacts of using green hydrogen gas for generating electricity in the KSA, employing the Economic and environmental evaluation illustrated in Figure 4. Hydrogen possesses the ideal economic and environmental qualities necessary to emerge as a future energy carrier. With developing technologies for production, storage, and utilization, it has the potential to become a clean, safer, and sustainable energy carrier.

Hypothesis 1 (H1):

The transition towards using green hydrogen gas for electricity generation in the KSA is an economically viable option.

The study results show as indicated in Figure 5, that the Case-1 of 100% natural gas and zero green hydrogen gas, registered the largest NPV in comparison to the other cases with different combinations of natural gas and zero hydrogen gas. Consequently, this result confirms the rejection of the first hypothesis of this study.

Hypothesis 2 (H2):

The transition towards using green hydrogen gas for electricity generation in the KSA is an environmentally friendly option i.e., reduces the CO2 emissions effectively.

Figure 6 shows that the introduction of green hydrogen gas into the turbine fuel has a significant impact on reducing CO2 emissions. With 100% natural gas in Case-1, the annual CO2 emission is 1.1 million tons per year while it is reduced by 25% in Case-2 and by 50% in Case-3 to zero emission in Case-5 with 100% hydrogen fuel. We find that the results of the study reject the second hypothesis.

The KSA has a significant potential to become a leading player in using green hydrogen gas for generating electricity. To achieve this goal, the country needs to address the current limitations and implement a strategic plan that includes increasing investment in Using Green hydrogen Gas, developing a comprehensive hydrogen strategy, fostering international cooperation, building hydrogen infrastructure, supporting research and development, developing local demand for green hydrogen, and promoting education and awareness.

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Conflict of Interest

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