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Distributed waste-to-hydrogen refuelling station implementation in South Africa: Techno-economic-socio-political and environmental indications

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ABSTRACT

The combustion of liquid fossil fuels in the transportation sector, disposal and incineration of municipal solid waste (MSW) are the main sources of greenhouse gas emissions in cities across the world. In an effort to decarbonize the transportation sector, the South African government is dedicated to advancing green transportation through the hydrogen economy. Waste-to-hydrogen production can simultaneously achieve the goals of green transportation and waste management through widespread availability of hydrogen refuelling stations. This study assesses the techno-economic and environmental viability of waste-to-hydrogen refuelling stations in five selected South Africa cities. The refuelling stations' capacity was determined based on assumption that a 5 kg hydrogen-fuel-cell vehicle is refuelled per day. The economic feasibility was premised on net present value (NPV), payback period (PBP), internal rate of return (IRR), and levelized cost of hydrogen refuelling (LCOHr). The environmental analysis was based on ecological efficiency and carbon emission reduction potential. Some of the main findings indicate that the City of Tshwane and City of Johannesburg have refuelling station capacities of 356 thousand kg/day H_2 and 395 thousand kg/day H_2, respectively. Economically, the project is viable with positive NPV between 1.099 and 8.0563 Billion \$, LCOHr in the range of 3.99 \$/kg - 5.63 \$/kg, PBP of 9.03–13.74 years and IRR of 18.16 %–39.88 %. An ecological efficiency of 99.982 % was obtained which indicates an environmentally friendly system with the potential to save 1439 million litres and 1563 million litres of diesel fuel and gasoline, respectively capable of preventing about 4 kilo-tons of CO_2 into the atmosphere annually. Sensitivity analysis indicates that reforming efficiency, selling price of hydrogen and station capacity are crucial parameters with great influence on the economic profitability of waste-to-hydrogen refuelling station.

1. Introduction

Population growth, industrialisation, and urbanisation are major proponents for increase in energy usage. Largely, the sources of energy have been fossil fuels contributing more than 84 % of global primary energy consumption [1]. The release of hazardous gases into the atmosphere is a well-known reason why burning liquid fossil fuels like petrol and diesel for transportation purposes is considered environmentally unfriendly. About 50 % of the liquid fossil fuels consumption is expended in road transport [2]. Given that this value is likely to triple by 2050 [3], increased carbon emissions from road transportation may be anticipated in the future. To mitigate the current impact and avert the looming danger of global carbon emissions, transition to energy sources with net zero emissions is urgently needed. In a bid to actualise this feat, decarbonisation of the transport sector could play a prominent role by using clean, sustainable and environmentally friendly fuels [4]. Hydrogen (H_2) is an environmentally benign energy carrier due to zero emissions of hazardous pollutants when combusted [5]. It also has a significantly high energy density (around 120 MJ/kg), in comparison to 45–50 MJ/kg of gasoline and diesel and 55 MJ/kg of liquefied natural gas [6]. Even though H_2 has many benefits for the environment and energy, ensuring its sustainability depends critically on its source of production. Coal gasification (CG) and natural gas steam methane reforming (SMR) process are two commercially available thermochemical technologies for H_2 production. About 19 % of global H_2 production is through CG, 62 % is contributed by SMR process [7] while other methods are responsible for the rest.

Even though CG and SMR processes are technologically mature, they are not environmentally sustainable. On the other hand, H_2 can be produced using renewable energy sources. Water electrolysis (WE) [8], biomass gasification (BG) [9] and biogas steam reforming (BSR) [10,11] are green H_2 production techniques. Solar/wind-powered water

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electrolysis is pollution-free free but it is economically expensive [12] and requires great energy consumption [8] for water splitting. Additionally, uncertainty in the output of wind and solar, and their location-specific peculiarities are major bottlenecks for the application of solar/wind-powered electrolyser for H_2 production. Given its abundance and renewability, BG could be a viable substitute for CG in the production of renewable H_2. However, inconsistency of biomass properties and reliable supply chain are major impediments to BG for H_2 production [7].

Biogas as a renewable energy could be a promising source of hydrogen production due to many environmental advantages it offers. Due to similarity in the chemical characteristics of bio-methane and natural gas, it can easily replace natural gas in all applications designed for natural gas. Therefore, natural gas steam reforming process can be replicated using bio-methane in place of natural gas. Biogas can be produced from a variety of organic-based sources including agricultural waste, animal manure, organic fraction of municipal solid waste (OFMSW) such as food waste etc. Food waste is highly biodegradable and, if improperly handled, has the potential to pollute the environment. Food waste accounts for about one-third of MSW component [13]. Traditionally, municipal solid waste (MSW) is disposed of through landfilling and incineration. Disposing of food waste in landfills may pose a serious concern to human health due to release of stench that pollutes the air and contaminates nearby water sources. On the other hand, high energy consumption is required for incinerating food waste due to high moisture content, and also the production of toxic gas during combustion [13], hence both landfilling and incineration are not environmentally suitable methods.

Alternatively, food waste can be subjected to anaerobic digestion (AD) in an oxygen confined environment to produce biogas [14]. AD has been acclaimed to be environmentally friendly and a promising waste treatment method in comparison to landfilling and incineration [15]. Transferring food waste to an AD facility might result in waste diversion from landfills, hence easing landfill stress, extending their lives, lowering greenhouse gas emissions, and offering an alternative fuel source. In light of the issue of food waste in landfills and the need to lower environmental emissions from the transportation sector, food waste can be converted into biogas, which can then be further processed using the steam reforming method to produce H_2. This approach could simultaneously proffer dual solution of ensuring a clean environment in terms of waste management and production of low carbon hydrogen fuel [16] to support green transportation. The H_2 production can be implemented on-site or at the centralised production facility. The usage of H_2 by the consumers requires building refuelling stations where the H_2 is injected into the H_2-fuel cell vehicles: on-site or off-site [5]. In the case of an on-site H_2 production, the refuelling station is built in close proximity to the end users. On the other hand, an off-site (a centralised) H_2 production plant requires setting up of refuelling networks which comprise extra storage systems and transportation infrastructure for H_2 delivery to the refuelling stations. Being a physical infrastructure, it is essential to examine the technical, economic, and environmental feasibility of a hydrogen refuelling station (HRS) prior to embarking on physical construction. Premised on this, a number of research activities have been conducted to investigate the viability of deriving H_2 from food waste through BSR. Cudjoe et al. [17] studied the energetic, economic and environmental assessments of H_2 production from food waste for provinces in China. It was concluded that bio-hydrogen from food waste is economically viable with 0.814 \$/kWh of average H_2 production cost, 29.8 % IRR and 7.2 years PBP. In their study, the hydrogen is meant to be fed to fuel cell for electricity generation and not as fuel for transport vehicles. Also, the cost of refuelling stations was not included in their economic assessment.

Taking a Brazilian state as a case study, Crispim et al. [18] examined the economic feasibility of hydrogen and ammonia generation from co-digestion of MSW and wastewater sludge via biogas reforming process in 28 sanitary landfills. It was inferred from this study that the LCOH of H_2 production via steam reforming varied from 7.01 \$/kg to 44.45 \$/kg. In this study, the environmental assessment was not included while also leaving out the cost of refuelling station. Lui et al. [16] investigated the technical and economic feasibilities of distributed waste-to-hydrogen systems to support green transport in Glasgow. It was concluded that the LCOH for the various waste-to-hydrogen systems considered is in the range of 2.02–2.29 GB P/kg of H_2. In their study, the cost of refuelling station was not considered and also the environmental assessment was left out. A review of bio-hydrogen generation potential through waste decomposition technologies was undertaken by Ref. [19] but an assessment of hydrogen refuelling station was left out.

Wijayasekera et al. [6] provided a comprehensive overview of the processes and production routes for waste-to-hydrogen focusing on their technological, economic, environmental and societal significance for sustainable energy production and transportation. It was concluded that waste-to-hydrogen routes are more environmentally friendly than fossil-based technologies, however, the cost of hydrogen production from these routes are presently not competitive. Scaling-up and government intervention in terms of incentives are expected to bring down the costs in the near future. In their study, no mention was made of the refuelling station investment. A techno-economic evaluation of a combined bioprocess for fermentative hydrogen production from food waste for Hangzhou in China was investigated by Ref. [13]. It was found in this study that the return on investment (ROI), PBP and IRR of the plant were 26.75 %, 5 years and 24.07 %, respectively. The environmental assessment was left out of the analysis in their study. Adekanbi et al. [20] conducted a review on the techniques, challenges and economic feasibilities of bio-hydrogen production from wastewater. It was revealed that the average investment cost of H_2 production lies in the range of 0.4–18.5 \$/m^3. It is noticed from the aforementioned studies that only cost of H_2 production was determined in the economic analysis without considering the LCoHr. Since levelized cost of refuelling was not considered, it will be difficult to set the minimum selling price for the sale of hydrogen at the refuelling station. Also, some of the studies did not consider environmental assessment.

Gokçek et al. [21] designed an optimal configuration of hybrid wind/solar-powered electrolyser for a hydrogen refuelling station based on the economic and environmental analyses of the city of Zaragoza, Spain. The system had an LCOH of 5.83 \$/kg and NPC of \$6,499,723 as well as annual carbon avoidance of 2,366,573 kg. Similarly, Okonkwo et al. [22] and Okonkwo [23] investigated the techno-economic analysis of hybrid renewable energy systems consisting of wind, PV and battery for hydrogen production at refuelling stations for the city of Muscat, Oman and city of Geelong and Australia, respectively. Using HOMER commercial software as the modelling tool, it was reported that the optimal energy system returned an NPC of 614,957 \$, LCOE of 0.4347 \$/kWh, and LCoH of 0.375 \$/kg for city of Geelong while NPC, LCOE, and LCoH for the city of Muscat are 529,361 \$, 0.0158 \$/kWh, and 0.401 \$/kg, respectively. However, in Refs. [21–23], PBP and IRR as economic indicators were not included in the economic performance metrics while ecological analysis was equally not considered in the environmental assessment.

Bahou [24] investigated a techno-economic evaluation of an HRS powered by a grid connected photovoltaic solar system for a location in Morocco. Technically, based on the solar resources of the selected location, about 152 kg/day of hydrogen produced is required to supply the fleet of taxis while the LCoH varies from 9.18 \$/kg to 12.56 \$/kg based on the scale (size) of the system. It was found that the cost of hydrogen is inversely proportional to the capacity of the refuelling station. A mathematical model was developed by Caponi et al. [25] to identify the least-cost range of LCoH for an on-site HRS for a fleet of fuel cell buses. It was revealed that the most optimum configuration has the least LCoH of about 10.5 €/kg with a value ranging from 12 €/kg (for 2 FCB) to 10.2 €/kg (for 30 FCB). In the study of Fragiacomo and Genovese [26], an investigation was conducted on the economic viability of hydrogen production to meet the hydrogen usage and needs of two end-users (hydrogen-mobility and power-gas) using different renewable energy resources in some locations in Southern Italy. With an average daily hydrogen production ranging from 22 kg/day to 287 kg/day, the LCOH for different scenarios of power purchase agreement (PPA) varies from 6.9 €/kg to 9.85 €/kg.

Fragiacomo et al. [27] analyzed a distributed hydrogen infrastructure to help support the transportation industry. In their study, economic assessment was conducted and validated in three geographical regions of Italy. Mobility of a heavy-duty fleet in three geographical regions of Italy. Although the designed distributed hydrogen infrastructure is economically viable, the overall performance is greatly dependent on external conditions such as hydrogen demand and prices of electricity. Pettinau et al. [28] investigated the techno-economic analyses of hydrogen production as fuel for transportation via renewable energy sources focusing on two opposite perspectives of assessing hydrogen production cost during the whole lifespan of the project and profitability metrics. Further analysis was carried out to compare the hydrogen-powered FCEVs with conventional diesel buses for urban public transport sector. It was concluded that with a total investment of 20.3 M€, the cost of hydrogen production can be 4.09 €/kg and a reduction to 2.97 €/kg when additional revenue from oxygen sales and excess electricity production from renewable energy sources are considered. Despite the environmental friendliness of hydrogen fuel, the high investment cost has been a major impediment to large-scale utilisation of hydrogen-fuelled buses for urban transportation systems, making them not competitive with petroleum-fuelled buses.

Locally in South Africa, some indigenous researchers have attempted to assess the possibility of H_2 production from renewable energy resources. Dell'Orto and Trois [29] reviewed the feasibility of extracting hydrogen from organic waste in South African municipalities. It was concluded that South Africa has a potential for bio-hydrogen production from municipal solid waste. Similarly, Alao et al. [30] investigated the techno-economic assessment of biogas-to-hydrogen for electricity generation via solid oxide fuel cells for two municipalities in South Africa. It was found that the LCOE were determined to be 0.2358 $/kWh. In their study, hydrogen as a fuel for transportation vehicles was not taken into account. Ayodele et al. [2] applied HOMER software to design an optimal configuration of a wind-powered HRS for selected locations in South Africa. It was found that the LCOH refuelling station ranges from 6.34 $/kg to 8.97 $/kg with a potential to reduce CO_2 and CO emissions by 73.95 tons and 0.133 tons per annum, respectively. Ayodele and Munda [31] conducted a comprehensive overview of green H_2 production routes and applications for South Africa. The study revealed the potential of H_2 production from various renewable energy sources.

It is observed that most of the previous studies have designed, modelled and conducted a techno-economic assessment of HRS via water electrolysis powered by renewable energy resources (mostly wind and solar). However, unpredictability and fluctuation of wind and solar power generation in addition to their location-specificity may affect the overall HRS. Although incorporating storage (battery) may make up for the period of wind/solar unavailability or insufficiency, the inclusion of the battery adds to the overall investment costs of the system. As a strategic method for waste management, converting waste generated within a locality to value-added products such as hydrogen gas could be a viable solution for both green transportation and waste management. Based on this, no research has, to the best of the authors' knowledge, been done to look into the technological potential, financial viability and environmental consideration of waste-to-hydrogen refuelling stations in South Africa. Attesting to its novelty, this research is the first to fill this gap by evaluating the techno-economic and environmental potentials of waste-to-hydrogen refuelling stations for a chosen number of South African cities. The main contributions of this study are fivefold: Firstly, the quantity of bio-hydrogen that could be derived from food waste in the selected cities is estimated. Secondly, the economic viability of bio-hydrogen refuelling stations based on NPV, PBP, LCoHr, and IRR are evaluated. Thirdly, the environmental assessment based on ecological analysis of bio-hydrogen production and fossil fuel replacement is conducted. Fourthly, a comprehensive sensitivity analysis is conducted to bring forth the impact of sensitive parameters on the general performance of the system. Lastly, the policy and social implications of the implementation of HRS are provided. The schematic representation of a waste-to-hydrogen refuelling station is shown in Fig. 1.

2. Case study description and general assumptions

South Africa has nine provinces, including Gauteng, Western Cape, Eastern Cape, Limpopo, KwaZulu Natal, Free State, Mpumalanga, Northern Cape, and North West. Three of these provinces (i.e., Gauteng, KwaZulu Natal and Western Cape) are largely populated and urbanized and are home to five largest municipalities (i.e., City of Johannesburg, City of Tshwane (Pretoria), City of Ekurhuleni, City of Cape Town and City of e-Thekwini) in South Africa. In this study, these municipalities will be considered for the implementation of waste-to-hydrogen refuelling stations. The choice of these municipalities is premised on their metropolitan nature, high population density [32], substantial economic contribution as well as high live vehicle population [33]. To facilitate motorists' access to recharge their hydrogen-powered fuel cell vehicles, it is envisaged that the refuelling station will be situated along the motorways. The map of South Africa indicating the location of the chosen is shown in Fig. 2 while the demographic details of the selected municipalities and their corresponding provinces are shown in Table 1 [32–34].

3. Methodology and specific assumptions

In this section, the methods adopted for determining the bio-hydrogen generated via BSR process are presented. Additionally, economic variables and indicators used for environmental analysis and financial viability are also described in detail.

3.1. Specific assumptions

In this paper, some assumptions are made for simplicity and brevity in the hydrogen production potential and economic assessments of the HRS project.

i. The economic life of the project is assumed as 20 years starting from the year 2025.
ii. The design, procurement and construction phases of the HRS are assumed to be completed within one year (i.e., 2024). This implies that the HRS will become functional in year 2025.
iii. The energy utilized during the construction of HRS is not considered

3.2. Determination of food waste quantity

Food waste is a major component of MSW and is the largest of the organic fraction of MSW (OFMSW). As a result of a dearth of reliable historical data on the yearly production of food waste in South African cities, this study adopts a model proposed by Ref. [15] which links rates of economic and population growth to waste generation. Food waste may include waste food items that are uncooked, raw, cooked, edible and inedible food such as bones, egg shells, fruits and vegetable peelings, food left-overs from restaurants, school cafeterias and industrial canteens [39,40] in both pre and post consumption stages. Using the stated model, the average annual food waste generated for each selected city is determined according to Eq. (1).

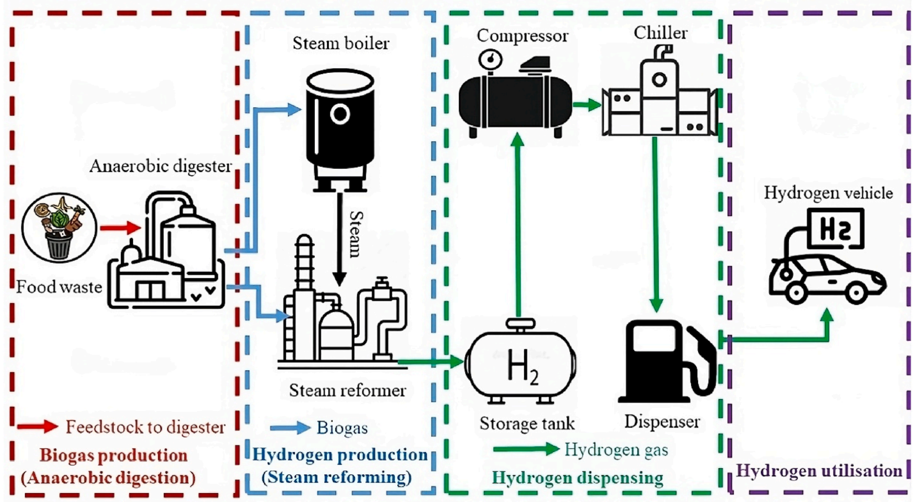

Fig. 1. Schematic representation of a waste-to-hydrogen refuelling station.

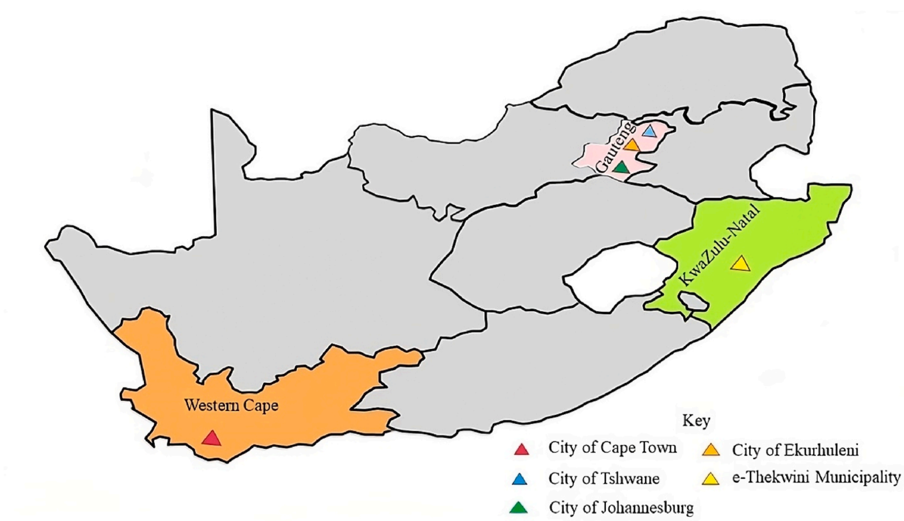

Fig. 2. Map of South Africa showing the selected municipalities.

Table 1
The provincial population and waste generation rate in South Africa.

Province	Provincial population	Vehicle population	City	City population	p_0 (%)	G_0 (kg/capita/day)	k_0 (%)	G_{org} (%)
Western Cape	7,433,019	1,353,340	CoCT	4,772,846	2.2	1.85	3.1	8.1[1]
KwaZulu Natal	12,423,907	1,074,809	e-Thekwini	4,239,901	1.5	0.43	2.9	28.6[2]
			CoJ	4,803,262	3.1	2.08	3.1	21.4[3]
Gauteng	15,099,422	3,240,545	CoT	4,040,315	3.1	2.08	3.1	28.2[4]
			CoE	4,066,691	3.1	2.08	3.1	18[5]

City of Cape Town (CoCT[1]) [35], e-Thekwini[2] [36], City of Johannesburg (CoJ[3]) [34], City of Tshwane (CoT[4]) [37] and City of Ekurhuleni (CoE[5]) [38]. Due to lack of specific data on the waste generation rate, economic growth rate population growth rate, the same data value for the CoJ is applied for the CoT and CoE because they are all in the Gauteng province.

$$\mathrm{Fw}_{\mathrm{av}(i)} = \left(\frac{\sum_{y=1}^{Y} \left(\mathrm{P}_{0(i)} (1 + \mathrm{p}_{0(i)})^{y} \times 365 \mathrm{G}_{0(i)} (1 + \mathrm{k}_0)^{y} \right) \times \mathrm{W}_{\mathrm{col}} \times \mathrm{G}_{\mathrm{org}(i)}}{1000 \times \mathrm{Y}} \right) \quad (1)$$

where, $Fw_{av(i)}$ (tons/annum) is the yearly food waste produced in the city i, $P_{0(i)}$ represents the initial population of city i, W_{col} stands for waste collection rate (i.e., 69 %) [41], $G_{0(i)}$ (kg/capita/day) is the per capita waste generation, $G_{org(i)}$ signifies fraction of food waste in the waste stream of city i, $p_{0(i)}$ (%) denotes rate of population growth, $k_{0(i)}$ (%) is the GDP growth rate, and Y is the planning horizon years and 1000 is a conversion factor from kg to tons. The data for determining the estimated food waste generation for each city is presented in Table 1.

3.3. Determination of bio-methane production from food waste

Food waste's high moisture content, combined with its high concentrations of salt and oil as well as high degradability, makes it a great substrate for anaerobic digestion for bio-methane production [42]. Theoretically, the biogas generated during anaerobic digestion of food waste (chemically represented as $C_lH_mO_nN_oS_p$) may be calculated using a modified version of Bushwell's model [43] which is based on the elemental composition of the feedstock as shown in Eq. (2).

In this research, the stoichiometric chemical equations of the SMR and WGS reactions in Eq. (8) are used to theoretically determine the amount of hydrogen. With regard to Eq.(8) and (8) kg of bio-hydrogen (bio-H_2) is equivalent to 16 kg of bio-methane (bio-CH_4). Thus, using BSR process, 0.5 kg of H_2 might be produced from 1 kg of bio-methane [47]. Being an endothermic reaction, SMR process requires an external heat source to provide the required energy to keep it running. In this instance, a portion of the bio-methane to be reformed is used to raise steam in the boiler, which produces heat energy. According to Ref. [48], about 30% of the bio-methane is utilized for this purpose. Therefore, the amount of bio-methane to be consumed in the boiler is estimated by using Eq. (9).

$$C_lH_mO_nN_oS_p + (l - 0.25m - 0.5n + 0.75o + 0.5p)H_2O = (0.5l - 0.125m + 0.25n + 0.375o + 0.25p)CO_2 + (0.5l + 0.125m - 0.25n - 0.375o - 0.25p)CH_4 + oNH_3 + pH_2S \tag{2}$$

The variables l, m, n, o and p are the atoms of carbon (C), hydrogen (H), oxygen (O), nitrogen (N) and sulphur (S)) that constitute the organic content of the food waste. These variables are calculated as shown in Eq. (3) [30].

$$MR = \frac{C_\alpha}{C_\beta} \times \frac{1}{C} \tag{3}$$

where C_α is the elemental composition (%) from the ultimate analysis of the food waste (see Table 2), C_β is the elemental molar mass, and C is the nitrogen mole ratio. For biogas to be used in the BSR process, it must be properly cleaned and upgraded to the standard of natural gas by removing impurities such as CO_2 and H_2S. The quantity of cleaned biogas $q_{bio-methane}$ (m^3) is found as in Eq. (4) and Eq. (5). Detail explication can be found in Ref. [44].

$$q_{bio-methane(i)} = \delta \times K_{bio-raw(i)} + (1 - \delta) \times K_{bio-raw(i)} \tag{4}$$

$$K_{bio-raw(i)} = K_{bio} \times Fw_{av(i)} \times (1 - \psi) \tag{5}$$

where $Fw_{av(i)}$ (ton/year) is the average amount of food waste generated per year (see Eq. (1)) while $K_{bio-raw(i)}$ (m^3/ton) is the theoretical raw biogas ((see Ref. [44] for more details). The parameter δ is the biogas enrichment rate with CH_4 content ranging from 0.95 to 0.99 [45] while the CO_2 becomes minimal in the range of 0.01–0.05 and $H_2S < 20$ ppm [46]. A conservative value of 0.98 is adopted for δ in this study. The value of ψ is taken as 0.15 [47].

3.4. Biogas steam reforming process

According to Ref. [48], steam methane reforming (SMR) is a well-established technique for producing hydrogen on a large scale, with a conversion efficiency ranging from 74% to 85%. After proper cleaning, the upgraded biogas (i.e., bio-methane) can be steam-reformed in the same as natural gas for hydrogen production. Eq. (6) - Eq. (8) illustrate the SMR reactions.

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \text{ (Steam methane reforming)} \tag{6}$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \text{ (Water – gas shift reaction)} \tag{7}$$

$$CH_4 + 2H_2O \leftrightarrow CO_2 + 4H_2 \text{ (Eq. (6) and Eq. (7))} \tag{8}$$

Table 2
Pollutant Emission factors from biogas combustion.

GHGj	β_j (lb/ft)	ε_j	GWP$_j$ (kg CO_2eq/kg bio-methane)
CO	84	3.556398 x 10^{-5}	1.9
SO_2	0.6	2.540284 x 10^{-7}	80
CH_4	7.6	3.217693 x 10^{-6}	25
NO_X	32	1.354818 x 10^{-5}	50
PM	2.3	9.737757 x 10^{-7}	67

$$q_{bio-consumed(i)} = 0.3 \times q_{bio-methane(i)} \tag{9}$$

The electric energy inherent in the bio-methane (kWh) is calculated according to Eq. (10)

$$E_{bio-methane(i)} = q_{bio-consumed(i)} \times LHV_{bio-methane} \times D_{bio-methane} \tag{10}$$

Since the biogas has been upgraded, its calorific (heating) value (LHV) is envisaged to be close to that of natural gas. Hence, $LHV_{bio-methane}$ is calculated according to Eq. (11).

$$LHV_{bio-methane} = LHV_{NG} \times \zeta \tag{11}$$

where, LHV_{NG} is the heating value of the natural gas suggested to be 49.934 MJ/kg or 13.871 kWh/kg [17], ζ is the degree of upgradation of bio-methane to natural gas standard value assumed as 0.98 and $D_{bio-methane}$ is the density of upgraded biogas assumed to be 0.72 kg/m^3 [49]. The remaining bio-methane left to be reformed is determined as shown in Eq. (12).

$$q_{bio-reformed(i)} = q_{bio-methane(i)} - q_{bio-consumed(i)} \tag{12}$$

According to Eq. (8), after steam reforming of 1 m^3 of bio-methane (CH_4) of density $D_{bio-methane}$, an equivalent of $(0.5 \times D_{bio-methane})$ kg of H_2 gas could be produced. It should be noted that the H_2 production rate depends on the combined efficiencies (η_C) of the boiler and that of the reformer (i.e., $\eta_C = \eta_R \times \eta_B$). So, the amount of theoretical bio-hydrogen (kg) produced from the reforming process is determined according to Eq. (13).

$$q_{bio-H_2(i)} = 0.5 \times q_{bio-reformed(i)} \times D_{bio-methane} \times \eta_C \tag{13}$$

Where η_B and η_R are boiler and reformer efficiencies whose values are respectively given as 80 % [50].

The inherent energy of H_2 (kWh) can be evaluated according to Eq. (14).

$$E_{H_2(i)} = q_{bio-H_2(i)} \times LHV_{H_2} \tag{14}$$

Where LHV_{H_2} (kWh/kg) is energy content of H_2 whose value is given as 33.3 kWh/kg [47] while q_{bio-H_2} (kg) is the quantity of H_2 produced.

3.5. Economic assessment

Economic assessment of the project is particularly important for long-term planning since it gives the investor(s) a sense of how risk-free, profitable, or otherwise investing in a project could be. The economic evaluation is based on LCOHr, NPV, PBP and IRR; and each of them is discussed in the subsequent sub-sections.

3.5.1. Levelized cost of hydrogen refuelling

The levelized cost of hydrogen refuelling (LCoHr) is the lowest cost at which H_2 is generated, compressed, and stored in accordance with the capacity (kg/day) of the refuelling station; such that when H_2 is sold at this price the investment can break even [49]. This cost is anticipated to be higher than the cost of H_2 production due to the additional cost of refuelling infrastructure. It is assumed that the H_2 service station will be situated near to the H_2 generating facility hence, there is no need to transport H_2 to the refuelling station. In addition to that, H_2 leakage is also prevented by using an airtight storage tank, hence all the H_2 produced from the reforming facility gets to the service station. The LCoHr is determined according to Eq. (15).

$$\mathrm{LCoHr(i)} = \frac{\mathrm{INV_{Tot}} + \sum_{t=1}^{T}\left(\frac{\mathrm{OM_{Tot}}}{(1+D)^t}\right)}{\sum_{t=1}^{T}\left(\frac{q_{bio-H_2(i)}}{(1+D)^t}\right)} \tag{15}$$

where, the parameter $\mathrm{INV_{Tot}}$ is the total investment cost, D denotes discount rate (i.e., 8 %), the total yearly operation and maintenance costs ($\mathrm{OM_{Tot}}$), $q_{bio-H_2(i)}$ is the quantity of bio-H_2 for each location i.

3.5.2. Net present value

The net present value (NPV) is an economic indicator which clearly illustrates a project's financial viability depending on the sign (positive or negative) of a real number obtained when it is calculated. A positive value (i.e., NPV >0) indicates that the project might be financially feasible while a negative number (i.e., NPV< 0) denotes the contrary. The NPV can be determined according to Eq. (16).

$$\mathrm{NPV} = -\mathrm{INV_{Tot}} + \sum_{t=1}^{T}\frac{C_F}{(1+D)^t} \tag{16}$$

$$C_F = \mathrm{REV} - \mathrm{OM_{Tot}} - C_{Tax} \tag{16a}$$

$$C_{Tax} = P_r \times T_{rate} \tag{16b}$$

$$\mathrm{Pr} = \mathrm{REV} - \mathrm{OM_{Tot}} - \mathrm{DEP} \tag{16c}$$

where, C_F is the cash flow and the total yearly revenue (REV). P_r is the profit made on the investment, C_{Tax} is the tax paid on profit, DEP represents depreciation on capital equipment (a double declining method) and T_{rate} is the corporate tax rate (assumed as 28 %) [41] while T is year of system planning (i.e., 20 years for this paper).

3.5.3. Internal rate of return

The internal rate of return (IRR) is the discount rate at which the NPV drops to zero. An investment needs to have an IRR higher than the selected discount rate in order to be financially appealing and to ensure a favourable return on investment. The IRR can be calculated according to Eq. (17).

$$0 = \mathrm{NPV} = -\mathrm{INV_{Tot}} + \sum_{t=1}^{T}\frac{C_F}{(1+\mathrm{IRR})^t} \tag{17}$$

3.5.4. The payback period

The payback period (PBP) indicates how long it will take for the project to pay for itself as it gives investors an idea of when they may likely recover the initial capital and start making profit. The PBP is calculated according to Eq. (18).

$$\mathrm{PBP} = \frac{\mathrm{INV_{Tot}} + \sum_{t=1}^{T}\frac{\mathrm{OM_{Tot}}}{(1+D)^t}}{\mathrm{Pr}} \tag{18}$$

3.6. Determination of cost components of bio-hydrogen production

Due to the similarity in the methane composition of the upgraded biogas (bio-methane) (>97 %) and the natural gas, the SMR process could be replicated using bio-methane without any significant changes in operational units [51]. The costs associated with biogas steam reforming process is comprised of the investment cost, operation cost as well as maintenance costs. The investment cost of the anaerobic digester (AD) was not considered as it was assumed to have been existing and the hydrogen production plant is seen as a refit for the AD plant.

Therefore, the total cost $C_{T_{reformer}}$ of hydrogen production from steam reforming process is determined as shown in Eq. (19).

$$C_{T_{reformer}} = \mathrm{OP}_{C_{reformer}} + \mathrm{MAIN}_{C_{reformer}} + \mathrm{INV}_{C_{reformer}} \tag{19}$$

where, $\mathrm{OP}_{C_{reformer}}$ is the operation cost, $\mathrm{MAIN}_{C_{reformer}}$ is the maintenance cost and $\mathrm{INV}_{C_{reformer}}$ is the investment cost of H_2 production.

3.6.1. The investment cost of hydrogen production via steam reforming process

The investment cost in reforming process is composed of the purchase cost of fixed equipment such as boiler, reformer, cleaning devices and other accessories. Because there is no specific cost data for biogas steam reforming plant in South Africa, the unit cost $I_{C_{reformer}}$ of a reforming facility is determined by cost-capacity technique of relevant data found in literature according to Eq. (20).

$$I_{C_{reformer}} = \left(\frac{\dot{m}_{H_2}}{A_{ref_{H_2}}}\right)^m \times C_{ref_{H_2}} \times C_{index} \times C_{conv} \tag{20}$$

The parameter ($\dot{m}_{H_2} = \frac{q_{bio-H_2}}{\vartheta}$) is the bio-hydrogen gas flow-rate in (kg/h). Where, δ (h)

($\vartheta = 8760 \times \theta$) is the stream factor which indicates the fraction of operating time (hours) of the system. In this study, θ is assumed as 95 %, while the remaining hours are allocated for scheduled and unscheduled maintenance. Other parameters such as $A_{ref_{H_2}}$, $C_{ref_{H_2}}$, C_{index} and C_{conv} are the reference plant's H_2 flow rate, the reference facility's cost, the reference cost's escalation (inflationary) index for the current year and the currency exchange rate, respectively.

The cost index takes into consideration the inflation of the reference year with respect to the present year. As previously mentioned, there is no specific cost data for bio-methane reforming facility in South Africa, hence data from a recent work by Ref. [52] was applied in this study. The referenced work [52] found the total investment cost of biogas reforming system composed of steam reformer, steam generating unit (boiler), cleaning unit (i.e., pressurised swing adsorption (PSA)), the compressor and the WGS unit with a hydrogen flow rate of 90 kg/h (1000 Nm^3/h) to be EUR 4.5 million. According to the referenced data, the costs were adjusted to EUR 2016. Therefore, in applying Eq. (20), the value of C_{index} is 1.27 [53]. (i.e., 1 EUR in 2016 is equivalent to EUR 1.27 in 2024). In the present study, the investment costs are converted into USD using an exchange rate of 1 EUR to 1.07 USD as at February 14, 2024 [54] and m is assumed as 0.67 [52].

The investment cost of the reforming facility can be calculated as in Eq. (21) [51].

$$\mathrm{INV}_{C_{reformer}} = \left(\frac{I_{C_{reformer}} \times \mathrm{AF}}{E_{H_2}}\right) \times E_{bio-methane} \tag{21}$$

Where, $I_{C_{reformer}}$ is the unit cost of the reforming system, AF is the annuity factor, $E_{bio-methane}$ is the energy of the bio-methane (see Eq. (10)) and E_{H_2} is the energy embedded in the H_2 (see Eq. (14)). The AF is determined according to Eq. (22) [17].

$$\mathrm{AF} = \frac{1-(1+s)^{-T}}{s} \tag{22}$$

The variable s is the interest rate (i.e., 3.8 %) while T denotes the number of years of system operation.

3.6.2. Operation cost of steam reforming

The cost of operation $OP_{(H_2)}$ of H_2 production from BSR process depends on the energy and cost of fuel that provides the heat source in the boiler as well as the cost and energy of biogas [51]. As previously stated, bio-methane is burnt in the boiler to provide heat. Therefore, $OP_{(H_2)}$ is determined according to Eq. (23).

$$OP_{C_{reformer(i)}} = \left(\frac{E_F \times C_{Fuel}}{E_{H_2(i)}}\right) \times E_{Fuel} + \left(\frac{E_{bio-methane} \times C_{bio-methane}}{E_{H_2(i)}}\right) \times E_{Fuel} \tag{23}$$

where E_F, C_{Fuel} and E_{H_2} are the energy of the fuel that provides heat in the boiler, cost of the fuel and energy of H_2 gas, respectively. Also, $E_{bio-methane}$ and $C_{bio-methane}$ are the energy and cost of bio-methane, respectively. Since bio-methane is utilized to provide the heat, hence Eq. (23) can be transformed into Eq. (24).

$$OP_{C_{reformer}(i)} = 2\left(\frac{E_{bio-methane(i)} \times C_{bio-methane}}{E_{H_2(i)}}\right) \times E_{bio-methane(i)} \tag{24}$$

3.6.3. Maintenance cost of steam reforming

In most studies, the cost of maintaining a projected ($MAIN_{C_{reformer}}$) is stated as a percentage of the cost of the investment. According to Ref. [55], 3% of the investment cost is assumed as the $MAIN_{Creformer}$. Hence, $MAIN_{Creformer}$ is determined as shown in Eq. (25)

$$MAIN_{Creformer} = 0.03 \times INV_{Creformer} \tag{25}$$

Therefore, the operation and maintenance costs of BSR is determined as shown in Eq. (26)

$$OM_{reformimg} = MAIN_{Creformer} + OP_{Creformer} \tag{26}$$

3.6.4. Capital investment cost of hydrogen refuelling station

The hydrogen is dispensed into storage tank of fuel cell vehicles at 350 or 700 bars [56] using a dispenser in a refuelling station. Compression of H_2 gas raises the temperature of the storage tank, hence there is a need for cooling using a chiller. The cost of the compressor, chiller, storage tank, dispenser, electrical, and pipe control systems make up the station's capital cost. Consequently, Eq. (27) provides an estimate of the investment cost of a refuelling station based on its capacity.

$$INV_{refuelling} = \left(\frac{R\dot{m}_{H_2}}{R\dot{m}_{H_2ref}}\right)^m \times C_{H_2ref} \tag{27}$$

The parameter ($R\dot{m}_{H_2} = \frac{q_{bio-H_2}}{365}$) is the capacity of the H_2 refuelling station in kg/day, $C_{H_{2ref}}$ is the reference refuelling station's capital cost whose value lies between \$ 0.84–7.84 million for capacity of 150–1000 kg/day [7], $R\dot{m}_{H_2ref}$ is the capacity of a reference refuelling station and m is the cost-capacity exponent of the plant. In this work, $R\dot{m}_{H_2ref}$ is taken as 1000 kg/day, $C_{H_{2ref}}$ is taken as \$ 7.84 million and m is assumed as 0.67. The cost of maintaining the refuelling station $OM_{refuelling}$ is given as 20 % of the capital investment cost.

3.6.5. Total cost of H_2 production and dispensing

The overall cost of producing H2 and making it available at the service station includes all expenses related to equipment acquisition, facility maintenance, and operations, including production, compression, storage, and dispensing. Therefore, the total investment and operation and maintenance costs are determined as in Eq. (28) and Eq. (29), respectively

$$INV_{Tot} = INV_{reformer} + INV_{refuelling} \tag{28}$$

$$OM_{Tot} = OM_{reformer} + OM_{refuelling} \tag{29}$$

3.6.6. Revenue stream for the project

In this study, the income accrued due to the sale of H_2 at the refuelling station forms the only revenue stream considered which is calculated as in Eq. (30).

$$R_{bio-H_2(i)} = q_{bio-H_2(i)} \times p_{bio-H_2} \tag{30}$$

Where, p_{bio-H_2} is the price of hydrogen. The selling price of hydrogen is assumed to be 10.66 EUR/kg [57] (i.e., 11.51 \$/kg at 1.08 \$ to EUR as at March 3, 2024).

3.7. Environmental analysis

The environmental assessment is done by considering two emission scenarios. The first scenario considers the ecological analysis of bio-methane steam reforming system while the second scenario evaluates the emission due to fossil fuel displacement.

3.7.1. Scenario 1. ecological analysis of bio-methane steam reforming process

The ecological study assesses the system's potential for contamination by considering the amount of pollutants released per kg of bio-methane fuel utilized in the reforming process [47]. Three elements are considered for ecological analysis: equivalent CO_2 emission, pollutant indicators, and ecological efficiency.

3.7.1.1. The carbon dioxide (CO_2) emission equivalent. The carbon dioxide equivalent $(CO_2)e$ of various GHGs is a hypothetical pollutant concentration factor which can be determined as follows in Eq. (31) [58].

$$(CO_2)e = LHV_{bio-methane} \times \sum_{j=1}^{J} \varepsilon_j \times GWP_j \tag{31}$$

Where, $LHV_{bio-methane}$ is expressed in MJ/kg of fuel (see Eq. (11)), ε_j (kg/MJ) is the emission factor of ith greenhouse gas and GWP_j is the global warming emission of ith greenhouse gas. The GHGs considered are carbon monoxide (CO), CH_4, sulphur dioxide (SO_2), nitrous oxide (NO_X) and particulate matter (PM). The value of ε_j is determined according to Eq. (32) [47]

$$\varepsilon_j = \frac{\beta_j \times 0.4556}{1020 \times 1055} \tag{32}$$

where β_j is the emission factor of each pollutant expressed in lb/ft. The values of β_j and GWP_i of each pollutant are presented in Table 2 [47]. It should be noted that CO_2 emitted due to combustion of bio-methane is regarded as carbon neutral, hence contributing nothing to global warming and is thereby not considered.

3.7.1.2. Pollutant indicators. The pollutant indicator ($\coprod_g$) (kg/MJ) specifies the environmental emission proficiency (impact) of a specific fuel that produces a minimal amount of $(CO_2)e$ (expressed in (kgCO$_2$/kg of fuel)) when combusted. To measure and quantify the impact on the environment, $\coprod_g$ is determined according to Eq. (33) [59,60].

$$\coprod_g = \frac{(CO_2)e}{LHV_{bio-methane}} \tag{33}$$

3.7.1.3. The ecological efficiency. Ecological efficiency is an indicator to measure the overall performance of a system in accordance with the environmental emissions associated with such a system. EE is key to green development strategy [61] for a country or a society. The ecological efficiency expressed in percentage can be determined mathematically as depicted in Eq. (34) [47,50].

$$\pi = \left(\sqrt{\frac{0.204 \times \eta_S \times \ln(135 - \coprod_g)}{\eta_S + \coprod_g}} \right) \times 100 \quad (34)$$

The typical value of π in fractional unit must be in the range of 0 and 1. From an ecological perspective, a value of 0 means that the fuel (or system) is completely harmful to the environment or the worst polluter, whereas a value of 1 means that the system foretells 0 % environmental threat and implies the most environmentally friendly fuel or system. It should be noted that these two extremes are idealistic which can hardly be achieved. However, an ecologically viable fuel should have its ecological efficiency close to 1 (or 100 %). When comparing two or more fuels or systems, a fuel with ecological efficiency value close to 1 or 100 % is environmentally considered as the best.

3.7.2. *Scenario 2: emission estimation due to fossil fuel displacement*

Diesel fuel and gasoline (petrol) are the major fuels used by vehicles in South Africa. The combustion of these fuels pollutes the environment with the release of greenhouse gases into the ambient. It is anticipated that some diesel or gasoline will be replaced if bio-hydrogen is offered to the transportation industry as a fuel for fuel cell vehicles. To quantify the volume of these fuels (diesel and gasoline) that might be displaced, a formula based on their heating values (LHV) can be adopted as presented in Eq. (35).

$$\mathrm{Q_{F(i)}} = \left(\frac{\mathrm{q_{bio-H_2(i)}} \times \mathrm{LHV_{H_2}}}{\mathrm{LHV_F} \times \mathrm{D_F}} \right) \quad (35)$$

where, F is a specific fuel (diesel or gasoline), Q_F (litre/year), q_{bio-H_2} (kg), LHV_{bio-H_2} (MJ/kg), LHV_F (MJ/kg) and D_F are the amount of diesel or gasoline replaced, the amount of bio-hydrogen (see Eq. (20)), the lower heating value of bio-hydrogen, the lower heating value of the fuel (i.e., diesel or gasoline) and their densities, respectively. In this paper, LHV_{bio-H_2} is 119.9 MJ/kg [47], LHV of diesel and its density are 43.2 MJ/kg and 0.833 kg/L, respectively while LHV of gasoline and its density are 44.3 MJ/kg and 0.748 kg/L, respectively [62].

Gaseous pollutants such as CO_2, CH_4 and N_2O are prominent GHGs that are emitted from combustion of fossil fuels. Based on the amount of diesel or gasoline fuels that could be replaced by bio-hydrogen as a transport fuel, the global warming potential $GWP_{(fuel)}$ can be determined as shown in Eq. (36).

$$(\mathrm{CO_2})\mathrm{e_{F(i)}} = \sum \left(\mathrm{Q_{F(i)}} \times \mathrm{GWP_{(p)}} \times \mathrm{EF_{(p)}} \right) \quad (36)$$

where Q_F is the amount of fuel avoided (see Eq. (40)), EF(p) is the pollutant emission factor of each fuel. EP for CO_2 for diesel and gasoline are 2.65 kg/L and 2.263 kg/L, respectively [63] while 0.0003612 kg is for CH_4 and 0.00002167 kg for N_2O for both diesel and gasoline. The GWP(p) for GHG is taken as 1 kg CO_2eq for CO_2, 28.5 kg CO_2eq for CH_4, and 264.80 kg CO_2eq for N_2O [64], F is a type of fuel (diesel or gasoline) and p is the type of GHG.

4. Results and discussion

The estimated bio-methane production from food waste, the potential for producing bio-hydrogen, the economic evaluation, and the environmental potential analysis of producing bio-hydrogen for the chosen municipalities are all presented in this section.

4.1. *The estimated food waste generation potential of the selected municipalities*

An average food waste generation over 20 years for each selected city is calculated using Eq. (1) and the results are provided in Table 3. The estimation is based on the population growth rate, GDP growth rate, and the composition of food waste in the waste stream of each city.

Table 3 shows that the amount of food waste generated annually in the chosen cities ranges from 0.2048 million tons to 1.1334 million tons. The CoCT in the Western Cape province has an estimated annual food waste generation of about 0.3097 million tons while e-Thekwini in KwaZulu-Natal province has the least annual food waste generation of 0.2048 million. By correlating Tables 1 and 3 and it is evident that CoJ, CoE, CoT and CoCT which belong to Gauteng and Western Cape provinces, respectively produce the highest amount of food waste. This could be attributed to the fact that these municipalities are primarily urbanized and industrialised, home to well-educated individuals with stable economic status [65]. have highlighted that the amount of food waste generated in households is influenced by socio-demographic characteristics, including age, race, type of job, population size, and education level. All these factors seem to favour CoT, CoJ, CoE and CoCT for their huge food waste generation potential. If disposed of in landfills, this huge food waste might have a major negative influence on the environment. Consequently, utilizing this food waste as a feedstock for bio-hydrogen production could significantly contribute to waste diversion from landfills, hence ensuring cleaner societies.

4.2. *The estimated bio-methane and bio-hydrogen production potential*

When anaerobically digested, the food waste produces biogas, and when the bio-methane is steam-reformed and cleaned, bio-hydrogen is produced. The quantities of bio-methane gas and bio-hydrogen that are produced in each selected city are depicted in Table 4.

Comparing Tables 3 and 4 and it is obvious that CoT, being the highest food waste generator, produces the highest bio-methane of about 625.35 million Nm^3/year, followed by CoJ with an estimated annual bio-methane generation of 564.17 million Nm^3/year while the least bio-methane is obtained in e-Thekwini produced 112.98 million Nm^3/year of bio-methane. When the bio-methane produced in each city is steam-reformed and cleaned, a daily hydrogen of about 395 thousand kg of hydrogen can be produced in the CoT, 356 thousand kg produced in CoJ. About 254 thousand kg per day of hydrogen can be produced in CoE municipality while a daily hydrogen of 108 thousand kg and about 72 thousand kg can be produced in the CoCT and e-Thekwini, respectively. Considering vehicle populations in the selected cities while emphasis is placed on smaller motor cars and station wagons with lower energy consumption, the produced H_2 has the potential to fuel certain number of vehicles. Assuming a 5 kg per day fuel cell electric vehicle, Table 5 shows the possible number of vehicles that can be fuelled by the produced hydrogen in the selected cities. This is an optimistic

Table 3
Average annual food waste generated in the selected municipality.

Municipality/City	Food waste (million tons/year)
CoCT	0.3097
e-Thekwini	0.2048
CoJ	1.0225
CoT	1.1334
CoE	0.7282
Total	**3.7941**

Table 4
The estimated average annual bio-methane gas and bio-hydrogen production.

Municipality	Bio-methane gas (million Nm^3/year)	Bio-hydrogen	
		(kilotons/ year)	(kg/day)
CoCT	170.86	39.365	107,849
e-Thekwini	112.98	26.031	71,418
CoJ	564.17	129.98	356,110
CoT	625.35	144.08	394,740
CoE	401.76	92.566	253,605
Total	1875.12	432.022	1183722

Table 5
Number of possible 5 kg per day fuel cell vehicles for the selected cities.

Province	Western Cape	Gauteng			KwaZulu Natal
Number of cars [33]	1,353,340	3,240,545			1,074,809
Selected city	CoCT	CoJ	CoT	CoE	e-Thekwini
Number of cars to be fuelled	21,570	71,222	78,948	50,721	14,284
% contribution	1.59	2.20	2.44	1.57	1.33

assumption as the results in.

Table 5 represents an average value and the potential of the refuelling station to fill all available cars in the selected cities.

According to Tables 5 and it is found that the H_2 produced from the food waste in the CoCT can contribute 1.59 % to fuel hydrogen-powered fuel cell electric vehicles in Western Cape Province while a total of 6.21 % can be contributed to fuel hydrogen-powered fuel cell vehicle in the Gauteng Province with the CoT contributing 2.44 %, CoJ contributing 2.20 % and 1.57 % is contributed by the CoE. The H_2 produced in the e-Thekwini municipality can contribute about 1.33 % to fuel hydrogen-powered fuel-cell vehicles in the KwaZulu-Natal.

4.3. The economic assessment results

Using several indices, including NPV, PBP, LCoHr, and IRR, the economic viability of bio-hydrogen produced from food waste was studied, and the results are presented in Table 6.

According to Table 6, the total investment cost of the project is highest for the CoT with over 2.02 billion USD while the least project cost is obtained for the e-Thekwini municipality having less than 1 billion USD investment cost. It is also observed that the PBP in investing in waste-to-hydrogen refuelling station is in the range of 9.03–13.74 years with CoT having the lowest PBP of 9.03 years, followed by CoJ (9.24 years) while the highest PBP (13.74 years) is obtained for the city of e-Thekwini. The PBP obtained for the CoT could be attributed to the fact that the city has the highest potential for hydrogen production and the largest refuelling station capacity (i.e., mass of hydrogen (kg per day)). According to Halder et al. [7], increasing the annual/daily H_2 production can result in reduction in the cost of refuelling station equipment due to economy of scale, which may eventually lower PBP. On the other hand, e-Thekwini metropolitan municipality records the highest PBP due to the fact that it generates the least hydrogen and has the smallest refuelling station capacity. The results for the LCoHr range from 3.9904 \$/kg H_2 - 5.6346 \$/kg H_2 for the selected cities. The CoT has the smallest LCoHr of 3.9904 \$/kg H_2 while the highest (5.6346 \$/kg) is recorded for the e-Thekwini metropolitan municipality. Even though the increased refuelling station's capacity for CoT causes an increase in capital investment, the LCoHr is decreased due to economies of scale. Therefore, the larger the capacity of the refuelling station (in terms of mass of H_2 (kg/day)), the less the LCoHr. In all the cities, the waste-to-hydrogen refuelling station returns positive NPV ranging from 1.0990 billion \$ to 8.0553 billion \$ with CoT producing the largest NPV while e-Thekwini municipality records the least. This is an indication that investing in waste-to-hydrogen refuelling stations will be economically profitable in the selected municipalities. Similarly, the IRR obtained from the investment in all the selected cities is also higher than the given discount rate (i.e., 8 %). The largest IRR of 39.88 % is obtained in CoT while 18.16 % is recorded for e-Thekwini municipality. In general, the CoT, CoJ, and CoE in the Gauteng province are the most economically advantageous sites for the construction of waste-to-hydrogen refuelling stations in South Africa since they have lower PBP and LCoHr and promising NPV with large IRR.

Table 6
Results of economic analysis for bio-hydrogen in selected municipalities.

Municipality	Economic metrics				
	Investment cost (Billion \$)	PBP (year)	IRR (%)	NPV (Billion \$)	LCoHr (\$/kg)
CoCT	0.9063	12.6550	20.49	1.7688	5.3020
e-Thekwini	0.6422	13.7396	18.16	1.0990	5.6346
CoJ	1.8862	9.2352	38.20	7.1832	4.0682
CoT	2.0209	9.0257	39.88	8.0553	3.9904
CoE	1.5025	9.9911	33.03	4.9033	4.3443

The results obtained in this study are comparable and competitive when compared to results obtained in similar studies for H_2 refuelling station in other cities around the world. For instance, in a study by Ref. [66], it was calculated that investing in ammonia-hydrogen refuelling station with maximum capacity of 100 kg/day H_2 in a location in Italy is economically feasible with LCoH ranging between 6.84 EUR/kg to 9.78 EUR/kg (7.39 \$/kg – 10.56 \$/kg) with payback periods falling between 7.2 and 9 years. The lower values recorded for the LCoHr (i.e., 3.99–5.63 \$/kg) in this research compared to 100 kg/day refuelling capacity for [66] could be attributed to the advantage of economy of scale in the capacity of refuelling station (see Table 4). Also, the results presented in Lui et al. [16] for a waste-hydrogen production facility in Glasgow indicated that the LCoH without considering the refuelling facility lied in the range of 2.02–2.29 GBP/kg (2.57–2.91 \$/kg at 1.27 \$ to GBP). The lower LCoH in Ref. [16] could be attributed to exclusion of expensive equipment (e.g., compressor and chiller) leading to lower investment cost with an overall reduced LCoH. For a 450 kg/day capacity biogas-hydrogen refuelling in a location in Italy [57], found the LCoH to be 7.25 EUR/kg (7.83 \$/kg).

In Ayodele et al. [2], the LCoHr for wind-powered hydrogen refuelling stations in selected cities of South Africa was calculated to be in the range of 6.34 \$/kg to 8.97 \$/kg. It could be seen that the LCoHr are higher than those reported in this work. This could be attributed small scale capacity (125 kg per day) of the refuelling station which may suffer from economies of scale. Again, the cost of electricity and electrolyser from wind-turbine plays a prominent role in water electrolysis-based hydrogen generation, as electricity shares about 90% of the total operating cost for the electrolysis [67] while about 42 % was recorded in Ref. [27]. It is inferred from Ref. [2] that the LCoHr are higher in mainland cities such as Johannesburg (CoJ) and Pretoria (CoT) both in Gauteng Province due to low wind energy resources. Incidentally, these cities (CoJ and CoT) have the best economic outlook for the siting of waste-to-hydrogen refuelling station in the South. Overall, economically, the findings indicate that investing in waste-hydrogen refuelling stations in the chosen South African municipalities appears to be financially promising.

4.4. Results of environmental assessment

The results of the environmental assessment are presented in the following subsection.

4.4.1. The ecological assessment

The ecological assessment was determined assuming a 98 % cleaning extent of bio-methane. By applying Eq. (31), it is possible to calculate $(CO_2)_e$ of combusting bio-methane in the boiler and reformer. With the methane content of 98 % in the bio-methane and using Eq. (11), the heating value of bio-methane ($LHV_{bio-methanel}$) was determined to be equal to (48.9353 MJ/kg). Using the total CO_2e obtained from Eq. (31) and the $LHV_{bio-methanel}$ in Eq. (11), the pollution indicator ($\prod_g$) was

Table 7
Result for ecological efficiency of biogas steam reforming.

Quantity	$(CO_2)_e$ (kg/kg of biogas)	$\prod_g$ (kg/MJ)	π (%)
Value	0.04458	9.10988 x 10^{-4}	99.962

determined according to Eq. (33). Considering the combined efficiency of the reforming process to be 64 % (i.e., 80 % for boiler and reformer, respectively) and applying Eq. (34), the ecological efficiency (π) was determined. The results of $(CO_2)_e$ the pollutant indicator and ecological efficiency are presented in Table 7.

According to Tables 7 and it is obvious from the ecological point of view that BSR for H_2 production is environmentally friendly as 99.982 % ecological efficiency obtained in this study is impressive. Compared with similar studies in other locations around the world, the ecological efficiency obtained in this study is similar to the results of previous studies such as 99.98 % in Bangladesh [68], 94.64 % in China [17], 93.36 % in Nigeria [47] and 94.95 % in Brazil [50].

4.4.2. *Emission abatement due to fossil fuel replacement*

The traditional fossil fuels used in the transport sector are diesel and gasoline. Due to the eco-friendly nature of bio-hydrogen, its use to power fuel cell vehicles with the same energy delivery as diesel and gasoline-fuelled vehicles will cause an abatement in the quantity and the associated emissions of these fuels in the selected cities. Table 8 presents the results for the quantity (litres/year) and carbon dioxide emission equivalent ($kgCO_2e$) for diesel and gasoline fuels.

A look at Table 8 shows that about 480 million litres/year of diesel fuel and 521 million litres/year of gasoline can be saved in the CoT with the use of hydrogen-powered fuel cell vehicles which translates to 1280 million $kgCO_2e$/year and 1188 million $kgCO_2e$/year emission avoidance into the atmosphere for using diesel and gasoline as vehicle fuels, respectively. Similar results for the quantity and emission avoided are obtained for other cities as depicted in Table 8.

5. Sensitivity analysis

The sensitivity analysis is used to investigate how changing certain input parameters affects the system's overall performance. Given that this research is predicated on theoretical evaluation utilizing assumed variables, a sensitivity analysis is conducted to look into how several factors may affect the study's overall performance. The H_2 conversion efficiency of SMR lies between 74 and 85 % [48]. The efficiency can be enhanced by increasing the methane content in the bio-methane through proper cleaning and also by improved catalytic reaction via the use of advanced nano-composite material. Adopting these techniques will contribute to a higher H_2 yield, increase capacity and by extension have a positive impact on the economic and environmental sustainability of the project. Another important parameter is the investment cost of the hydrogen refuelling station equipment. Since most of the equipment used in this project (such as boiler, reformers, cleaning facilities, compressor, H_2 tanks, dispensers etc.) are imported, government support and policy directives toward reducing costs of importing this equipment such as reduced import duties and taxes, subsidies etc., can be initiated. Also, the price at which hydrogen is sold is a significant and highly sensitive factor that could have a significant impact on the project's economic viability. A special (dedicated) price can be formulated and implemented in terms of feed-in tariff to encourage investors to invest in waste-hydrogen refuelling projects.

Table 8
Quantity of diesel and gasoline and carbon dioxide emission prevention.

Province	Amount of fossil fuel displaced (Million Litres/year)		Carbon dioxide emission avoided emission (Million $kgCO_2e$/year	
	Diesel fuel	Gasoline	Diesel fuel	Gasoline
CoCT	131.16	142.44	349.68	324.62
e-Thekwini	86.734	94.191	231.23	214.67
CoJ	433.09	470.33	1154.6	1071.9
CoT	480.06	521.34	1279.9	1188.1
CoE	308.42	334.94	822.26	763.34
Total	1439.464	1563.241	3837.67	3562.63

As previously stated, the optimistic scenario (base case) adopted in this study is based on the average of the food waste generated over the system planning period from which the hydrogen production and the station capacity are determined. However, to capture the reality of different scenarios of system capacities (scales) and station development, we have expanded the sensitivity analysis to look into the impact of capacity changes (from small scale to large scale) and station expansion within the timeframe of system planning horizon on all the economic metrics considered in this study. The sensitivity analysis conducted takes into consideration the effect of variations in reforming system efficiency (from 40 to 90 %), changes in investment cost (i.e., from ± 10 % to ± 70 % of the original cost), fluctuation in the cost of selling bio-hydrogen (2–12 \$/kg H_2) on refuelling station capacity, LCoHr, NPV, PBP, and IRR as well as the ecological efficiency (π). The impact of the station capacity changes (small to large scale) or station development is implemented by changing the capacity from ± 20 % to ± 80 % of the original (base case) station capacity on the economic metrics. The CoT and e-Thekwini municipalities are selected to carry out this analysis. The choice of these locations is premised on the fact that CoT has the highest bio-hydrogen generation potential and largest live vehicles while e-Thekwini gives the least bio-hydrogen generation potential and live-vehicles among the selected cities. Figs. 3–7 depict the results of the sensitivity analysis.

The effect of the variation of the reforming efficiency on the station capacity and the ecological efficiency is presented in Fig. 3. According to Fig. 3, as the efficiency of the reforming process increases, the bio-hydrogen yield increases. An increase in bio-hydrogen yield implies that more bio-hydrogen will be available for storage in the refuelling station, hence increase in the refuelling station capacity. Conversely, a decrease in the reformer efficiency leads to decline in the hydrogen yield and by extension a decrease in capacity of the refuelling station. For instance, as the efficiency increases from 64 % (reference value) to 90 %, there is a corresponding increase in the refuelling station capacity by 40.62 %.

However, a decrease in the reforming system efficiency from 64 % to 50 % leads to 21.88 % reduction in the station capacity. Similarly, an increase in reforming efficiency (i.e., 64 %–90 %) improves the ecological efficiency by 0.02 % whereas a decrease in the reforming efficiency reduces the ecological efficiency by 0.04 %. Therefore, for enhanced productivity in the bio-hydrogen refuelling station project and environmental sustainability, the efficiency of bio-hydrogen production (SBR) must be maintained at a high rate.

Due to the changes in bio-hydrogen refuelling station capacity occasioned by variation in the reforming efficiency, the economics of the projected is expected to be impacted. The effects of reforming efficiency

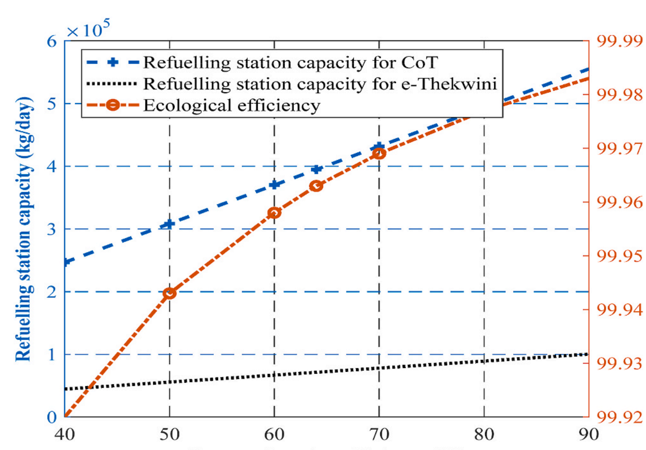

Fig. 3. Effect of changes in steam reforming efficiency on refuelling station capacity and ecological efficiency.

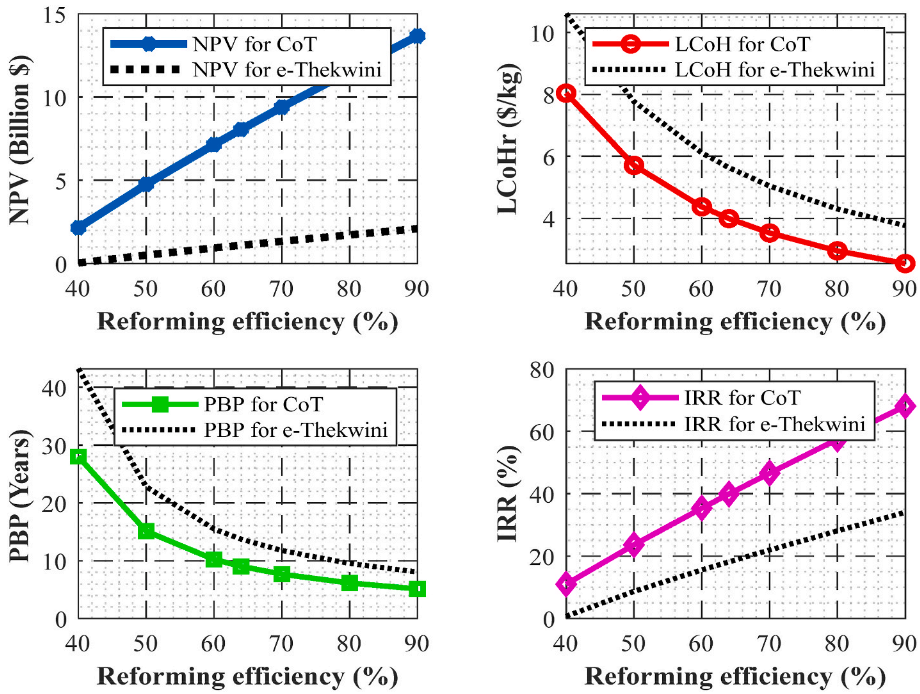

Fig. 4. Impact of variation in steam reforming efficiency NPV, LCoHr, PBP and IRR.

on the NPV, LCoHr, PBP and IRR are presented in Fig. 4.

It is observed from Fig. 4 that as the reforming efficiency increases, it causes a linear increase in the NPV and IRR while there is an exponential decline in the LCoHr and PBP for both selected cities. This could be ascribed to the fact that increased reforming efficiency leads to increased bio-hydrogen production and refuelling station capacity, which could result in more bio-hydrogen availability for sale at the refuelling station, hence generating more revenue from the project. Although increasing station capacity may result in higher construction and operating expenses for the plant, the increased overall costs may be offset by increased revenue from bio-hydrogen sales and economies of scale from capacity expansion.

The effect of changes in the calculated total capital investment cost of the project was investigated, and the results are presented in Fig. 5. It was deduced that an increase in capital investment cost from 10 % to 70 % has an impact on the profitability of the project. For instance, for the CoT, an increase and decrease in investment cost from 10 % to 70 % causes the NPV to decline by 2.08 % and appreciate by 14.52 %, respectively. Similarly, there is a corresponding decrease and increase of 4.90 % and 33.88 %, respectively for e-Thekwini municipality. The LCoHr and PBP increase linearly for both selected cities as shown in Fig. 5. This implies that investors will have to spend extra to get the

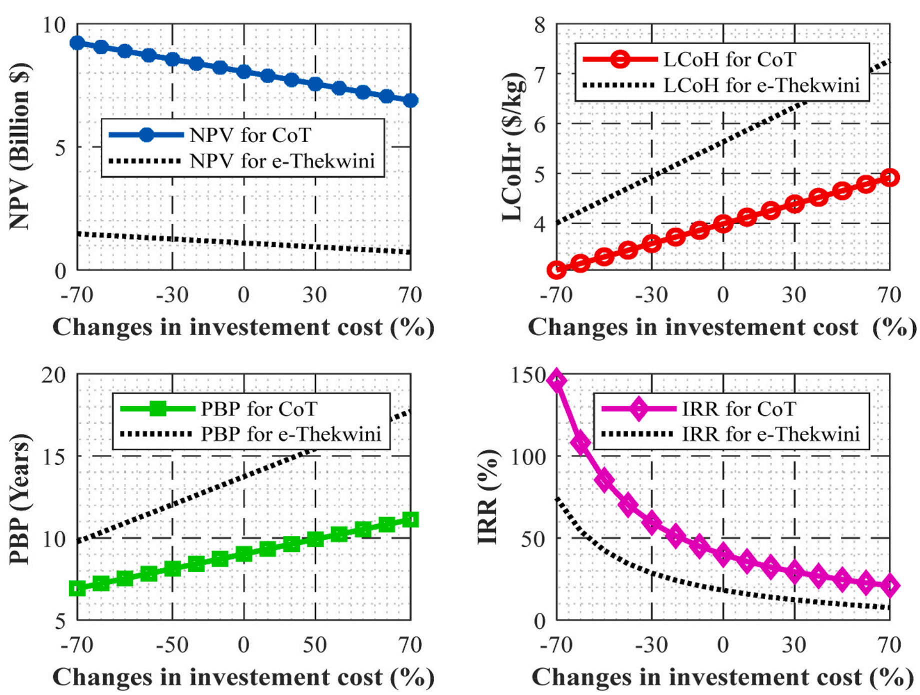

Fig. 5. Impact of changes in investment cost on NPV, LCoHr, PBP and IRR with respect to base case.

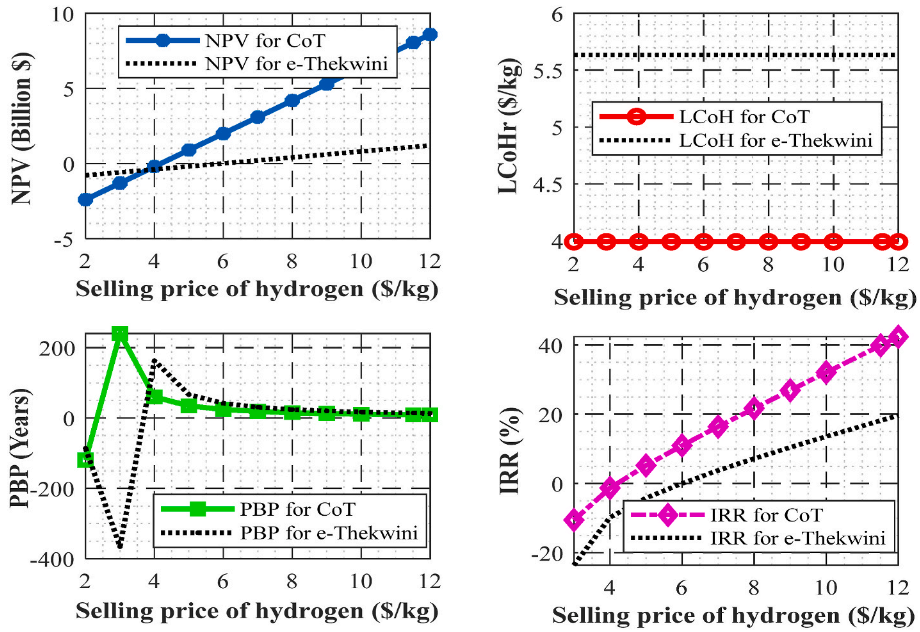

Fig. 6. Impact of changes in selling price of hydrogen on NPV, LCoHr, PBP and IRR.

facility up and running. Due to increased capital cost, the investor may have to increase the selling price of hydrogen at the refuelling station in order to recoup the investment as soon as possible. Therefore, higher investment cost has a negative impact on both investors and vehicle owners (hydrogen users). The IRR also shows a declining trend as the investment cost increases. A quick synopsis of Fig. 5 indicates that even though the NPV is positive with the changes in the investment cost which implies economic feasibility, a little return is gotten from the investment leading to increased payback period and possibly an elevated LCoHr.

The impact of changes in the cost of the selling price of bio-hydrogen on the economic metrics is depicted in Fig. 6. It is inferred from Fig. 6 that when the cost of selling bio-hydrogen is 2 $/kg, all the economic metrics are worse off and deteriorated. The NPV, PBP, and IRR for both cities are negative indicating infeasibility in the profitability of the project.

In the case of CoT, as the selling price increases above 3.99 $/kg H_2, the economic indicator starts to appreciate. It implies that selling hydrogen below 4 $/kg will make the investment not profitable. On the other hand, for e-Thekwini municipality, the selling price of hydrogen must not be less than 6 $/kg for there to be any positive economic return in the waste-to-hydrogen refuelling station investment. However, it is found that a change in the selling price of hydrogen is independent of LCOHr. Although hydrogen selling price has no impact on the LCOHr as presented in Fig. 6, it is a very sensitive variable to the economic profitability of HRS project [28]. It is evident that hydrogen selling price varies based on where the hydrogen production infrastructure is located and the source of energy for hydrogen production, hence, a special tariff

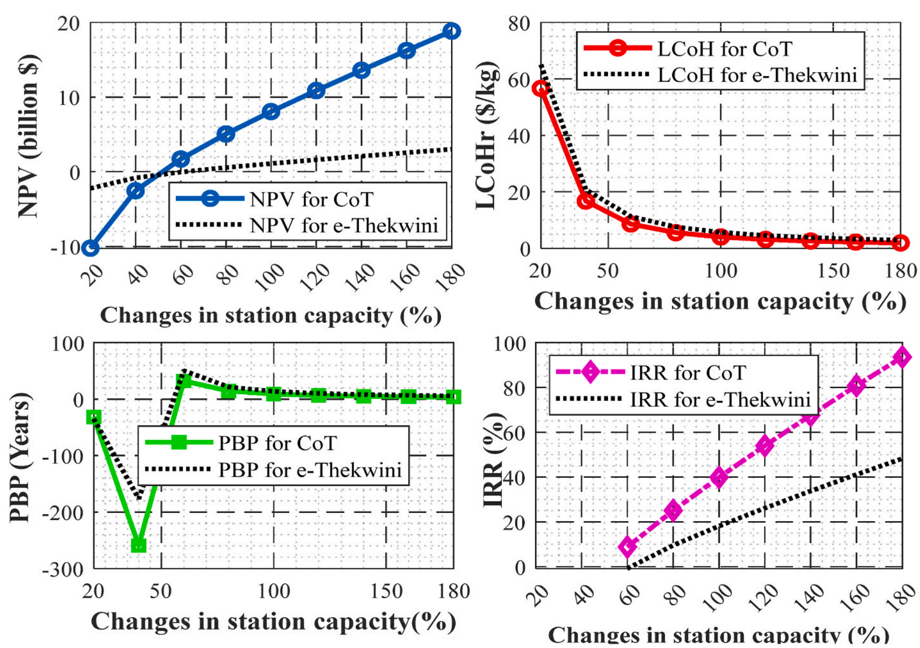

Fig. 7. Impact of changes in station capacity on NPV, LCoHr, PBP and IRR.

for hydrogen selling price and other financial supports from the side of the government are needed which can guarantee a better return on investment within the shortest time possible.

Lastly, the impacts of changes in the scale (size) of HRS ranging from small-scale to large-scale based on the growth in HRS capacity and station development on the economic metrics are elicited in Fig. 7.

As shown in Fig. 7, the station capacity between 20 and 50 % of the base case indicates the small scale capacity which corresponds to early years of system operation. During this period, the system is not economically realistic as the economic metrics (NPV, PBP, IRR and LCoHr) do not produce encouraging outcomes. In particular, the IRR gives infeasible results indicated by 'not a number' (NaN) while NPV and PBP return negative outcomes. The LCoHr is extremely large during this period. However, as the capacity grows from 60 % to 180 % of the base case station capacity representing medium to large-scale station capacity, the system is gaining market confidence due to potential interest of end-users in procuring FCEVs and an expanded revenue generation from hydrogen sales. Within this capacity scale, all the economic metrics have begun to show positivity in profitability of the project. For instance, the NPV begins to grow linearly exponentially and IRR increases linearly in the positive direction. The PBP and LCoHr begin to linearly decline as the capacity increases. Specifically, it is found that the LCOHr is inversely proportional to the capacity of the HRS, and the hydrogen cost is about 56.6412 $/kg for small scale, 3.9904 $/kg for medium scale and 1.8888 $/kg for large scale. This assertion is in tandem with the conclusion of a recent work by Ref. [24] where it was stated that the costs of hydrogen produced have an inverse relationship with the capacity of the hydrogen refuelling station (i.e., 9.18 $/kg for the larger and 12.56 $/kg for the smaller station). In essence, it implies that station development and capacity growth have a significant impact on the economic viability of HRS. This could be attributed to economies of scale and the advantage of cost reduction over time.

6. Socio-political implications

The transportation industry is essential to a nation's socioeconomic growth. An efficient transportation system facilitates the movement of people, goods and services which could have great impact on the GDP of a country. However, the conventional transport system depends heavily on fossil fuels such as diesel and petrol with their attendant environmental implications.

The overdependence on fossil fuels (diesel and petrol) for transport sector contributes immensely to environmental degradation and human health issues. Hence, there is a need to look inward for sustainable and more environmentally friendly fuel. As a part of its nationally determined contribution (NDC) for the realisation of the Kyoto protocol and national development plan, the South African government is currently pushing for the decarbonisation of the transportation sector. Hydrogen, as a non-toxic-emission generating fuel, could play a major role in the just energy transition paradigm shift by using H_2 fuel cell-powered vehicles (HFCVs) [69]. Using H_2 as a fuel in transport is still at an incipient stage in Africa, hence its successful implementation requires assessing the social acceptability and political implications. Driving a social acceptance campaign through public awareness and sensitization on the benefits of using hydrogen as a fuel in the transportation sector is necessary for the sustainable implementation of waste-to-hydrogen refuelling stations in key provinces of South Africa. For instance, setting up waste-to-hydrogen refuelling station allows waste diversion from landfills, hence elongating the lifespan of landfills and reducing the pressure for constructing new landfill sites leading to land saving for more productive use. Reducing waste landfilling would also reduce health-related hazards caused by air pollution, water contamination and soil degradation from dangerous gases which could improve the health-related human development index. Furthermore, using H_2 generated from waste would reduce the lifecycle emissions. It is also important to educate the public and allay any fears about the risks associated with the use of H_2. A major safety concern in H_2 usage is explosion due to leakage. This could be achieved through public awareness of the current technological advancement made on safety measures in hydrogen storage. For example, strong high-pressure cylinders have solved leakage-related safety concerns during on-board storage. Additionally, innovative composite materials have been developed to endure high pressures and reduce impacts locally, resulting in increased safety standards for HFCVs. Furthermore, Internet of Things (IoT) devices such as H_2 sensors are now used in stationary applications to find even the smallest leaks [6].

Moreover, it is also important to ensure adequate availability of food waste for bio-hydrogen generation. One strategy to achieve this is to make sure that all municipalities have higher rates of waste collection by bolstering and expanding capacity utilization and providing sufficient infrastructure to facilitate waste collection. This will create new jobs and stabilise the existing ones in the waste management sector. In addition, political goodwill must be summoned to promulgate laws and regulations for source separation of food waste. A carrot-and-stick approach could possibly be adopted by providing incentives to those who complied and adequate punishment or fines to deviant persons who may have violated the law.

7. Conclusion

This research investigated the technical, economic and environmental assessments of food waste-to-hydrogen refuelling station in five selected municipalities in three South African provinces. The food waste generation potential of the selected cities was first determined using their population and gross domestic product contributions. The bio-hydrogen production was theoretically determined using an analytical approach based on steam reforming process. Thereafter, economic viability, ecological analysis and carbon emission mitigation potentials for the waste-to-hydrogen refuelling stations were determined. The refuelling station capacity (kg/day of H_2) was determined based on the assumption that each HFCV with a 5 kg cylinder will be refuelled per day. With a total estimated average food waste generation of 3.7941 million tons/year in the selected municipalities, an estimated 1.18 million kg/day of hydrogen could be produced which is capable of refuelling about 236 thousand of 5 kg hydrogen-fuel-cell vehicles per day in all the selected cities. Based on the study's findings, the project appears to be financially promising. Positive NPV was observed in all of the selected cities, with CoT offering the best economic outlook. Premised on this, it is indicated that CoT and CoJ (both in Gauteng Province) are the best locations for the establishment of waste-to-hydrogen refuelling stations. The sensitivity analysis indicated that if the H_2 is sold at a price less than 4 $/kg, the project could be economically bleak. The ecological efficiency of 99.963 % indicates an environmentally friendly system while about 1439 or 1563 million litres of diesel fuel or gasoline could be saved. This could lead to prevention of about 4 thousand tons of carbon dioxide from being emitted into the atmosphere annually. Sensitivity analysis indicates that reforming efficiency and the selling price of hydrogen are crucial parameters with great influence on the general performance of the waste-to-hydrogen refuelling station.

8. Limitation and future research work

Pointing out the limitation of this study, specific location for the physical construction of refuelling stations in the selected cities was not captured. Therefore, a future research exercise is anticipated to capture this by finding the optimal location of the refuelling stations in the selected cities. The geographic information system (GIS) coupled with multi-criteria decision making (MCDM) method could be explored for this problem. Further environmental analysis would be conducted using life cycle assessment (LCA). Also, social cost-benefits assessments (SCA) based on COBRA simulation tool is proposed to be conducted for the installed waste-to-hydrogen refuelling stations in South African cities.

Again, we intend to extend the scope of this study in the future by taking into consideration the flexibility in the growth rate of the hydrogen demand by FCEVs.

CRediT authorship contribution statement

Moshood Akanni Alao: Writing – original draft, Software, Methodology, Conceptualization. **Olawale Muhammed Popoola:** Writing – review & editing, Validation, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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