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A comprehensive carbon dioxide reduction framework for industrial site using pinch analysis tools with a fuel cell configuration

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ABSTRACT

Removing anthropogenic carbon dioxide emissions from existing industrial sites is essential to slow down climate change. A multipronged approach is required to reduce the carbon dioxide footprint of an existing industrial site by including carbon dioxide capture and utilisation, industrial symbiosis, heat integration and the introduction of renewable power sources. This work extends the current systematic framework for low carbon dioxide industrial site planning by proposing an alternative carbon dioxide lowering sequential framework for existing high carbon dioxide footprint industrial sites. The sequential framework will set out a four-step process using a suite of optimisation tools to guide industrial site managers to lower the carbon dioxide footprint of an existing industrial site that also features a fuel cell configuration. The framework includes a baseline study to analyse the current carbon dioxide footprint of the industrial site. The study then proposes a carbon capture and utilisation step to collate the carbon dioxide captured for chemical mineralisation for in-situ utilisation. The inclusion of the Direct Methanol Fuel Cell configuration is important to the site because it generates clean carbon-neutral power to the hybrid power system while utilising methanol, a carbon dioxide mineralised product. The following steps involve using Pinch Analysis tools to optimise the energy usage and renewable power usage within the industrial site. The energy produced at the site would be integrated to reduce external utilities required by using the Total Sites Heat Integration technique. The Power Pinch Analysis technique optimises power distribution from the hybrid power system hub. The illustrative case study is a typical industrial site in the Western Cape province in South Africa. It was determined that a potential 105 ton/day of carbon dioxide could be captured from the flue gas from industries on the site. The overall heat utility saving of 79.95% of the hot utility requirements for the participating industries in the site. It was also determined that the renewable sources of power which incorporated the fuel cell configuration would be sufficient to provide carbon-neutral power to the industrial site. The rate of return on the investment of the hybrid power system is found to be 20.68%. The carbon dioxide lowering framework for existing industrial sites could provide a sustainable, impactful guide for site planners to assist the country's commitment to limit greenhouse gas emissions.

1. Introduction

The Glasgow Climate Pact, an agreement reached at the 2021 United Nations Climate Change Conference (COP26), declared that limiting global warming required rapid, deep and sustained reductions in global greenhouse gas emissions. This includes reducing the global carbon dioxide emissions by 45 per cent by 2030 relative to the 2010 level (UNFCCC, 2021). The importance of lowering the carbon dioxide (CO_2) footprint of a high emitting industrial site through devolution of CO_2 processes and the introduction of cleaner production has become consequential in the retardation of the effect of greenhouse effect. The South African government has committed to sustaining the national greenhouse gas emissions below the 398–440 million tonnes of CO_2 equivalent by 2030 (Modise, 2021). The adverse effects of climate change due to the global increase of greenhouse gases have started to

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Nomenclature

CC	Carbon capture
CCU	Carbon capture and utilisation
CCUS	Carbon capture and utilisation and storage
CW	Cooling water
ChW	Chilled water
CO_2	Carbon dioxide
DMFC	Direct Methanol Fuel Cell
GHG	Greenhouse gas
LPS	Low Pressure Steam
HPS	High Power Steam
HyPS	Hybrid Power System
IPCC	Intergovernmental Panel on Climate Change report
IS	Industrial Symbiosis
MEA	Membrane Electrode Assembly
MER	Maximum Energy recovery
PA	Pinch Analysis
PoPA	Power Pinch Analysis
PTA	Problem Table Algorithm
RE	Renewable Energy
TS	Total Site
TSP	Total Site Profile
TSHI	Total Site Heat Integration
TSI	Total Site Integration
TS-PTA	Total Site Problem Table Algorithm
TSST	Total Site Sensitivity Table
TSUD	Total Site Utility Distribution
VHPS	Very High Pressure Steam

increase ocean levels, hotter summers, colder winters, and other natural disasters as reported in the Intergovernmental Panel on Climate Change report (IPCC, 2018). Maintaining the global average temperature to under 2 °C above pre-industrial levels and ensuring the temperature increase to keep within 1.5 °C above pre-industrial levels has become important to avoid permanent climate change.

2. Literature review

Pinch Analysis (PA) developed by (Linnhoff, 1979) was initially used for energy targeting and conservation and Heat exchanger network design. John and Rabiu (2013) applied the energy targeting to a petroleum plant to reveal a potential 34% saving from energy usage. Pinch Analysis has also seen practical application in mass recovery (El-Halwagi and Manousiouthakis, 1990), supply chains planning (Singhvi and Shenoy, 2002), water recovery (Wang and Smith, 1994), hydrogen recovery (Alves and Towler, 2002), renewable and traditional power usage and recovery (Wan Alwi et al., 2012), and waste management (Ho et al., 2017). Singh and Leena (2019) use Linear Pinch Analysis (LPA) to target the reduction of Green House Gases (GHG) in the development of a sustainable municipal solid waste management system. Bandyopadhyay (2020) introduce the Economic Pinch Analysis (EPA) for economic appraisal of project sustainability. Chin et al. (2021) applied pinch analysis to target multiple contaminants water recycling/reuse network by assigning separate plots and analysing them sequentially to meet the sink requirements.

The term "Total site", first coined by Dhole and Linnhoff (1993), refers to a centralized utility hub that is served by integrating processes from different factories. The authors proposed a two-stage system using the pinch technology approach. Firstly, site-wide targets are set based on levels and pressures of the process stream levels and secondly, designing a total site system based on the site targets. Klemeš et al., 1997 further optimized the targeting and design methodology of the streams involved in the Total Site Integration (TSI) to improve energy savings. Total site targeting methodologies used a single T_{min} for all processes in the Total site study. Varbanov et al. (2012) asserted that such an assumption was too simplistic and could lead to an unrealistic estimation of the overall Total Site heat recovery targets. The authors proposed a methodology that allows separate ΔT_{min} specifications for heat exchange between process and process and also process and utilities. To improve the estimation of the maximum energy requirements (MER) targets, Chew et al. (2015) expanded on the effects of pressure drop on the total site heat integration by including the pressure drop factor during the MER targeting stage of the graphical Pinch-based TSHI methodology. Liew et al. (2012) developed a numerical technique that determined the sensitivity of a TSHI system to individual plant maintenance shutdown, which is essential to determine the minimum utility requirement for storage to mitigate the effect of planned and unplanned plant shutdowns. The paper presented the following numerical tools:

1. Total Site Sensitivity Table (TSST),
2. Total Site Problem Table Algorithm (TS-PTA),
3. Multiple Utility PTA (MU-PTA), and
4. Total Site Utility Distribution (TSUD) Table.

Jamaluddin et al. (2019) extended TSHI to a trigeneration system by introducing a new method, Trigeneration System Cascade Analysis (TriGenSCA) to estimate the optimum size of utilities for generating power, heating and cooling by a trigeneration power plant. Varbanov et al. (2017) explored the integration of waste water in the aim of reducing the fresh water usage in a total site scenario by introducing the Total Site Centralised Water Integration (TS-CWI) tool. Fan et al. (2021) extended pinch analysis to a circular economy in a total site context by integrating solid waste, water and energy to achieve symbiosis by implementing a Total EcoSite Integration (TESI) design. The integration of waste hydrogen of differing concentrations using pinch analysis for a total site using principles of circular economy as described by Gai et al. (2021) by turning waste hydrogen into valuable products.

A cost-effective retrofit option for TSHI is proposed by Liew et al. (2014) by applying the Plus–Minus Principle to scope for the correct locations of heat surpluses and deficits that would lead to an appropriate TS retrofit solution. The practical implementation of retrofitting TSHI system has been comprehensively covered by Chew et al. (2013), laying out major issues to consider, e.g., the current layout of the industrial site, considering the distances between the industries, the current available space for the retrofit. The other factors to consider for TSHI retrofit are the possible contamination between the hot and cold streams, the operating pressures of the streams that would affect the pressure rating of the required equipment, the characteristics of the fluids such as viscosity influencing stream matching and the selection of appropriate utilities. The role of energy integration and intensification in the lowering of the CO_2 footprint of an industrial site cannot be understated. The inclusion of renewable sources of power could provide a more impactful reduction of footprint. This is evidence that 76% of the estimated 436 million tonnes gross avoided CO2 emissions was due to the EU's usage of renewable sources of power between 2005 and 2015 (Swain and Karimu, 2020).

It has been reported that around 77% of the electricity produced in South Africa is coal-based, producing 232 TW of electricity, which results in 438 million tonnes CO2 emissions, making South Africa the largest emitter of CO2 in Africa (Jain and Jain, 2017). Electricity is a significant driver of South Africa's economic growth. The effects of the erratic supply of electricity and the high annual increase in electricity tariffs in South Africa since 2008 has had detrimental consequences on the economy (Inglesi-Lotz and Ajmi, 2021). The unpredictable rolling blackouts have caused severe losses due to production disruption, e.g. reagent/product spoilage due to mid-process stoppage or the amount and quality of value-added products. In 2021, the South African government announced that industries were allowed to produce 100 MW of power to assist business in avoiding the consequences of load shedding and improving economic growth by raising the licence-exemption cap for embedded generation projects from 1 MW to 100 MW (Creamer, 2021). The development of a hybrid power hub which sources power from sustainable renewable sources in conjunction with the mainstream national power grid has gained increased popularity in recent times.

Hybrid renewable systems, as presented by Esfahani et al., 2016, could bring a reliable alternative power source to meet the power demands of a selected site. Wan Alwi et al. (2012) extended the Pinch Analysis concept used to determine the minimum target for outsourced electricity and the amount of excess electricity for storage by introducing Power Pinch Analysis (PoPA) tools. Power Pinch Analysis (PoPA) using the Power Cascade Analysis (PoCA) and storage Cascade Table (SCT) numerical tools were introduced by Rozali et al., 2013a. These tools can be used to determine the minimum (target for) outsourced electricity supply (MOES), the excess electricity for storage during start-up and normal operations, the transferrable power, the maximum storage capacity, the outsourced electricity needed at each time interval and the time interval where the maximum power demand occurs. Furthermore, Rozali et al., 2013a studied various scenarios to find the optimal size of generators of renewable energy (RE) in a hybrid power system (HyPS) using PoPA to find the lowest payback period. Esfahani et al. (2015) further introduced Extended Power Pinch Analysis (EPoPA) as an extension to the existing PoPA by storing wasted electricity that cannot be stored in the existing batteries. The energy is stored in the form of hydrogen and released back as electricity. EPoPA was used to design renewable energy systems with battery and hydrogen storage (RES-BH) systems. Rozali et al., 2014 expanded PoPA to allocate the optimum power allocation of the renewable energy sources to the site. Rozali et al., 2016a applied PoPA to integrate a HyPS into a primarily diesel plant to effectively manage electricity demands.

In 2019, the South African government signed the carbon tax bill (South African Government, 2019). It essentially gives large companies a carbon tax penalty on emissions using the polluter-pays-principle for future production, consumption and investment decisions. The bill also incentivizes existing industries towards adopting cleaner technologies such as CO2 capture. The captured CO2 has to be stored either through geological avenues or chemical mineralisation. According to Butt et al. (2012), carbon capture and storage (CCS) involves the separation and capturing of CO_2 from high-density energy-related sources e.g., flue gases stacks from industries and transporting to storing it by.

1. Stable chemical storage through the reaction of CO_2 with metal oxides to carbonates;
2. Liquid storage in the ocean; and
3. Gaseous storage in various deep geological formations such as oil and gas fields.

At this stage, there is no feasible geological CO_2 that have been practically applied mainly due to possible pollution/poisoning of the large water basin that is required in water-stressed South Africa (Omarjee, 2021).

The concept of carbon capture and utilisation (CCU), as explained by Zimmermann and Kant (2017), is an umbrella of technologies that captures CO2 utilisation describes a range of technologies that consume CO2 chemically to provide products to be either economically or environmentally beneficial or both. The sequestration of CO2 for the permanent storage of CO2 in building materials, products, landfills or in the ocean as an alternative to geological storage. The life cycle environmental impact as explained by Cuéllar-Franca and Azapagic (2015) using stable CCU is essential in reducing the global warming potential. The introduction of Carbon Emissions Pinch Analysis (CEPA) by Tan and Foo (2007) has been used to reduce CO2 emissions based on the introduction of cleaner technologies to target CO2 emissions. Munir et al. (2012) approached the reduction of the carbon footprint of an industrial park by introducing a carbon management hierarchy (CMH) to induce a holistic methodology for lowering the CO2 emissions by identifying CO2 emission sources and matching them to CO2 sinks. Source and Demand Curves (SDC) is a visualisation tool to provide insightful sequences for an effective emission planning system. The Generic Carbon Cascade Analysis (GCCA) tool, an algebraic approach developed by Manan et al. (2014) to complement the SDC, enables the minimum CO_2 targets to be determined for different concentrations of CO_2 concentration captured from stationary emission sources. This tool was further expanded on by Sanghuang et al. (2019) with the addition of the Total Site CO_2 Integration (TSCI) which utilizes centralised CO_2 headers. The tool considered one high concentrated CO_2 and various headers with different concentrations for accepting CO2 sinks/demands whilst unused CO2 is sequestrated. The approach of integrating heat and captured CO2 in an industrial park, as shown by Hassiba et al. (2017), uses surplus energy to power the CO2 compression and capture process. The proposed method has three steps, namely:

1. Energy Integration throughout the industrial park,
2. CO2 Integration throughout the industrial park,
3. Utilising excess energy from Step 1 to improve the CO2 integration.

Almost every source of CO_2 is contaminated and requires separation and purification; this step is called CO_2 capture (Zimmermann and Kant, 2017). After the CO_2 capture step, the captured CO_2 is chemically converted into commercial products by various processes; this step is called CO_2 utilisation.

Reusing waste products/by-products can be accomplished through industrial symbiosis (IS) by adding value by reusing it in a network of industrial operations (Frosch and Gallopoulos, 1989). The use of IS prioritises the waste to resource by improving the environmental and economic benefit to the otherwise discarded effluents. Lee Chan et al. (2020) developed network models where CO_2 process is allocated between existing ammonia plants and methanol plants, including numerous models restricting the CO_2 between the source and sinks. One of the challenges of capturing CO_2 emissions from various stationary sources is the varied concentration of the CO_2 that is captured. Hasan et al. (2015) presented a multi-scaled framework that should be considered when designing a CO_2 capture, utilisation, and sequestration/storage (CCUS) supply chain network with the aim of reducing the cost. The framework followed the following CO_2 reduction routes:

1. Selection of advanced CO_2 capture processes by using innovative materials,
2. Simultaneous selection of materials and process optimisation,
3. Selecting CO_2 capture options for various emission sources, and
4. The optimisation of the supply chain networks.

Carbon footprint can be lowered by introducing renewable feedstocks within a total site scenario by combining Total Site Analysis (TSA) and exergy concepts in identifying opportunities to improve energy efficiency and integrate renewable feedstocks within such clusters (Hackl and Harvey, 2013). The framework did not consider a more holistic approach to lower carbon footprint that includes emission capture. The framework for a low carbon dioxide impact planning for new industries in a greenfield site is shown by Aziz et al., 2017 who propose four stages that the site planner should follow. This includes:

1. Stage1: Requires the site planners to acquire resource information, including power consumption, heating and cooling consumption, and CO_2 emissions. This is essential to ensure the industries are placed correctly to ensure optimum symbiosis.

2. Stage 2: Utilizes Total Site Heat Integration analysis to create a centralized system that will provide the optimum amount of heating and cooling utilities to the industries.
3. Stage 3: Power Pinch Analysis is used to create a centralized Hybrid Power System to provide the optimum amount of Renewable Energy as a power source to the industries in the site.
4. Stage 4: The exchange of CO_2 captured from various concentrations to industrial CO_2 sinks using Carbon Dioxide Emissions Pinch Analysis.

From the state-of-the-art research, there has been little guidance for industrial site managers to lower the CO_2 footprint from an existing industrial site through a systemic framework that includes a holistic approach of CO_2 capture from stationary industrial sources, industrial symbiosis, the inclusion of a RE power sources and the inclusion of a fuel cell configuration. The study extends the work done by Aziz et al., 2017 that provided a framework for industrial site planners to utilise or lower the CO_2 footprint for a new industrial site using a suite of pinch analysis tools.

The study will propose a new framework that industrial site managers or third-party companies could use to reduce the CO_2 footprint of an existing industrial site also referred to as brownfield). The study will propose a 4-step sequential approach that would introduce appropriate post-combustion CO_2 capture, purification and permanent storage using CO_2 fixing plants, including a fuel cell configuration. The study will utilise a case study in an industrial site situated in the Western Cape, South Africa to illustrate the applicability of the proposed 4-step sequential approach.

The case study illustrated the creation of a subsidiary industry producing value-added products from captured CO_2 for consumption within the industrial site. A constant high-quality captured CO_2 feedstock (>90%) was distributed to the proposed CO_2 fixing plants. A ratio distribution approach was conducted to manage the distribution of CO_2 to the CO_2 fixing plants. The study examined the case study to investigate the economic feasibility of building new CO_2 fixation plants for usage distribution within the industrial site with a fuel cell configuration to reduce the CO_2 impact of an industrial park.

The CO_2 footprint is further reduced by using Total Site Heat Integration pinch analysis techniques to reduce the external utility requirement by maximising heat recovery from processes within the site, including the new subsidiary CO_2 fixation plants. The use of HyPS system that incorporates mainstream electricity, renewable sources of electricity, and the fuel cell configuration is then used to supply the industrial site's electricity requirements, including the carbon capture system and the subsidiary CO_2 fixation plants.

From the state of the art review, a comprehensive economic analysis of the CO_2 reducing tools has not been conducted before to study the economic impact of the CO_2 framework. a multi-sensitivity analysis to determine the robustness of the CO_2 lowering tools has not been conducted.

3. Problem statement

Considering a cluster of various plants in a high CO_2 footprint industrial site, the study aims to develop a comprehensive CO_2 reduction framework applying distribution and pinch analysis tools such as TSHI and PoPA to a brownfield with the inclusion of a fuel cell configuration. It is also desired to establish the robustness and sustainability of the cleaner production interventions, i.e., the TSHI system and the HyPS. To achieve this aim, the following objectives will be considered:

1. The sequential 4 step framework considering
   a. The base-line study to establish the current CO_2 footprint of the industrial site,
   b. CO_2 capture, purification, and the distribution of CO_2 through ratio distribution, CO_2 chemical fixation and usage,
   c. TSHI and Total Site Utility Distribution, and
   d. The introduction of renewable sources of power and fuel cell configuration to an integrated HyPS. The use of PoPA for the optimum distribution of power to the industries on the site.
2. The sensitivity analysis of the TSHI and HyPS to evaluate its robustness.
3. An approximate economic analysis of the TSHI and HyPS to evaluate sustainability.

This study expects that the comprehensive CO_2 lowering framework applied to a typical industrial site can be conducted in a sustainable and compressive way that can be replicated similarly to other high emitting industrial site. The study will also determine the sensitivity of the TSHI system and the HyPS and cost analysis of the TSHI system and the HyPS as shown in the research approach in Fig. 1.

The following assumptions were made for this work.

- The captured flue gas after purification is 90% CO_2 concentration.
- The co-generation potential is not considered for the HyPS.
- The pressure drop was not considered for the TSHI.
- The hot and cold utilities are provided by a centralised utility.
- The renewable energy sources are assumed to be consistent with average solar and biomass power for the time interval suggested for the case study.
- There is sufficient space in the site for the CCU system, the TSHI system and HyPS including the centralised hub for the management of the captured, purification and utilisation of the CO_2. The management of the distribution of the hot and cold utilities for the TSHI system and power storage, invertor, rectifier and fuel cell configuration are available at the existing sites.

4. Proposed framework for the reduction of the CO_2 footprint of an existing site

Process integration play a critical role in industrial site planning by taking into account the topology of the site by placing plants near to each other based on the "best fit" material and energy integration between plants determined by economic and environmental benefits (Ch'ng et al., 2021). The best location of the centralised heating, power and resource hubs can also be determined to optimise the distances between these hubs and the industries.

Industrial sites have been established to zonally cluster industries and emerged spontaneously in the identified zone over a long period without centralized planning to emit undesirable emissions away from the residential and farming sectors of a region. However, this clustering of industries has created a concentrated area of high CO_2 emissions that adversely contributes to the regional carbon footprint. The presented framework takes into account the fact that there are established industries in the industrial site that are running their operations independent of each other. In this work, a comprehensive framework is presented with four sequential steps to reduce the CO_2 footprint of a brownfield. This framework builds on the work by Aziz et al., 2017 titled "An integrated Pinch Analysis framework for low CO_2 emissions industrial site planning", by moving from site planning of a greenfield to the decarbonisation of an existing industrial site. The primary considerations that need to be taken into account when designing this framework for existing sites compared to new sites are:

1. The topology of industries in the site, i.e., the designer has to consider the distances between industries that would affect how the resources are distributed.
2. The type of CO_2 capture that has to be installed, i.e., the designer is limited to the post-combustion CO_2 capture for an existing site.
3. The planning of the location of centralised storage and distribution of resources, i.e., the designer, is limited to the location of vacant land within the site.

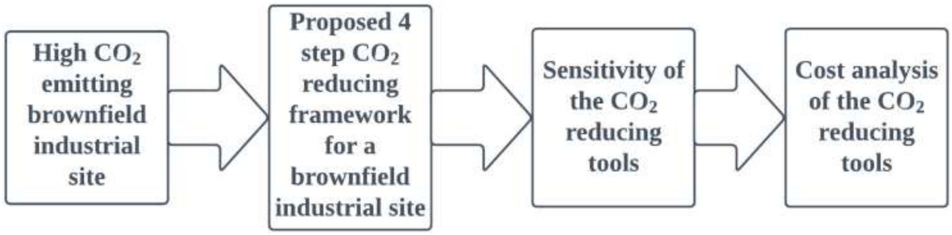

Fig. 1. Overview of the research approach.

3.1. *Baseline study*

The fundamental requisite for the optimum design of a low CO_2 footprint industrial site is to collect the most accurate data in order to find the best opportunities for CO_2 reduction. In this study, typical industrial site data from an illustrative case study is used.

The data that would be required are:

1. The component compositions of the flue gas from the chimney stacks of industries in the site to determine the concentration of the CO_2 emissions. From the data collected, it is then used to determine the amount of potential CO_2 that could be captured and utilised within the industrial site.
2. From the carbon capture system, the power requirements are calculated from the chosen industrial flue gas composition and flowrate.
3. The captured and purified CO_2 determines the size of the CO_2 fixing plants. The energy and power requirements are calculated (John et al., 2020).
4. The data required for the total site heat integration are extrapolated from process flowsheets to extract the cold stream and hot streams of the process from selected industries in the industrial site (see Klemeš et al., 1997).
5. The data from the cold and hot streams from the CO_2 fixing plants are collated and included for the total site heat integration.
6. The power requirements from the existing industries and the new envisaged CO_2 fixing plants are collated for the power pinch analysis.
7. In this study, two renewable sources will be considered for inclusion in the hybrid power system, which are solar and biomass, together with a fuel cell configuration. The potential power sources will be calculated using the available parking space area for solar and the possible availability of biomass feedstock in the area.

3.2. *Tool 1: target reduction of CO_2 from stationary sources using a ratio-based approach*

In this step, the CO_2 reduction is targeted from capturing the flue emitted from the stack chimneys by using a post-combustion of CO_2 capture technology. The introduction of CO_2 fixing plants, as described by John et al. (2020), should be created as chemical storage mechanisms to create possible value-added products that could be sold within site. The advantage of reuse within the industrial site is that the transportation costs could also mitigate the high cost of chemical fixing.

1. The stationary CO_2 from the stack gases captured is analysed and the correct purification process is chosen to get a 90% concentration. Porter et al. (2015) described various CO_2 purification tools used to improve the quality of the captured gas, Flue Gas Desulfurization (FGD) is used to remove SO_2, and the Low NO_x Burners (LNB) to remove the NO_x from the post-combustion captured CO_2. The main reason for getting to that high CO_2 concentration is, according to Hasan et al. (2015) and Zimmermann and Kant (2017), most of the CO_2 utilisation needs high concentration. Other components of the flue gas could poison the end product. It also complicates the storage of multiple concentrations of CO_2 if the other impurities are different. The other impurities of the flue gas could create undesired by-products.
2. The site manager has to decide the suite of CO_2 fixing plants that would be part of the subsidiary industry.
3. A ratio distribution system of the purified CO_2 is conducted, taking into consideration
   a. The reagent requirements for the industries in the site, i.e., Calcium Carbonate for the papermaking and glass making industry,
   b. Baking soda for the industrial Bakery and Methanol for the DMFC configuration and the economic viability of the CCUS system.

$$m_{CO_2}R_T = m_{CO_2}R_1 + m_{CO_2}R_2 + m_{CO_2}R_3 + m_{CO_2}R_i \ldots \qquad \text{Equation 1}$$

where m_{CO_2} is the amount of CO_2 captured per day (tons/d), $R_T = 1$, where R_i is the fractional ratio for distribution to a CO_2 mineralisation plant, i.e., for this example the Methanol production plant, the Baking Soda production plant and the Calcium Carbonate plant.

4. The addition of the DMFC to utilise the methanol produced by the subsidiary industry. The size of the DMFC is directly linked to the daily production of methanol from the Methanol production plant. The fuel cell configuration in this study is the two Molar utilisation DMFC. It is assumed that the fuel cell configuration is running at a 90% efficiency level. The following factors also need to be taken into consideration when determining the size of the DMFC:
   a. The fuel cell size is determined by taking into account the energy density of Methanol is 6.1 kWh/kg (Scott and Xing, 2012).
   b. The fuel cell size of a 200W stack of DMFC occupies 1 $m^{2,}$ as shown in Sgroi et al. (2016), is used to estimate the size of the fuel cell configuration. The size of the DMFC configuration is estimated using Equation (2).

$$A_{FC} = \frac{A_{ref}}{P_{ref}} \times P_{potential} \qquad \text{Equation 2}$$

where A_{FC} is the total size of the Fuel cell stack (m^2), A_{ref} is reference size of the DMFC stack, i.e., 1 m^2 of the 200W (P_{ref}) DMFC stack, $P_{potential}$ is the potential power from the methanol provided from the subsidiary industry (W).

3.3. *Tool 2: target total site heat recovery including the subsidiary industry with TSHI*

The targeting for heat recovery is performed to determine the maximum energy recovery amongst the process streams by matching heat sources from process streams in the industry. Targeting for total site heat recovery is based on the established Pinch Analysis Targeting mechanisms and has been widely used. The Total Site targeting methodology includes data extraction, construction of Total Site Profiles (TSP), Total Site Composite Curves and the Site Utility Grand Composite Curve. The procedure for obtaining site wide targets is based on the thermal profiles for the industrial site, known as the Total Site Profile (TSP) (Klemes et al., 2014). The procedure can be summarised by the following steps.

1. Obtain the heat sources and heat sinks of the individual industries participating in the TSHI.
2. Plot the Grand Composite Curves (GCC) for individual industries.
3. Identify the GCC segments of the individual industries where the T and ΔH values can be obtained, and eliminate the heat recovery pockets of GCC.
4. Obtain the heat source and heat sink profile by double shifting each starting temperature (T**). The first shifted temperature (T*) values is obtained by shifting the temperature downwards by $0.5 \cdot \Delta T_{min}$ for the supply and target temperatures of the hot streams and shifting the temperature upwards by $0.5 \cdot \Delta T_{min}$ for the supply and target temperatures of the cold streams. The second shifted temperature (T**) is obtained by shifting $0.5 \cdot \Delta T_{min}$ downwards for the heat source temperature and $0.5 \cdot \Delta T_{min}$ upwards for the heat sink temperature.
5. The two Site Composite Curves are shifted by shifting the Site Utility Generation Composite Curve towards the Site Utility Use Composite Curve until it cannot be shifted further. The area where the curves touch is referred to as the Total Site Pinch (Klemeš et al., 2010). The possible amount of heat recovered is indicated by the overlap between the composite curves.
6. The estimation of the possible co-generation available in the site utility system by utilising the Site Utility Grand Composite Curve (SUGCC). The SUGCC subtracts the Site Utility Use Composite Curve segments from those of the Site Utility Generation Composite Curve (Klemes et al., 2014).

Total Site Problem Table Algorithm (TS-PTA), developed by Liew et al. (2012), is a numerical tool that compliments the visual insights provided by the graphical TSHI methods. It represents the numerical version of the Site Composite Curve (SCC), which is a part of the graphical TSHI analysis.

The following steps can summarise the procedure Liew et al. (2012).

1. Net heat sinks, which are heat sinks above the pinch region and net heat sources, which are heat sources below the pinch region, are identified for the utility region.
2. The net heating requirement for each utility level is calculated by subtracting the net heat source from the net heat sink.
3. The net heating requirements are cascaded from top to bottom for the utility region.
4. The highest negative value from the last cascade is used to start the new cascade by altering it to a positive value.
5. The PTA involving multiple utilities is performed by cascading from top to bottom for the utility region's net heat requirement for above the total site pinch region and cascading the net heat requirement from the coldest utility to the pinch region. A negative cold utility value is included when a positive value occurs in a cascade with a utility region.
6. Construct the TSUD by listing the heat sources and heat sinks of each plant according to utility levels, which includes the external utility requirements. The arrows are used, as shown in Table 7, to designate possible utility exchanges from heat sources/external utilities to heat sinks within the site.
7. Construct TSST to analyse the effects of the plant shutdown of participating industries. The sensitivity of the TSHI is calculated by determining the variation of plant shut down from Normal operation.

Both the graphical and numerical methods are considered for this study. The graphical method is used for visual insights and to calculate the estimated cost based on the heat exchanger area. The numerical method provides accurate analysis for Total Site Utility Distribution (TSUD) as well as the sensitivity of the TSHI system.

3.4. Tool 3:Target for hybrid power system with PoPA for the industrial site

The targeting for the HyPS is done using Power Pinch Analysis (PoPA) to plan for the optimisation and distribution of the renewable sources and the power generated from the fuel cell configuration. The HyPS should be able to provide electricity to the existing industries in the site, the post-combustion of CO_2 capture and storage and distribution system, the power needs of the envisaged subsidiary industry and the power needs of the TSHI system. Rozali et al., 2013a introduced the Power Cascade Analysis (PoCA) and the Storage Cascade Table (SCT) to complement the graphical PoPA methods (Wan Alwi et al., 2012). After acquiring all the power sources and power demands at each time interval, this data is used to determine:

1. The minimum outsourced electricity supply (MOES),
2. The available excess electricity for the next day (AEEND), the amount power that should be transferred from HyPS to demands, and the maximum battery required for sustaining the HyPS.

For this study, the numerical tools are utilised to allocate power accurately and to determine targets for each time interval. It will also be used to determine the sensitivity of the HyPS when a RE power source shuts down due to intended or unintended reasons. The disturbance due to power generation fluctuation was not factored in the sensitivity analysis. Fig. 2 shows the sequential procedures that site managers of high carbon footprint sites can use to lower their site carbon footprint using the tools as mentioned above. The procedure of each of the tools in the framework will not change depending on any other brownfield. However.

1. The suite of industries in the site determines the CO_2 fixed products for the site. The study recommends having a DMFC as a part of the HyPS (methanol production will be part of the subsidiary industry).
2. The procedures for the TSHI and PoPA will not essentially change. The results will entirely depend on the internal resources within the site.
3. The cost of the CO_2 lowering tools will be affected depending on the internal available resources within the site.

4. Case study

In South Africa, industries were clustered in industrial zones and away from residential areas because of the toxic emission and effluents associated with large scale production. Most of these industries vied for space in the industrial site not because of potential symbiosis and process integration but because of the zonal permit requirements needed to operate the industry. As a result, the industries would independently run their operations to manage the energy and heating requirements independent of each other whilst outsourcing waste management to external vendors for safe disposal of chemical waste. A comprehensive framework as shown in Fig. 3 is presented with four sequential steps to reduce the CO_2 footprint of a brownfield.

In order to conceptualize the low carbon dioxide footprint framework, a case study of a typical mix of industries (Fig. 4) in an industrial site will be used as the baseline study.

4.1. Baseline study

The baseline study will consider a typical industrial mix in an industrial site. For this study, the following industries were selected to represent a sample of industries that would occupy a site such as in the Sacks Circle Industria, Western Cape, South Africa (City of Capetown, 2017). The industries selected are:

1. The glass-making plant

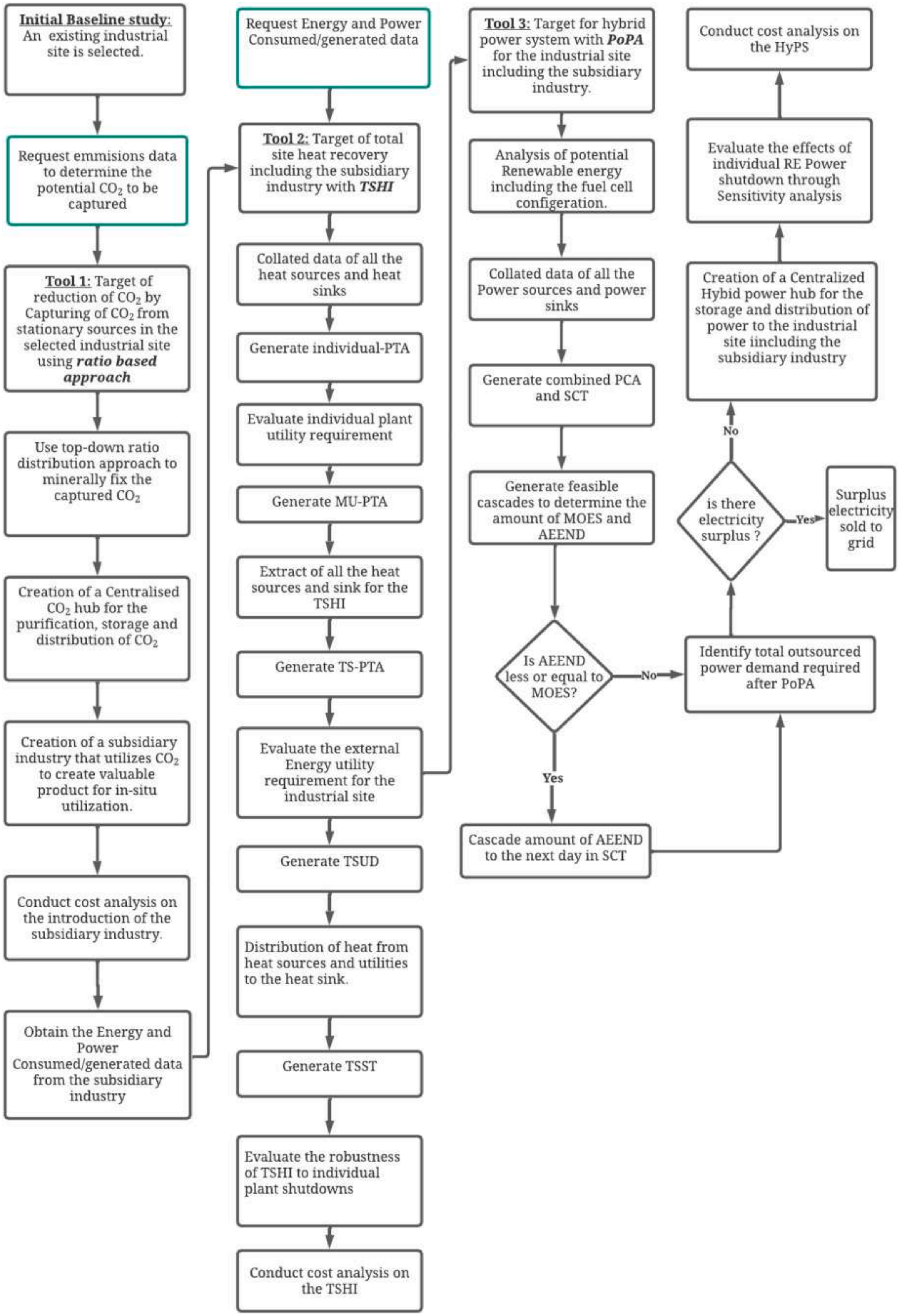

Fig. 2. Sequential procedure to reduce CO_2 of a brownfield industrial site.

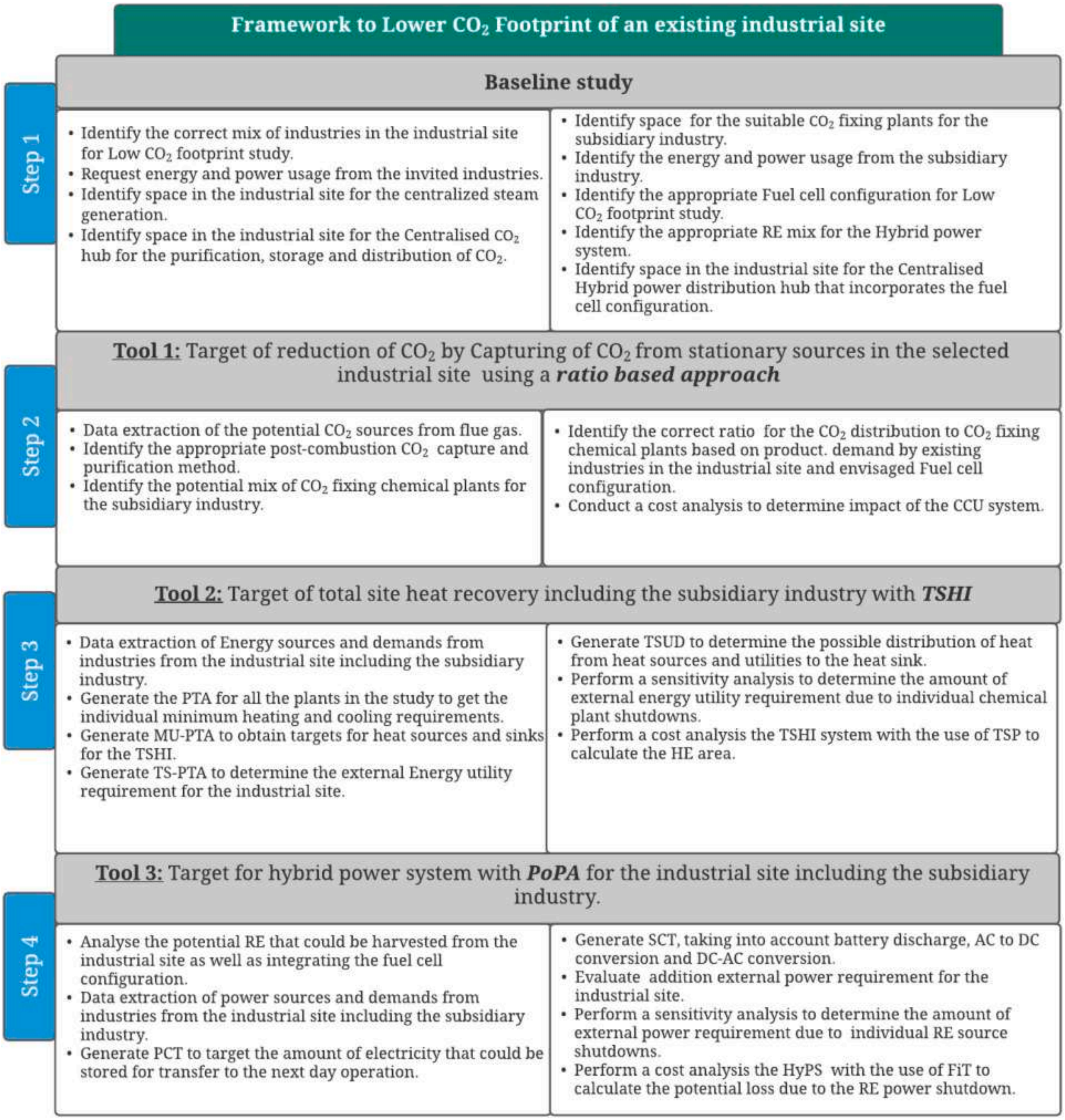

Fig. 3. Framework to lower CO_2 in an existing industrial site that includes a fuel cell configuration.

2. The steel processing plant
3. The industrial bakery
4. The paper making plant
5. The waste water treatment plant
6. Landfill site for domestic garden waste

It is assumed that these industries operate independently, with no apparent symbiosis or resource integration visible. To reduce the CO_2 footprint of the industrial site, it is proposed that a framework be introduced to guide industrial role players on a systematic CO_2 reduction tool that should be followed to achieve a sustainable low CO_2 footprint in an industrial site.

The data that is required to start the CO_2 lowering footprint of an industrial site:

1. The stationary CO_2 from the stack gases captured is analysed to examine the percentage of CO_2 in the flue gas stacks. Table 1 shows the flue gas composition in the steel industry, the waste paper recycling industry, and glass-making plant. The mass flow rate of the purified CO_2, according to John et al. (2020), is 105.56 tons per day (t/d). Because the captured gas is purified to >90% CO_2, the site storage and distribution to the subsidiary industry becomes less complicated than dealing with the storage and distribution of different CO_2 purity headers.
2. The heating and cooling data of the sources and sinks of the existing plants in the site that will be used in the TSHI analysis.
3. The power demands of the existing plants in the site.

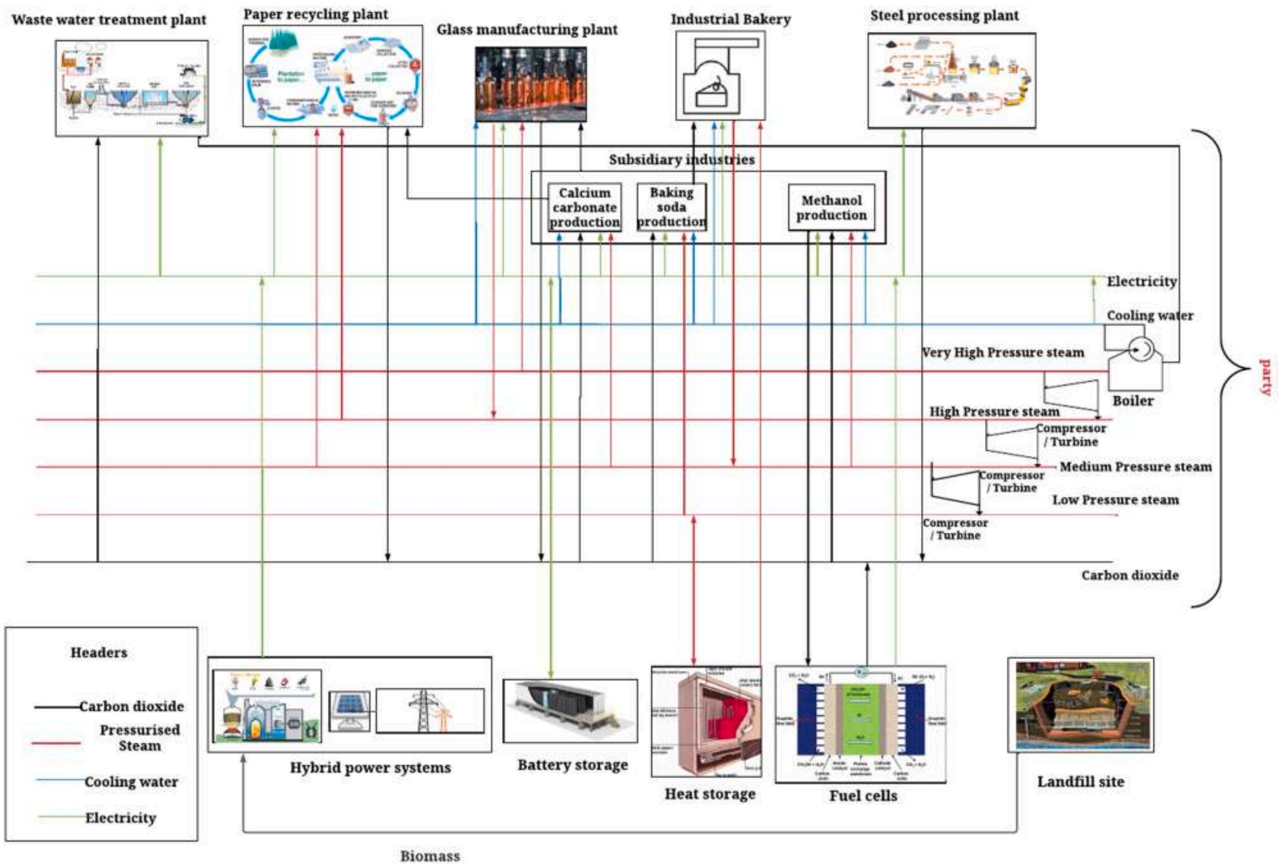

Fig. 4. Illustration showing the of the CO_2 capture, distribution, and usage.

Table 1
Composition values of flue gas of industries.

Steel industry		Waste paper industry		Glassmaking industry	
Components	% Composition	Components	% Composition	Components	% Composition
H_2	3.6	H_2	24.1	Cl comp	0.9
CO	22.1	CO	30	CO	4.9
CO_2	22.8	CO_2	24.2	CO_2	35.5
N_2	48.3	N_2	0.2	NO_2	7.2
H_2O	3.2	H_2O	15.9	NO_x	12.9
		HC's	5.6	O_2	5.4
				SO_2	31.6
				F comp	0.14
				Dust	1.44

4.2. *Tool 1: target reduction of CO_2 from stationary using a ratio based approach*

The study would use the post combustion based on the gas-liquid absorption method described by Cormos and Cormos (2017) as the technologically advanced and economically viable option that utilizes alkanol amines like Methyl-Di-Ethanol-Amine (MDEA) solvent by employing absorption - desorption cycle using the following reversible reaction:

$$MDEA + CO_2 + H_2O \rightarrow MDEAH^+ + HCO_3^- \qquad \text{Equation 3}$$

The most essential aspect in the devolution of CO_2 from a site is the permanent stable storage of the captured gas. The distribution of a single high concentration of gas to chemical fixing industries is the most effective way of introducing industrial symbiosis in the site. According to John et al. (2020), the construction of the subsidiary industry consisting of chemical fixing plants could depend on the following factors.

1. Economic sustainability of the subsidiary industry,
2. Tax rebates for the sequestration of CO_2 from a site,
3. The government stimulus package for job creation initiatives.

The addition of a fuel cell configuration is to have a dependable high-density source of power that could be added to the HyPS. In this study, the direct methanol fuel cell (DMFC) was chosen because methanol production is a viable CO_2 fixing process and would provide the methanol required to fuel the fuel cell. The DMFC, according to Joghee et al. (2015) has made significant improvements in the fabrication of the membrane electrode assemblies (MEA) to improve longevity and efficiency for large-scale applications.

The ratio distribution approach was conducted on the captured CO_2 and is allocated to the individual plants, as shown in Table 2. The ratio is higher for the baking soda plant below because of the profitability of the baking soda plant. The baking soda sold to the bakery could also be used as cleaning the working surfaces, floors, baking equipment and utensils.

Table 2
Distribution of CO_2 to chemical fixing plants.

Flue gas sources	Methanol Plant	Baking soda plant	Calcium carbonate plant
The ratio of CO_2 distribution	1	2	1
Total CO_2 distribution (t/d)	26.39	52.78	26.39
Cost per day of CO_2 ($)	1,502	2,786	1,502
Cost per annum ($)	548,075	1,016,770	548,075

It can also be argued that the using of baking soda produced within the site for use within the site also reduces the carbon footprint within the site despite the purpose of the product because the outside of the site source is avoided, i.e., the carbon foot print attributed to transport. The methanol will be used in the DMFC configuration, and the calcium carbonate will be sold to the paper-making and glass-making industry for use as one of the reagents. The baking soda will be sold in the industrial bakery. This permanent storage through CO_2 mineralisation and the reuse of these added-value products with the site ensures an immediate reduction of the CO_2 footprint of the site. The cost analysis of the CO_2 fixing units has revealed that the only profitable CO_2 fixing process in the current configuration of the CCU system and the cost of the DMFC can be better sustained if the cost of getting methanol from the subsidiary industry is lowered (see details in John et al. (2020)). The suite of subsidiary industries could change depending on the composition of industries in the brownfield.

In the study, the cost analysis for the CCU system revealed that the only profitable CO_2 fixing plant in the proposed CCUS configuration was the baking soda production plant. It was revealed that an overall loss of $2.75M from the CCU system considering the sale of the products for reagents to the existing plants and the fuel cell configuration. Since the underground storage of the captured CO_2 has not received governmental approval, it becomes prudent to maintain the CO_2 mineralisation option to store the captured CO_2. In order to keep these costs low, the price of resources such as hydrogen and wollastonite could be reduced by creating hydrogen through solar-chemical water splitting and getting the wollastonite from steelmaking slag. The cost could also be brought down through governmental sponsorship for cleaner production projects and the international funds that subsidize climate change mitigation projects.

4.3. Tool 2: target total site heat recovery including the subsidiary industry with TSHI

The TSHI that includes the subsidiary industry in a brownfield has to ensure that there is sufficient space for the piping, heat exchangers, auxiliary equipment and the centralised utility system to ensure the successful implementation of the total site heat recovery system.

4.3.1. The individual problem table algorithm (PTA)

The individual PTA is used to determine the heating and cooling requirement for individual Plants. The first step is to establish the QH_{min}, the $QC_{min,}$ and the pinch temperature of each of the individual industries on the site as well as the envisaged CO_2 fixing plants by constructing the individual PTA. The single utility PTA tables are considered for the sites: industrial bakery, paper recycling plant, glass making industry, methanol production plant, calcium carbonate production plant, and the baking soda production plant. Table 3 shows the thermal data, which includes the minimum heating and cooling requirements derived from the individual PTA (Tables S1–S6 from the supplementary data). The steel industry was not considered for the TSHI because the thermal contribution to the TSHI was deemed insignificant. The Plant manager could also request exclusion from the TSHI project. The individual PTA is required to construct the MU-PTA which will be used to target for heat sources and sinks.

4.3.2. Multiple utility problem table algorithm (MU-PTA)

The MU-PTA for each plant participating in the TSHI is constructed to obtain targets for multiple utility levels as heat sources and sinks for TSHI (Tables S7–S12 from the supplementary data) following the procedural methodology shown in Liew et al. (2012). The illustrative example will use the utility temperature levels in Table 4 for the TSHI. As explained earlier, the MU-PTA is the algebraic representation of the GCC that uses utility temperature boundaries to differentiate the amounts of heat sources and sinks by utility type. The multiple utility cascades must be performed based on the pinch regions, i.e., above and below the pinch region. Above the pinch, the heat is cascaded starting from the temperature point towards the pinch temperature. When there is a negative value during the cascading between temperature intervals, an external utility is added to that point (column 8 of the MU-PTA Tables S7–S12 from the supplementary data). The multiple utilities below the pinch are cascaded from the bottom to the pinch temperature. When there is a positive value during the cascading between temperature intervals, the cascading must be zeroed to generate utilities (column 8 of the MU-PTA Tables S7–S12 columns 7 and 8 from the supplementary data). The amount of utilities generated was determined by summing the amounts of excess heat per utility interval (above the utility temperature to the next utility level) to get the total amount of the utility per utility interval, as summarised in Table 5.

4.3.3. Total Site Problem Table Algorithm(TS-PTA)

The TS-PTA is applied to establish the utilities exchanged between processes within the Total sites. It is the algebraic representation of the graphical Site Composite curve. The utilities generated below the pinch region are added to determine the total heat sources. Above the pinch region, the utilities used by the industries in the TSHI study are added together to determine the total Heat sink. The heat requirement is acquired by subtracting the heat sink from the heat source. As shown in

Table 4
Proposed Site utility data.

Utility	Temperature (^oC)
Very High Pressure Steam (VHPS)	500
High Pressure Steam (HPS)	240
Medium Pressure Steam (MPS)	198
Low Pressure Steam (LPS)	150
Hot water(HW)	50
Cold water (CW)	20
Chilled Water (ChW)	10

Table 3
Heating and cooling requirements of the individual plants of the CO_2 reduction study.

Thermal data	Industrial bakery	Paper recycling plant	Glass making industry	Methanol production plant	Calcium production plant	Baking soda production
Minimum temperature difference ΔT_{min} (^oC)	10	10	20	5	10	10
Shifted Pinch temperatures (^oC)	225	25	1090	43.5	370	65
Hot utility requirement (MW)	28	233.05	22.48	3.09	0.074	2.325
Cold utility requirement (MW)	173.6	14.7	126.13	0	3.539	3,7

Table 5
Summary of results from Multiple utility heat cascade table.

Utility	Utility Temp (°C)	Heat source (MW)						Heat sinks (MW)					
		Bakery	Paper making	Glass making	Methanol	Calcium Carbonate	Baking soda	Bakery	Paper making	Glass making	Methanol	Calcium Carbonate	Baking soda
VHPS	500			45								0.074	
HPS	240			39.58		2.835		28					
MPS	198	13.5		4.62		0.7938			38				0.645
LPS	150	24		5.28		0.1562			96.45		4.93		1.7
CW	20	118.1	7.35	26.9			3.31						
ChW	10	18	7.35	4.75	0.263		0.39						

column 5 of Table 6, the positive value, as seen in Column 5 is heat surpluses, and the negative values represent the heat deficits. The initial heat cascade represented by Column 6 of Table 6 is found by starting at zero and cascading by adding the heating requirements acquired in Column 5 from top to bottom. The most negative value is used to determine the external heating utility requirement by making it positive as seen in column 7 of Table 6, by cascading it heating values and getting external heating requirement of 34.034 MW and cooling requirement of 186.413 MW (of which 155.66 MW of cooling water utility and 30.753 MW chilled water).

4.3.4. *Total site problem utility distribution (TSUD) table*

The distribution of utilities in a total sites' scenario can be a complicated task depending on the distances between processes and the sensitive nature of the streams to cross-contamination. The TSUD tool developed by (Liew et al., 2012) provides a visual representation, as shown in Table 7, of how heat sources and utilities can be distributed to heat sinks. The arrows show the proposed distribution to the same or lower utility levels. The Plant manager can then use this tool to determine the best distribution option for processes on the site.

4.3.5. *The total sensitivity table (TSST) table*

The most important feature of the TSHI is to ensure the system's robustness to plant shut downs and to ensure the utility cushion for the utility loss due to individual plant shutdown. Plant shutdown could be due to predictable reasons such as planned maintenance or unplanned reasons such as unit operations failures and accidents in the plant. Table 8 shows the impact of the individual plant downs by discounting the impact of the individual plant heat sinks and heat source data, as shown in Table 8. According to Liew et al. (2012), the consequence of the sensitivity study will provide insights to the TSHI designer on planning for the maximum heating and cooling utility requirements for individual shutdowns. The excess heating and cooling duties can be sold to interested parties or stored in heat storage, as shown in the conceptual diagram in Fig. 4.

4.4. *Tool 3: target for hybrid power system with PoPA for the industrial site*

The introduction of renewable sources for power generation is the most consequential way to reduce the carbon footprint from outside sources. Power Pinch Analysis (PoPA) is an ideal tool utilised for the power allocation of HyPS comprising renewable energy sources. The introduction of numerical tools by Rozali et al., 2013a was used to determine the minimum target for outsourced electricity, the maximum power storage required for the HyPS, and the system's sensitivity with the shut down during operations (Rozali et al., 2016b).

The first step in developing a HyPS is to evaluate the possible power sources apart from the outsourced mainstream electricity supply. Table 9 summarises the possible RE sources of power and the proposed DMFC that could be sourced to provide the electricity needs for the selected plants in the industrial site. Solar power was determined using the parking area of the selected plants in the industrial area. This is done by evaluating the amount of electricity that could be generated by placing the solar panels on parking lot rooftops in the identified parking areas of the selected industries. As a result, it was determined that the possible electricity generated per day as calculated from Equation (2) (Rozali et al., 2017) was 14.28 MWh. The industrial site also has a landfill area that collects garden waste comprising mainly felled trees and excess branches from garden service vendors from the surrounding residential and company premises. The Biomass plant is presumed to operate optimally between 08:00 and 18:00, generating 20 MWh of possible electricity per day calculated from Equation (4). The fuel cell configuration is expected to deliver 4.383 MWh of electricity supply per day, operating 24 h.

$$\sum \text{Electricity Source/Demand} = \sum \text{Power Rating} \times \text{Time interval} \quad \text{Equation 4}$$

The electricity demands for the envisaged TSHI system consider the

Table 6
Total site problem table algorithm (TS-PTA).

1	2	3	4	5	6	7	8	9
Utility	Utility Temp (°C)	Net heat source (MW)	Net heat sink (MW)	Net heat requirement (MW)	Initial heat cascade	Final single heat cascade	Multiple utility heat cascade	External Utility requirement (MW)
					0	34.034	44.926	
VHPS	500	45	0.074	44.926				0
					44.926	78.96	14.415	
HPS	240	42.415	28	14.415				0
					59.341	93.375	0	
MPS	198	18.9138	38.645	−19.7312				0
					39.6098	73.6438	0	
LPS	150	29.4362	103.08	−73.6438				34.034
					−34.034	0(Pinch)	0	
CW	20	155.66		155.66				−155.66
					121.626	155.66	0	
ChW	10	30.753		30.753				−30.753
					152.379	186.413	0	

Table 7
Total Site Utility Distribution (TSUD) table.

Utility	Utility Temp (°C)	Heat source (MW)							Heat sinks (MW)						
		Bakery	Paper making	Glass making	Methanol	Calcium Carbonate	Baking soda	Site utility	Bakery	Paper making	Glass making	Methanol	Calcium Carbonate	Baking soda	Site utility
VHPS	500			45									0.074		
HPS	240			39.58		2.835			28						
MPS	198	13.5		4.62		0.7938				38				0.645	
LPS	150	24		5.28		0.1562		34.034		96.45		4.93		1.7	
CW	20	118.1	7.35	26.9			3.31								155.66
ChW	10	18	7.35	4.75		0.263	0.39								30.753

consumption for the existing plants, i.e., the industrial bakery, steel processing plant, wastewater treatment plant, glass-making plant and paper recycling plant. The Power demands also consider the plants of the chemical fixing plants which are the calcium carbonate production plant, methanol production plant and the baking soda production plant. The post-combustion CO_2 capture system is also considered in the power demands because of the high power consumption requirements for capturing and purifying the CO_2. Table 10 summarises all the electricity requirements for the proposed low CO_2 footprint industrial site. This study considers the power losses due to conversion from Direct Current (DC) to Alternating Current (AC) using a rectifier as calculated using Equation (5) and power losses (due to conversion from AC to DC with the use of a rectifier using Equation (6).

Amount of converted AC electricity to DC (MWh) = AC electricity surplus (MWh) × Rectifier efficiency Equation 5

Amount of DC electricity converted to AC (MWh) = DC electricity MWh) × Invertor efficiency Equation 6

The power sources and demands data for the illustrative study, as shown in Table S13 from the supplementary data, consider the power losses due to the conversion arranged on an hourly basis, showing the possible power sources and sinks within the industrial site. It is assumed that all the industrial sinks require AC electricity to meet their electricity requirements. Therefore, the total power sinks and power sources at each hourly interval are calculated as shown in the last two columns in Table S13 from the supplementary data. These total power sinks and power sources at each hourly interval are in the Power Cascade Table (PCT), Table S14 from the supplementary data.

4.4.1. The Power Cascade Table

The PCT, a tool in the PoPA, as described by Rozali et al., 2013a, is a method to target the amount of electricity stored for transfer to the next day's operation. The amount of electricity sources and demands for each hourly interval is calculated in Columns 3 and 4 of Table 12 using Equation (7).

$\sum$ *Electricity source/demand* = $\sum$ *Power Rating* × *Time interval* Equation 7

The net electricity surplus and deficit are seen in Column 8 of Table S14 from the supplementary data using Equation (8). The positive net electricity value represents the stored electricity sources, and the negative net electricity value represents the sinks. Electricity is supplied from external sources to meet the deficit.

Net Electricity surplus/ deficit = $\sum$ *Electricity source* - $\sum$ *Electricity demand* Equation 8

The infeasible electricity cascade from Column 9 of Table S14 from the supplementary data shows negative electricity flows due to the net electricity being cascaded down. The feasible electricity cascade from Column 10 of Table 12 takes the largest negative value (−6.965 MW), making it positive and cascading it cumulatively across the surplus and deficit seen in Column 8. The minimum amount during start-up is 6.965 MW of outsourced electricity would be required to ensure stability to the HyPS. This means that a net avoidance of 6,834 ton CO_2 per annum during HyPS normal operation could be achieved using the estimated 0.53 kg CO_2/kWh of electricity production from coal (Hawkes, 2014).

4.4.2. The Storage Cascade table

The sustainability of a HyPS to ensure there is sufficient reliable

Table 8
Total site sensitivity Table(TSST).

Utility	Total Site external utility requirement, MW												
	Normal operation	Bakery Plant shutdown	Variance from Normal operation	Paper recycling Plant shutdown	Variance from Normal operation	Glass making Plant shutdown	Variance from Normal operation	Methanol production Plant shutdown	Variance from Normal operation	Calcium Carbonate production Plant shutdown	Variance from Normal operation	Baking soda production Plant shutdown	Variance from Normal operation
VHPS	0	0	0	0	0	45	−45	0	0	−0.074	0.074		0
HPS	0	−28	28	0	0	39.58	−39.58	0	0	2.835	−2.835		0
MPS	0	13.5	−13.5	−38	38	4.62	−4.62	0	0	0.7938	−0.7938	−0.645	0.645
LPS	34.034	24	10.034	−96.45	130.484	5.28	28.754	−4.93	38.964	0.1562	33.8778	−1.7	35.734
Pinch													
CW	155.66	118.1	37.56	7.35	148.31	26.9	128.76	0	155.66	0	155.66	3.31	152.35
ChW	30.753	18	12.753	7.35	23.403	4.75	26.003	0	30.753	0.263	30.49	0.39	30.363

power to the industrial site is fundamental for the decarbonisation of the site. The Storage Cascade table (SCT) is used to gauge the maximum power storage capacity for a battery configuration to ensure that the excess power produced per hourly interval is stored and the battery storage provides for the power deficit per hourly interval. The SCT as shown in Table S15 from the supplementary data can be used to find the maximum power storage of 20.20 MW after considering 5% rectifier and inverter losses and a battery charge and discharge loss of 10% as well as the self-discharge rate losses of 0.004%/h while storing as DC power as explained in Rozali et al., 2013b. Considering all these losses, it was also determined that the AEEND was 8.55 MW, that was cascaded to the next day operation. Therefore, it was established that the HyPS requires only RE sources of power to supply electricity to the industrial during normal operation apart from the 6.965 MW of outsourced electricity required during start-up.

4.4.3. *Sensitivity of the hybrid power system*

The sensitivity of the HyPS to resource shutdown is important for the site manager to plan for how much extra electricity would be required to fulfil the electricity deficits due to individual renewable energy shutdowns. Rozali et al., 2016b approached the sensitivity of a HyPS by looking at the system's profitability by considering the Feed-in Tariff (FiT) as shown in Table 12 related to the RE resource. The sensitivity table shown in Table 11 shows the potential losses based on FiT penalty rates (Table 12) to the HyPS when the solar PV power source or the biomass power source fails. The FiT of renewable sources as ratified by the DEA (2021) shows the tariff discrepancy between solar PV power source and the biomass power source as almost four fold. From the sensitivity table, Table 11 shows a loss of $1461.30 per day if the biomass fails and a loss of $1327.30 per day if the solar PV fails on FiT penalty rates.

5. Economic analysis of the TSHI and HyPS used to reduce the CO_2 footprint

The analysis of the economic sustainability of the TSHI and the HyPS is crucial in a site manager's decision of how to plan for the funds necessary to start the TSHI and HyPS from potential investors. The analysis would also allow the managers to know how much external sponsorship is required from national and international incentive funds to attain sustainability.

5.1. *The economic analysis of the TSHI system*

The Total Site Heat Integration cost estimate will utilise the total site profiles to evaluate the heat recovery potential between processes with the industrial site of the TSHI system. The assumption made for the economic analysis is that the system is running at 90% efficiency. The Total annualised cost considers that the initial capital cost is calculated by dividing over a payback period of 10 years. According to Peters et al. (2003), the operating labour cost can be categorized as either highly skilled or low skilled employees that operate the plant. It is estimated that the operating labour cost amounts to about 10–20% of the total product cost. For this study, operating labour cost is estimated as 10% of the annualised capital cost.

A site source and sink profile from all the available processes from the industrial site is combined into a single profile analogous to a Composite Curve for a single process as described by Klemeš et al., 1997. The GCC for each plant in the industrial site are combined as heat source segments placed on the left-hand side of the Y-axis, while the combined heat sinks segments are placed on the right-hand side of the Y-axis, as seen in Nemet et al. (2012). The data for the site source and sink profile as shown in Table 13a and Table 13b was used to construct the total site profile in Fig. 5, which has the site source and sink profiles. Using changes in the slopes of the site profiles and site composite curves, Enthalpy intervals (EIs) are chosen. The heat exchange areas are

Table 9
Power sources for the case study.

Power sources		Time, h		Time interval, h	Power generated, MW	Electricity generation, MWh
AC	DC	From	To			
Biomass		08:00	18:00	10	2	20
	Fuel cell	00:00	23:59	24	0.183	4.383
	Solar	09:00	17:00	8	1.785	14.28

Table 10
Power demands for the case study.

Power demands		Time, h		Time interval, h	Power consumed, MW	Electricity consumption, MWh
AC	DC	From	To			
Industrial Bakery		00:00	23:59	24	0.049	1.181
Steel Processing		00:00	23:59	24	0.563	13.5
Waste water treatment		00:00	23:59	24	0.033	0.792
Glass-making industry		00:00	23:59	24	0.379	9.096
Paper recycling industry		00:00	23:59	24	0.096	2.304
Calcium carbonate production plant		00:00	23:59	24	0.090	2.170
Methanol industry		00:00	23:59	24	0.023	0.552
Baking soda production plant		00:00	23:59	24	0.198	4.752
CO_2 Capture system		00:00	23:59	24	0.045	1.080

determined from EIs using the general heat transfer area equation (Equation (9)).

$$A = \frac{Q}{U \Delta T_{LM}} \quad \text{Equation 9}$$

There were 17 EIs that were identified to estimate the heat exchanger area. This was crucial for the estimation of the cost of the heat exchangers.

The calculation results of the heat transfer area for the TSHI system are then collated as shown in Table 14 to illustrate the area for each enthalpy interval (Boldyryev et al., 2015). This heat transfer area is calculated from the complete TSP, including the source and sink profiles.

The study uses the shell and tube HE types for the TSHI heat exchanger network. The costing of the HEN is calculated from Equation (10) developed by Reza et al. (2004) using the cost indexes in Table 15. The cost is then interpolated to the 2020 cost values using the 2020 Nelson-Farrar cost index. The cost from each EI, which is collated to give the estimated total cost of the HEN, $30,856,695. This cost is then used as a basis for calculating the estimated capital cost of the TSHI network.

The estimated capital cost of the TSHI was calculated based on the estimated cost of HEN. The typical cost factors (Smith, 2005) were used to estimate the total cost of the TSHI network, as shown in Table 16. It was found that the total estimated capital cost is $ 83,313,077.

The cost of utilities varies immensely in different countries depending on the market fluctuations and the country's available natural resources. Therefore, Ulrich and Vasudevan (2006) proposed a two-factor utility cost equation such as the following:

$$\mathbf{C_{S,u}} = \mathbf{a}(\mathbf{CEPCI}) + \mathbf{b}(\mathbf{C_{S,f}}) \quad \text{Equation 11}$$

where $C_{S,u}$ is the price of the utility, a and b are utility cost coefficients (see (Ulrich and Vasudevan, 2006)), $C_{S,f}$ is the price of fuel in $/GJ, and CE PCI is the inflation parameter for projects.

Tables 17 and 18 show a summary of the estimated annual cost of the required utility for the TSHI and the potential cost saving from the heat integration of the TSHI network. It was found that $1,252,605 of utilities were required to meet the energy requirements of the TSHI network. It was also found that a potential cost saving of $1,483,194 due to the HI from the TSHI.

The utility avoidance cost savings calculated and summarised in Table 18 determine if the TSHI is economically viable. This cost-saving takes into account the maximum potential saving from the heat integration.

The estimated total annual cost analysis was calculated considering that the initial capital cost was divided over a payback period of 10 years. The annual operating labour cost and fixed operation and maintenance cost is estimated as 10% of the annualised capital cost. The total cost analysis of the process was found to have an annual loss of $ 9,766,980 (see Table 19).

The rate of return for the project is 1.78%, which is very low, but the purpose of the study was to lower the CO_2 footprint of the industrial plant. The TSHI plays an important role in lowering the amount of

Table 11
Sensitivity analysis of hybrid power systems using Feed-in Tariff.

1.Operation	2. RE electricity MW/d		3. FIT paid USD			4. Deviation MW/d		5. Penalty, USD			6. Outsourced electricity	7. Electricity Cost,	8. Total profit/ Loss,
	Biomass	Solar	Biomass	Solar	Total	Biomass	Solar	Biomass	Solar	Total	MW/d	USD	USD
Normal	5.46	17.08	429.90	4492.80	4922.70	–	–	–	–	–	16.72	1425.90	3496.80
Biomass system fails	0	2.73	0	716.70	716.70	5.190	13.503	40.80	354.70	395.60	20.90	1782.30	−1461.30
Solar system fails	6.67	0	524.90	0	524.90	0	16.229	0	426.30	426,30	16.72	1425.90	−1327.30

Table 12
Feed-in tariff rates of renewable sources (DEA, 2021).

Technology	Tariff (South African Rand/ kWh)	Tariff (US dollar/ kWh)	FIT penalty (US dollar/ kWh)
Landfill gas power plant	0.9	0.06	0.0060
Small hydro power plant (less than 10 MW)	0.94	0.063	0.0063
Wind power plant	1.25	0.083	0.0083
Concentrating solar power (CSP) with storage	2.1	0.140	0.0140
Concentrating solar power (CSP) without storage	3.14	0.209	0.0209
Biomass solid	1.18	0.079	0.0079
Biogas	0.95	0.063	0.0063
Photovoltaic systems(large ground or roof mounted)	3.94	0.263	0.0263
Concentrating solar power (CSP) Central tower with storage capacity of 6 h	2.31	0.154	0.0154

utilities required in the industrial site. It is estimated that the hot utilities saving valued at $1,483,194 could be saved from the TSHI network. One of the main contributors to the escalated loss is the cost multipliers added to the original cost of the total sites heat exchanger network. If the multipliers were reduced, the effect on the total cost analysis would be significant. The carbon tax incentives and international sponsorship for CO_2 reducing projects could also be used to alleviate the economic impact of the TSHI on the suite of CO_2 reduction projects in the industrial site.

5.2. The economic analysis of the HyPS system

The roof area of the parking space of the industries in the industrial site was considered for the installation of the solar PV panels, as shown in Table 20. In this study, monocrystalline solar panels were considered the preferred PV because of their higher efficiency (Hidayanti, 2020) and longevity (Sadek, 2016). Using the manufacturer's solar PV panel size of four panels occupying 8 m^2/kW, it was determined that the number of panels that are needed for the proposed parking area was 7, 140 panels. The panels' cost and installation usually come as a package from the solar PV company (Solar Advice (PTY) Solar Advice LTD, 2021). The average size of the panels was approximated to occupy 8 m^2/kW (Howell, 2021).

Table 13a
Data for the site source profile.

Segment	T^{**}_{start} (°C)	T**end (°C)	ΔH (MW)	CP (MW/°C)	Type of medium	H (MW/ m^2 °C)
1	220	80	70	0.5	Liquid	0.0005
A2	80	40	32	0.8	Liquid	0.0008
A3	40	27	10.4	0.8	Liquid	0.0008
A4	27	10	61.2	3.6	Liquid	0.0008
B1	20	10	14.7	1.47	Liquid	0 0008
C1	1080	580	45	0.09	VHPS	0.014
C2	400	280	34.08	0.284	HPS	0.012
C3	280	25	28.05	0.11	HPS	0.012
C4	25	5	19	0.95	Liquid	0.0008
E1	365	203.05	3.06	0.02	VHPS	0.014
E2	80	20	0.235	0.0039	Liquid	0.0005
E3	15	10	0.263	0.0526	Liquid	0.0008
F1	60	50	0.58	0.058	Liquid	0.0006
F2	50	10	3.12	0.078	Liquid	0.0006

Table 13b
Data for the site sink profile.

Segment	T^{**}_{start} (°C)	T**end (°C)	ΔH (MW)	CP (MW/°C)	Type of medium	H (MW/ m^2 °C)
A1	230	240	28	2.8	HPS	0.012
B1	175	185	38	3.8	HPS	0.012
B2	130	175	52.2	1.16	LPS	0.01
B3	80	130	58	1.16	Steam	0.008
B4	70	80	23.3	2.33	Liquid	0.0005
B5	45	70	56.75	2.27	Liquid	0.0007
B6	30	45	4.8	0.32	Liquid	0.0008
C1	1100	1120	22.48	1.124	VHPS	0.014
D1	57	67	2.23	0.223	Liquid	0.0008
D2	51	57	0.47	0.0783	Liquid	0.0008
D3	46	51	0.39	0.078	Liquid	0.0008
E1	375	385	0.074	0.0074	HPS	0.012
F1	175	180.5	0.226	0.041	MPS	0.011
F2	70	175	2.144	0.020	Steam	0.008

$$N_P = \frac{A_I}{A_P} \quad \text{Equation 12}$$

where, N_P= Number of panels that can be installed in the installation area, A_I = Size of the installation area, (m^2), A_P = Size occupied by 1 kW of solar panels, (m^2).

The cost of the inverter (Live Stainable, 2021a) and battery storage (Live Stainable, 2021b) required for the solar PV system is also considered when costing the solar PV system, as shown in Table 21. The size of the inverter was slightly oversized to cater for the fuel cell configuration. This was done using the latest prices available in South Africa. It was determined that 21 invertor units of 100 kW (Live Stainable, 2021b) at a reasonable cost of $520,934 would be required for the study. It was further established that the maximum storage capacity required for the HPS stored is 20.20 MW. The number of battery units with a 17.75 kW capacity (Live Stainable, 2021a) required for the power storage of the HPS was 1138 units. Therefore, the capital cost of the battery storage required is $5,999,194; the total capital cost of the PV solar system includes the installed PV cells, and the inverter and battery storage system is $8,015,959, as seen in Table 21, the summary of capital costs. Although the maintenance of running a PV solar plant is low compared to other renewable sources of energy, the cost of maintenance for the PV system was estimated to be $20,850 (Tidball et al., 2010).

For this study, three units of 1 MW biomass gasifier power plants were considered due to the efficiency of the Biomass plant. Breaking the biomass plants into three modules has the benefit of alleviating the effects of plant shutdowns due to maintenance. The three modules could also be advantageous if the biomass material becomes a limiting factor. Then one or two units could be used instead of all of the three biomass gasifier power units. The cost multipliers use the typical capital cost factors as explained by Smith (2005) to estimate the capital cost for the Biomass plant, as shown in Table 22. The maintenance cost of the biomass could be conducted in three or two phases because the three 1 MW biomass plants could run concurrently. The reason three 1 MW biomass plants were selected was to cater to the efficiency losses and to ensure that a steady, reliable 2 MW of power source was available for the site.

The HyPS will estimate the selling price of the solar and biomass produced power at the approved FiTs (see Table 12). It was found that the HyPS is economically viable, with a potential annual profit of $476990. The negative values in Table 23 are the annual capital and operational cost required to run the HyPS. The positive is the maximum expected annual cash flow from the project. The rate of return for the

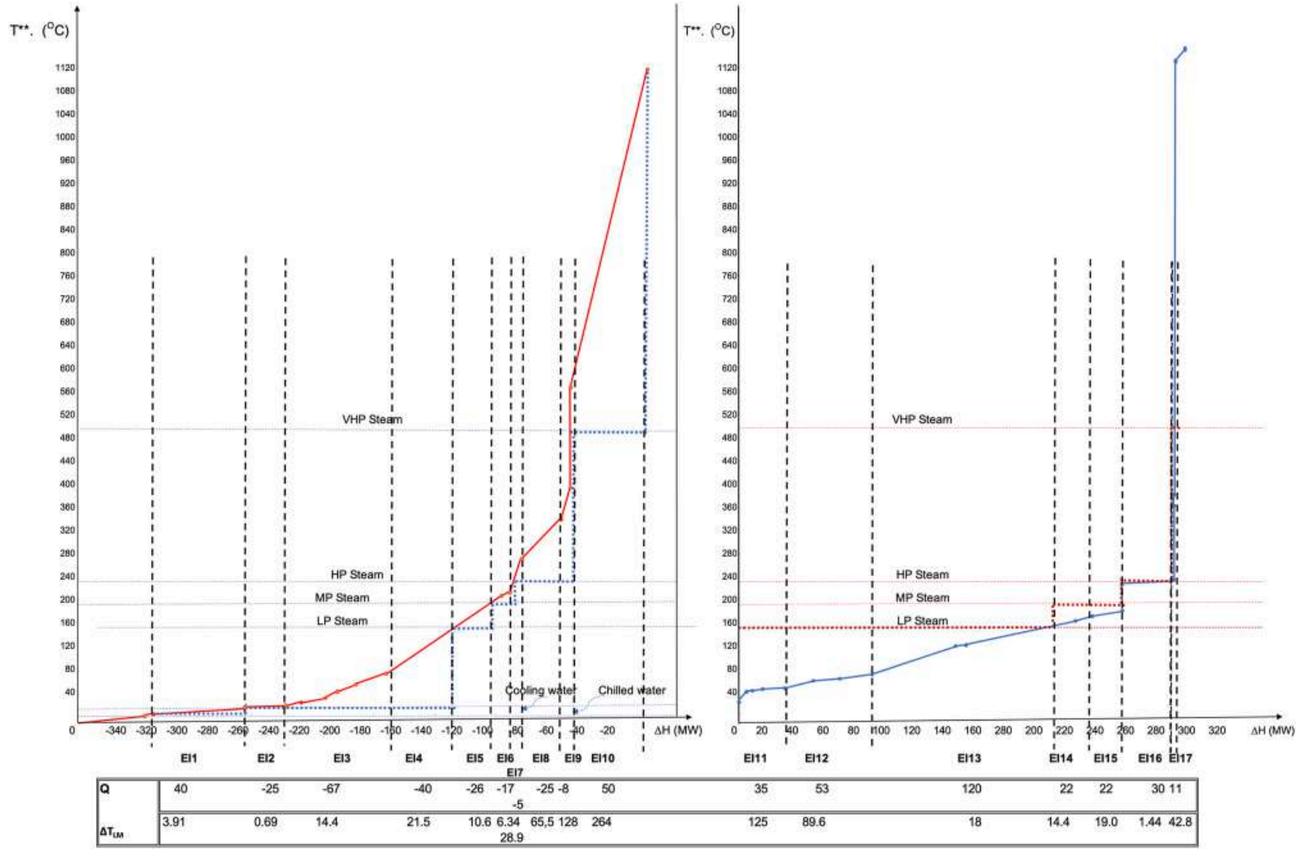

Fig. 5. Total site profile that includes the enthalpy intervals.

Table 14
Calculations of the estimated heat transfer area for each enthalpy interval for the total site heat recovery.

Enthalpy interval	Hot stream	Cold stream	Q MW	U (MW/(m^2 ^{O}C)	ΔT_{LM} interval (^{o}C)	Area (m^2)
EI1	A3+B1+E3+F2	ChW	40	0.000528	3.909	19382.03
EI2	C4+C3+E2	CW	25	0.000677	0.693	53275.30
EI3	A2+A3+C3+ E2+F2	CW	67	0.000652	14.410	7131.15
EI4	A1+C3	CW	40	0.00071	21.498	2620.67
EI5	A1+C3	LPS	26	0.00384	10.572	640.43
EI6	A1+C3+E1	MPS	17	0.0049	6.342	547.02
EI7	C3+E1	HPS	5	0.00624	28.854	27.77
EI8	C2+E1	HPS	28	0.00624	65.481	68.53
EI9	C2+E1	HPS	8	0.00624	127.659	10.04
EI10	C1	VHPS	50	0.007	263.711	27.09
EI11	LPS	B5+B6+D1+D2+D3	35	0.00073	124.933	383.77
EI12	LPS	B4+B5+D1	53	0.000625	89.628	946.13
EI13	LPS	B2+B3+F2	120	0.00464	18.028	1434.54
EI14	MPS	B1+B2+F1+F2	22	0.0053	14.427	287.72
EI15	MPS	B1+F1	22	0.00562	18.982	206.22
EI16	HPS	A1	30	0.006	1.443	3465.74
EI17	VHPS	C1	11	0.007	42.791	36.72

Table 15
Cost models for carbon steel and stainless steel for tube costs and shell costs adapted from (Reza et al., 2004).

Exchanger Specification (Materials of Construction)	Capital Cost ($) $C = a + b.A^C$ Equation 10 Cost indices/constants		
	a	b	C
Shell (CS)	10508	255.874	0.81
Tube (CS)	20292	494.125	0.81
Shell (SS)	10508	560.877	0.81
Tube (SS)	20292	1083.123	0.81

Table 16
Estimated capital cost based on cost factors (Smith, 2005).

Item (installed)	Cost multipliers	Estimated capital cost, $
Heat Exchangers	1	30,856,695
Site preparation	0.1	3,085,669
Equipment erection	0.4	12,342,678
Piping	0.7	21,599,686
Instrumentation & controls	0.2	6,171,339
Electrical	0.1	3,085,669
Building	0.2	6,171,339
Total		83,313,077

Table 17
Estimated cost of required utility for the TSHI.

Utility	CEPCI	$C_{S,u}$	a	b	$C_{S,f}$ ($/Gj)	A_S ($/Y)
Chilled water	607.5	74.92	0.12	0.03	2	479,062
Cooling Water	607.5	29.62	0.05	0.03	1	479,581
LPS	607.5	0.630	0.001	0.0037	3	293,963
				Total utility cost ($/y)		1,252,605

Table 18
Estimated Potential utility cost saving from TSHI.

Utility	CEPCI	$C_{S,u}$	a	b	$C_{S,f}$ ($/Gj)	A_S ($/Y)
LPS	607.5	0.717	0.0012	0.00368	3	632,414
MPS	607.5	1.371	0.00223	0.00389	4.5	268,644
HPS	607.5	0.952	0.00149	0.00417	11	290,885
VHPS	607.5	1.0094	0.00157	0.00426	13	291,251
					Total saving ($/y)	1,483,194

Table 19
Summary of cost estimate of TSHI.

TSHI	Cost ($/Y)
Annualised Capital cost ($/y)	8,331,308
Operating labour cost ($/y)	833,131
Amount of the utility required for TSHI($/y)	1,252,605
Fixed operation and maintenance cost ($/y)	833,131
Amount of saving from the utility saving from TSHI ($/y)	1,483,194
Annual total cost ($/y)	**−9,766,980**

project was 20.68%, making it highly desirable for the site to include a HyPS as a crucial tool to lower the CO_2 footprint.

6. Conclusion

The decarbonisation of an industrial site through a multiple approach is essential in sustaining the reduction of anthropogenic carbon dioxide emissions in a of a brownfield. In this paper, a four-step sequential framework is proposed that would lead to a low carbon footprint site. The framework presented started with the application of post-combustion CO_2 capture and purification to above 90% concentration. Next is selecting suitable subsidiary CO_2 fixing industries that would directly use reagents within the industrial site. The CO_2 footprint of the site is further reduced with the implementation of pinch analysis tools for heat integration and to optimise the distribution of renewable sources of power for a HyPS. The TSHI for the project revealed a 79.95% of hot utility usage reduction. Although the rate of return for the TSHI was 1.78%, the cost could be further reduced if the cost of utility saved was increased from the above retail price payments for the utility saved by the industries involved. The study also showed that RE sources of power and the additional DMFC power supply, would be sufficient to provide a sustainable power source for the industrial site. The amount of CO_2 avoided from the addition of the HyPS is 6,834 ton/y. The rate of return for the project was 20.68%, making it highly desirable for the site to include a HyPS as a crucial tool to lower the CO_2 footprint. This framework could be used to assist high CO_2 emitting industrial zones to attain deep and sustainable reductions in global CO_2 emissions as per COP26 Glasgow Climate Pact This work presents a viable framework

Table 21
Summary of capital costs for the solar PV system including storage.

Item	Cost ($)
Capital cost of the solar panels required	953,190
installation	542,640
Cost of required invertors	520,934
Cost of required batteries	5,999,194
Total cost	**8,015,959**

Table 22
Capital Cost of Biomass power plant for the industrial site (Indiamart, 2021).

Item	Cost Multipliers	Cost($/y)
Capital cost ($) of a 1 MW biomass plant		400,000
3×1 MW biomass power plant	1	1,200,000
Site preparation	0.1	120,000
Installation ($)	0.15	180,000
Electrical connections	0.1	120,000
Total ($)		**1,620,000**

Table 23
Summary of cost estimates of the HyPS.

RE- power source	Solar PV source	Biomass source	General HPS
Annualised capital cost ($/y)	149,583	162,000	
Fixed operation and maintenance cost ($/y)	196,350	289,170	
Invertor for HyPS ($/y)			52,093
Battery for HyPS ($/y)			599,919
Operating labour cost ($/y)	34,593	45,117	65,201
Selling price of power produced using FiTs ($/Y)	1,318,568	674,739	
Total cost analysis (annualised) ($/y)	**478,990**		

Table 20
Cost of monocrystalline solar panels for the industrial site (Solar Advice (PTY) Solar Advice LTD, 2021).

	Industry	Total covered parking area (m^2)	Power generated (kW)	Number of Panels	Cost of Solar panel ($)	Cost per Installation ($)
1	Industry Bakery	1300	162.5	650	86775	49400
2	Waste- water treatment industry	280	35	140	18690	10640
3	Glass-making industry	3800	475	1900	253650	144400
4	Paper recycling industry	2700	337.5	1350	180225	102600
5	Steel processing plant	5900	737.5	2950	393825	224200
6	Calcium carbonate production plant	100	12.5	50	6675	3800
7	Methanol industry	100	12.5	50	6675	3800
8	Baking soda production plant	100	12.5	50	6675	3800
Total		14280	1785	7140	**953190**	**542640**
					Total installed solar panel cost	**1495830**

that would result in lowering the CO_2 footprint in four sequential steps. However, the cost of holistic decarbonisation of an industrial site is impeded by the cost of the CO_2 lowering systems. Recent incentives by the European Union for decarbonisation projects could assist in the viability of the proposed project. Future work will have to give emphasis in the inclusion of the co-generation potential for the HyPS. The method should also consider the effects of pressure drop to the TSHI. In addition, future work will consider the fluctuation of renewable power due to seasons change and resource availability.

CRediT authorship contribution statement

Joe Mammen John: Writing – original draft, Methodology, Data curation, Investigation, Formal analysis, Funding acquisition. **Sharifah Rafidah Wan Alwi:** Supervision, Resources, Conceptualization, Formal analysis, Validation, Writing – review & editing. **Peng Yen Liew:** Validation, Writing – review & editing. **Daniel Ikhu Omoregbe:** Supervision. **Uaadhrajh Narsingh:** 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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Appendix A. Supplementary data

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