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Resource Efficiency as a Guide to Clean and Affordable Energy: A Case Study on Trinidad and Tobago

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Abstract

In mitigating the effects of climate change, the global community has begun a sustainable energy transition to curtail anthropogenic emissions- with Small Island Developing States (SIDS) being slow to adapt. Trinidad and Tobago is one such SIDS located in the southern Caribbean, endowed with hydrocarbon resources supporting an active petrochemical sector; which consumes over 50% of electricity generated by outdated, low-efficiency, simple-cycle (SC) gas-based technologies. Our study utilizes techno-economic and environmental assessments to investigate how improved resource and energy efficient power generation can be achieved. Twenty (20) cases were explored, reflecting SC and combined-cycle (CC) operations, renewable energy (RE) penetration and electrification of the petrochemical sector through power-to-X systems. Our results indicate a shift towards greater energy efficiency (50%) and reduced gas utilization (7.2 GJ/MWh reduction) through CC over SC systems, with RE penetration further increasing efficiencies. Furthermore, LCA results fully support a hybrid CC-RE transition, achieving the greatest reduction (55.4 %) in CO_2 emissions. While power-to-X cases show consolidated environmental benefits through avoided emissions, it is associated with substantially higher costs. Thus, CC systems offer reduced environmental and economic burdens-with RE deployment further supporting sustainable operations and active decarbonization of the local power sector.

Keywords: Resource Efficiency, Energy Efficiency, Sustainable Development Goals, Power Generation, Clean Energy, Life Cycle Assessments.

Nomenclature

BAU - Business as Usual
CAPEX- Capital Costs
CC - Combined Cycle
CEPCI- Chemical Engineering Cost Indices
FC- Fixed Costs
FCI - Fixed Capital Investment
GDP- Gross Domestic Product
GHG - Greenhouse gases
GJ - GigaJoule
IPP - Independent Power Producers
IRR - Internal Rate of Return
KPI - Key Performance Indicators
LCA - Life Cycle Assessment
LCI - Life Cycle Inventories
LCIA - Life Cycle Impact Assessment
LNG - Liquified Natural Gas
MM - Million
MSP - Minimum Selling Price of Electricity
MW- Megawatt
MWh- Megawatt hour
NPV - Net Present Value
OPEX - Operating expenditure
PEM- Polymer Electrolyte Membrane
RE - Renewable Energy
RWGS - Reverse Water Gas Shift Reaction
SC - Simple Cycle
SDG- Sustainable Development Goals
SIDS - Small Island Developing States
Syngas- Synthesis Gas
SNG - Synthetic Natural Gas
SOEC - Solid Oxide Electrolysis
SP_{IRR} - Selling Price of Electricity which guarantees an IRR=15%.
UNFCCC - United Nations Framework Convention on Climate Change
USD- United States Dollar
WC - Working Capital

1. Introduction

Approximately 50% of the world's community does not have guaranteed access to affordable, reliable, and sustainable energy. Sustainable energy is a major contributor to transforming societies, economies and safeguarding the future of our environment (International Renewable Energy Agency, 2020a; World Bank, 2020). Currently, approximately 82% of primary energy consumption is derived from fossil fuels (Ahmad and Zhang, 2020). As the world seeks to find solutions to impending climate change, power generation is transitioning away from fossil fuels to low carbon solutions- more so in the field of renewable energy (Intergovernmental Panel on Climate Change, 2014). Past studies have shown that to promote low carbon solutions, greater resource and energy efficiency takes precedence-reducing both annual operating costs as well as environmental burden (World Bank, 2020). Thus, this global energy shift is necessary in meeting sustainable development goals (International Renewable Energy Agency, 2020a; World Bank, 2020) while also reducing climate change impacts in the future (International Renewable Energy Agency and International Energy Agency, 2017).

Achieving decarbonisation of the energy sector through the use of RE has been the most obvious suggestion which encompasses several challenges. The most important issue is to ensure that technological alternatives are accessible at varying scales and at a sustainable cost, particularly for petrochemical and energy industries which are difficult to decarbonize. While there are many liquid and gaseous carriers that will be used now and, in the future, hydrogen and energy have shared a long history (Verkehrswende and Energiewende, 2017; International Energy Agency, 2019).

Hydrogen is a versatile fuel and a sustainable energy carrier, capable of replacing fossil fuels while decreasing carbon dioxide (CO_2) emissions- thus, reducing global warming (Hosseini and Wahid, 2020). Hydrogen can be produced from a diverse range of low carbon energy sources and is a proposed environmental solution for globally increasing energy demand. Hydrogen ensures long- term energy security due to its high energy content per unit mass, and mass productivity at industrial scale (International Energy Agency, 2019; Timmerberg and Kaltschmitt, 2019). However, the deployment of hydrogen production technologies coupled with transmission, storage and distribution carries with its high production costs which are highly energy intensive (Glenk and Reichelstein, 2019). The decarbonization of the energy sector has been gaining increased attention while hydrogen generation from renewable energy is not yet economically feasible.

As a small island developing state (SIDS), Trinidad and Tobago have traditionally depended heavily upon its oil and gas reserves, petrochemical and other hydrocarbon related downstream industries. This has led to significant energy wastage and increased CO_2 emission quotas per capita (Knoema, 2019). With inevitable climate change effects forecasted for SIDS, active decarbonization takes precedence in ensuring national sustainable development (Government of the Republic of Trinidad and Tobago and Ministry of Planning and the Economy, 2012). For Trinidad and Tobago, natural gas carries the highest share in the country's primary energy demand and it is used in almost all secondary energy carriers and end-use energy sectors. More than 50% of the country's electricity is consumed by Trinidad and Tobago's energy intensive industries- driven mainly by ammonia, methanol and LNG production. Currently, power generation is met by independent power producers (IPPs) utilizing gas-based technologies; mainly SC and CC power plants. Within the Caribbean region, electricity rates in Trinidad and Tobago are among the lowest -approximately $0.04 per kilowatt-hour (kWh) (Government of the Republic of Trinidad and Tobago and Ministry of Planning and the Economy, 2012; National Renewable Energy Laboratory, 2015). driven by Trinidad and Tobago's significant gas reserves.

Trinidad and Tobago has agreed to the UNFCCC's key resolution to "limit the temperature increase to well below 2 °C compared to pre-industrial levels, with efforts to limit it to 1.5 °C" (United Nations Framework Convention on Climate Change, 2019). The country's objective is to achieve a 15% reduction in overall emissions by 2030 through a sustainable energy transition. However, with limited guidance on how this can be achieved, very little has been done nationally to secure greater resource and energy efficiency aligned to reduced GHG emissions. Here, we examine the potential for multiple decision criteria, through environmental and economic assessments, to provide results-based evidence required to promote and guide increased sustainable operations of the national power generation sector. Consequently, our work seeks to also outline initiatives for both IPPs and national agencies to consider for the provision of affordable, reliable, sustainable and modern energy services by 2030 (United Nations, 2019).

2. Methodology

Here, we present our modelling framework and case-specific descriptions that align to the Trinidad and Tobago power sector. Our analysis considers current and future energy sources, taken from national projects and reports, that link directly to multiple decision criteria through techno-economics and environmental impact. For each case considered, mass and energy balances were derived from process design considerations and the impacts of resource and energy efficiencies were calculated and investigated.

2.1 Country-Level Power System Overview

Trinidad and Tobago, a twin-island industrialized developing nation within the Caribbean Region, is located at the southernmost area of the Leeward Islands (World Atlas, 2021). The country sits on a specific reserve of natural gas which drives its petrochemical and power sectors. Recently, viability for further exploration has been reduced due to a transition from shallow to deep water projects which accompany high risk (Offshore Energy, 2021; Oil and Gas Journal, 2021). As such, natural gas productivity has decreased rapidly, increasing concerns on the survival of its downstream operations. Thus, with the closure of several notable processes on the island (Energy Chamber, 2020), the total electrical energy demand for the country has subsequently reduced leading to capacity issues among the three IPPs that serve the power sector. This, coupled with low energy efficiencies of aging SC power generation systems (Inter-American Development Bank, 2015), take-or-pay contractual agreements (Energy Chamber of Trinidad and Tobago, 2018) and international climate change policies (United Nations Development Programme, 2018), have led state agencies to consider new pathways to drive greater resource efficiency while lowering net CO_2 emissions (Solaun et al., 2015).

Among the projects considered are RE grid utilization through solar and onshore wind (Lightsource bp, 2021), transitioning to CC technology with higher energy efficiencies (John-Lall, 2017) and the diversification of the power sector to promote a hydrogen economy (NewGen Energy Ltd, 2021), aiding in the further decarbonization of downstream sector operations- which contributes greatly to the country's national carbon footprint. Thus, our study seeks to investigate the environmental and economic sustainability of 20 cases (**Figure 1**) that align to the national agenda as follows:

1. Conventional gas-based cases comprising the business-as-usual (BAU) SC system and proposed CC technology.

2. RE penetration of up to 10% grid capacity using solar PV and onshore wind.
3. Power-to-X cases linked to the national petrochemical sector employing energy from both CC and RE technologies.

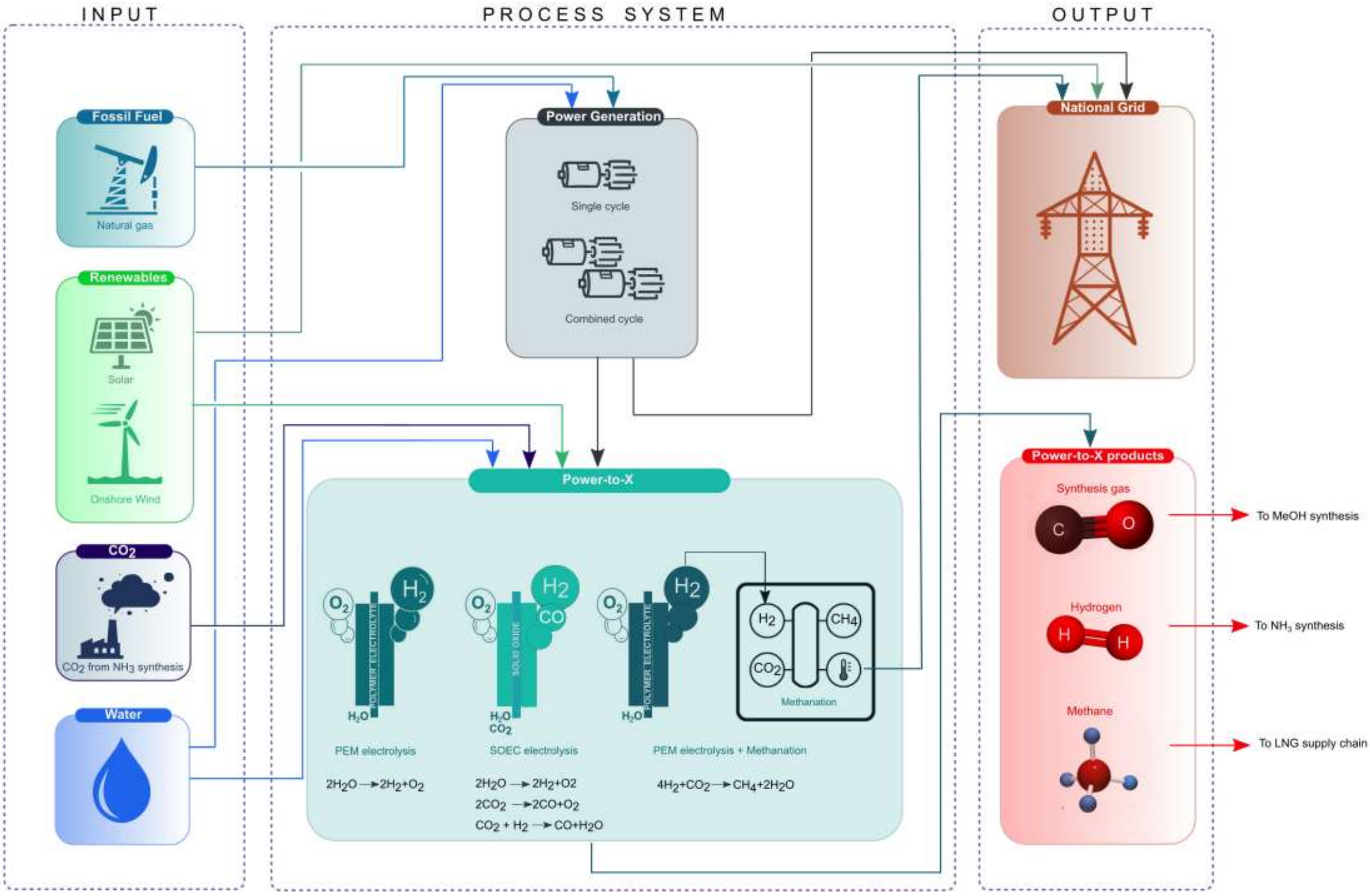


Figure 1: Case specific system boundary definitions for power generation considering conventional, RE and power-to-X process systems.

2.2 Case-specific Descriptions and Process Overviews

In this section, process overviews for each case are presented. **Table 1** gives case-specific net power utilization by both gas-based and RE technologies, in fulfilling the energy commitments for grid and power-to-X systems. Validation for each case was considered by utilizing data produced from literature within the wider context of Trinidad and Tobago operations. As such, conventional and RE process systems were modeled based on actual local process operations currently deployed (Inter-American Development Bank, 2015; Lightsource bp, 2020a). For power-to-X cases, models were derived based on current literature and designed using Aspen Plus together with the Peng Robinson fluid package while employing process conditions and reactivity which has been previously validated and reported. This fluid package is applicable to small compounds such as those examined in this study (Haydary, 2019; Davarnejad and Azizi, 2014).

2.2.1 Conventional gas-based systems-SC and CC technologies

One of the largest power plants on the island employs SC gas turbine technologies, with an installed capacity of 842MW and an average efficiency of 24.4% (Inter-American Development Bank, 2015). On the operation of the gas-based systems, we considered a (BAU) SC sub-system supporting the national grid with a net power output of 757.8 MW at a capacity factor of 90% (Spath and Mann, 2000). Furthermore, we also investigated the option of a CC system transition to meet the current grid support-whereby half the installed capacity of the current SC sub-system was decommissioned due to non-applicability of the current aging infrastructure to support CC technology (Inter-American Development Bank, 2015). Thus, the total energy efficiency improved to 50% in accordance with literature (Storm, 2013; International Petroleum Industry Environmental Conservation Association, 2013).

2.2.2 Renewable energy (RE) technologies

In alignment with national RE targets, we considered solar PV and onshore wind penetration onto the national grid. The total installed capacities and capacity factors for both solar PV and onshore wind RE systems were taken from literature aligned to national projects-approximately 112 MW/28.4% and 120MW /38% respectively (Lightsource bp, 2020a; Lightsource bp, 2020b).

2.2.3 Power-to-X technologies

Diversification of the power sector supply chains were linked to three main sectors: hydrogen generation (H_2) (International Renewable Energy Agency, 2020b; Cheddie, 2012) linked to ammonia production through polymer electrolyte membrane electrolysis (PEM), synthesis gas (Syngas) generation linked to methanol production through solid oxide electrolysis (SOEC) and synthetic natural gas (SNG) generation linked to LNG production through CO_2 methanation (Perna et al., 2020). For each system the total capacity of the electrolyser was fixed based on the total power produced from CC, governed by the assumptions given for the conventional gas-based systems. The CO_2 feedstock was assumed to be readily available from the ammonia process at the desired power-to-X process conditions and an operating year of 365 days was used. **Table 1** gives an overview of the power requirements for each sub-system while **Figure 2** illustrates the individual flowsheets for each process.

2.2.3.1 Power-to-H_2

Hydrogen production was facilitated by the electrolytic reduction of water (**Eq 1**) utilizing PEM electrolysis. Ideally, the system was designed according to literature (González-Garay et al., 2019), considering the enthalpy of water electrolysis (32.92 kWh/kgH_2) and an average electrolyser efficiency of 70.5%. The total hydrogen productivity was 194.77 tonne/day, with an oxygen by-product and water consumption rate of 1558.19 and 3505.93 tonne/day respectively.

$$H_2O \leftrightarrow 0.5O_2 + H_2 \qquad (1)$$

2.2.3.2 Power to Syngas

Syngas production flowsheet was designed using Aspen Plus V10, following the work done by (Todd Knighton et al., 2020; Fu et al., 2010). Syngas generation through the co-electrolytic reduction of water and CO_2 was carried out using SOEC at a system efficiency of 82% (International Renewable Energy Agency, 2020b). Fresh CO_2 and water were mixed with recycled syngas and water, and fed to the electrolyser with a molar composition (%) of $CO/CO_2/H_2O/H_2$ of 1.6/20.2/72.2/5.95 at 1.5 bar, preheated to 300^oC whereby the reverse water gas shift reaction (RWGS, **Eq 2**) occurs adiabatically-modelled as an equilibrium reaction. Mainly electricity and electrical heating are required to drive the reduction process at 800^oC and 1.5 bar. Ideally, heat recovery from hot syngas and O_2 products allow for a reduction in the total heat input required for feedstock preheating by the power plant, thus the total utility heat required was 29.26 MW. The circulation rate was set at 10% and the fractional conversion of water and CO_2 in **Eqs 1,3** (modelled as conversion reactions) were assumed to be 95 and 5% respectively. Lastly, the RWGS occurs once more at 800°C, increasing the CO concentration in the outlet syngas stream. The overall conversion of water and CO_2 are 94.2 and 74.5% respectively at a syngas productivity of 1093.37 tonne/day with a calculated R value (**Eq 4**) (Lu et al., 2020; Jaggai et al., 2020) of 2.03 -desirable for methanol synthesis (Lu et al., 2020; Holm-Larsen, 2001). The CO_2 and water consumption rates as well as oxygen productivity of the process were 1174.27, 1213.64 and 1294.54 tonne/day respectively.

$$CO_2 + H_2 \leftrightarrow CO + H_2O \quad (2)$$

$$CO_2 \leftrightarrow CO + 0.5O_2 \quad (3)$$

$$R = \frac{H_2 - CO_2}{CO + CO_2} \quad (4)$$

<u>2.2.3.2 Power to SNG</u>

SNG production was modelled as an ideal methanation reaction in Aspen Plus V10 according to literature (Zimmermann et al., 2019), using an equilibrium reactor with overall conversions >98%. Incoming CO_2 and H_2 were fed to the reactor at 5 bar and 120°C in a molar ratio of 1:4 in accordance with **Eq 5**. H_2 production was modelled using PEM electrolysis as previously stated (*<u>Section 2.2.3.1</u>*). The methanator was designed similarly to methanol conversion reactors based on the previous work by some of us (Narine et al., 2021; Mahabir et al., 2021a). The exothermic heat of reaction was used to produce medium pressure steam at 48 bars, which was utilized to produce power (15.96 MW) fed to the national grid as well as to preheat the feedstock to the reaction temperature of 230°C. The effluent water produced was separated at 40°C using cooling water, and recycled to the electrolyser as feedstock. The total SNG and O_2 production, and CO_2 and water consumption were 408.44, 1558.17, 1071.24 and 2648.31 tonne/day respectively.

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad (5)$$

Table 1: Case-specific overview of the total export power (MW) from both gas-based and RE technologies.

Net Power Export/ MW								
	Grid Power				**Electrolyser**			
Cases Description	**Gas-based**		**RE**		**RE**		**Gas-based**	**Total Grid**
Conventional	**SC**	**CC**	**Solar**	**Wind**	**Solar**	**Wind**	**CC**	
SC	757.8							
CC		757.8						
Conventional + Power-to-X								
H_2	378.9	378.9					378.9	
Syngas	378.9	378.9					378.9	
SNG	378.9	378.9					378.9	
Conventional + Renewables								
SC-Solar	725.99		31.81					
CC-Solar		725.99	31.81					757.8
SC-Wind	712.20			45.6				
CC-Wind		712.2		45.6				
SC-Hybrid	680.39		31.81	45.6				
CC-Hybrid		680.39	31.81	45.6				
Conventional + Power-to-X + Renewables								
CC-H_2-Solar	347.09	410.71			31.81		347.09	
CC-H_2 Wind	333.30	424.50				45.60	333.30	
CC-H_2-Hybrid	301.49	456.31			31.81	45.60	301.49	
CC-Syngas-Solar	347.09	410.71			31.81		347.09	
CC-Syngas-Wind	333.30	424.50				45.60	333.30	

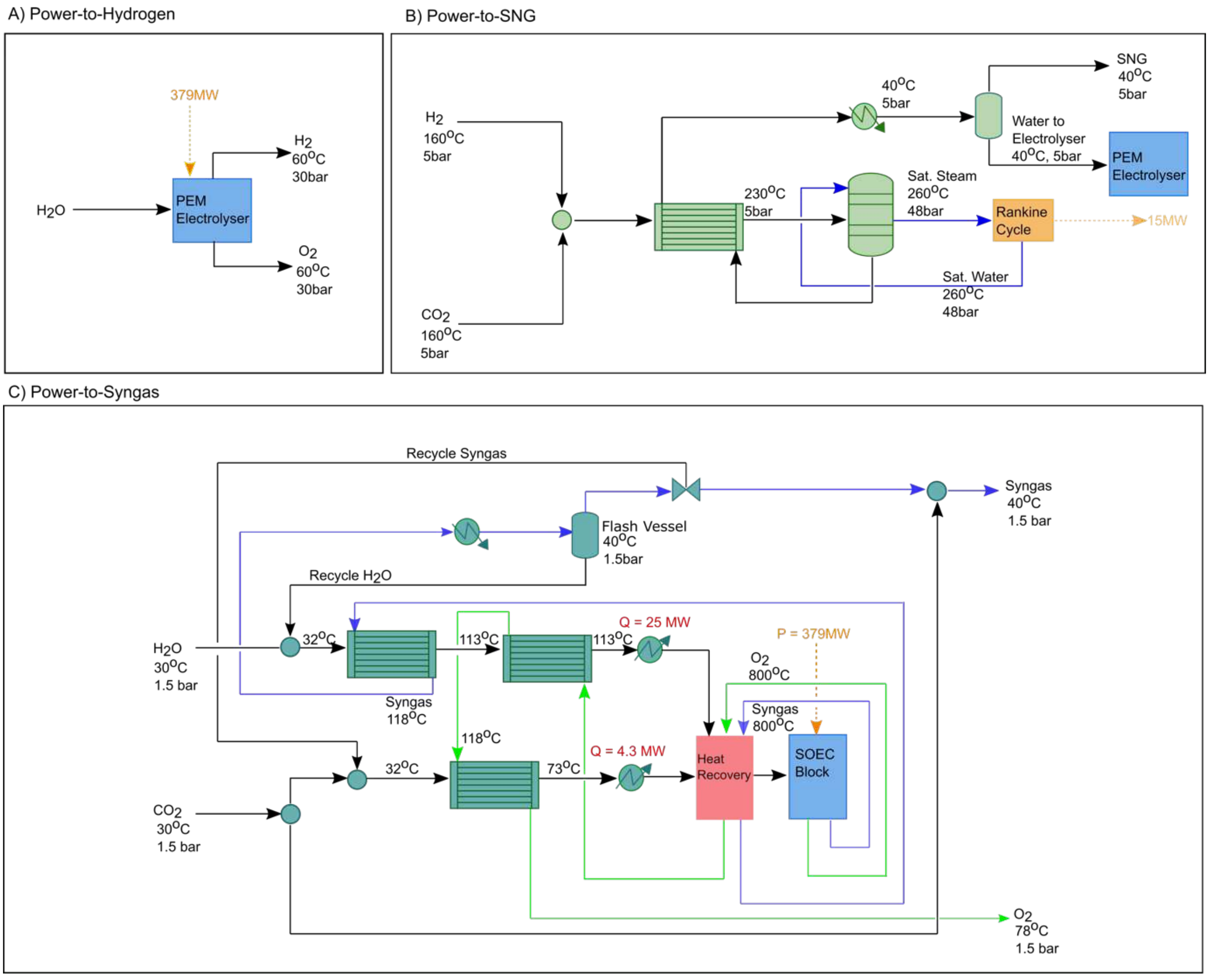


Figure 2: Individual power-to-X flowsheets for electrolytic H_2 (a), SNG (b) and Syngas production schemes (c).

2.3 Environmental Assessment

To guarantee sustainable operations of the Trinidad and Tobago power sector, a life cycle assessment (LCA) which governs the environmental impact of each case was investigated. A cradle-to-power generation gate was studied, following the ISO 14040:2006 methodology (International Organization for Standardization, 2016). The methodology outlines four stages of the LCA which include, goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA) and lastly interpretation. **Phase 1:** In the goal and scope definition phase, the main aim of the study is derived and considers the boundaries of the system under investigation in space and time. The goal of this study seeks to compare and assess the environmental performance of CC and hybrid energy systems over conventional SC processes in Trinidad and Tobago. **Figure 1**, details all given sub-systems within the system boundary for a given functional unit of 1MWh of grid energy produced. **Phase 2**: **Figure 1** also details set inputs and outputs for each sub-system. Case-specific mass and energy balances were compiled and used to derive life cycle inventories (LCI) normalized to a functional unit of 1 MWh of grid energy (**Table 2**). For all cases, inputs include: natural gas, process water, CO_2 and energy in the form of heat from CC and electricity supplied from RE linked to solar and wind. Environmental impacts consolidated through commissioning as well as fugitive emissions were neglected as these source emissions constitute negligible impacts as compared to supply chain and process-based burdens (Narine et al., 2021; Mahabir et al., 2021a). Environmental burdens embedded within inputs were retrieved from Ecoinvent v3.4 databases using the SimaPro LCA platform (**given in Supplementary information**). **Phase 3:** A midpoint approach, using the ReCIPe 2016 hierarchist method (Narine et al., 2020; Mahabir et al., 2021b), was considered in the LCIA stage to characterize environmental burdens across each case-specific system boundary. The hierarchist method was chosen based on scientific agreement and classifies burdens over a 100-year time horizon. For the power-to-X cases, a substitution allocation (Sandin et al., 2015; Liu et al., 2020) approach was used to distribute environmental burdens among co-products. **Phase 4:** Guided by the results generated from the LCIA, environmental benefits can be evaluated and interpreted to support decision-making which aligns to greater sustainable operations of the national power sector.

Table 2: Case-specific LCI normalized to 1MWh of grid energy production.

	Conventional					Solar					Wind					Hybrid				
Cases	SC	CC	CC-H2	CC-Syngas	CC-SNG	SC-Solar	CC-Solar	CC-H2-Solar	CC-Syngas-Solar	CC-SNG-Solar	SC-Wind	CC-Wind	CC-H2-Wind	CC-Syngas-Wind	CC-SNG-Wind	SC-Hybrid	CC-Hybrid	CC-H2-Hybrid	CC-Syngas-Hybrid	CC-SNG-Hybrid
Inputs																				
Natural gas [kg/MWh]	301.1	146.9	301.1	301.1	294.8	288.5	140.8	288.5	288.5	282.1	283.0	138.1	283.0	283.0	276.6	270.3	131.9	270.3	270.3	264.0
Process Water [kg/MWh]	-	15.1	207.9	81.8	160.4	-	14.5	207.2	81.2	159.8	-	14.2	207.0	80.9	159.5	-	13.6	206.3	80.3	158.9
CO2 [kg/MWh]	-	-	-	64.6	58.9	-	-	-	64.6	58.9	-	-	-	64.6	58.9	-	-	-	64.6	58.9
Solar [MWh]	-	-	-	-	-	0.04	0.04	0.04	0.04	0.04	-	-	-	-	-	0.04	0.04	0.04	0.04	0.04
Wind [MWh]	-	-	-	-	-	-	-	-	-	-	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Cooling load (MJ/MWh)	-	3142.2	3142.2	3202.2	3360.5	-	3010.4	3010.4	3070.3	3228.6	-	2953.2	2953.2	3013.2	3171.4	-	2821.3	2821.3	2881.3	3039.5
Heating Load (MJ/MWh)	-	-	-	139.0	-	-	-	-	139.0	-	-	-	-	139.0	-	-	-	-	139.0	-
Outputs																				

Grid Power (MWh)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Electrolyzer Power (MWh)	-	-	0.5	0.5	0.5	-	-	0.5	0.5	0.5	-	-	0.5	0.5	0.5	-	-	0.5	0.5	0.5
Syngas (kg/MWh)	-	-	-	60.1	-	-	-	-	60.1	-	-	-	-	60.1	-	-	-	-	60.1	-
H_2 (kg/MWh)	-	-	10.7	-	-	-	-	10.7	-	-	-	-	10.7	-	-	-	-	10.7	-	-
SNG (kg/MWh)	-	-	-	-	22.5	-	-	-	-	22.5	-	-	-	-	22.5	-	-	-	-	22.5
O_2 (kg/MWh)	-	-	85.7	71.2	85.7	-	-	85.7	71.2	85.7	-	-	85.7	71.2	85.7	-	-	85.7	71.2	85.7
CO_2 Emissions (kg/MWh)	743.8	363.0	743.8	750.9	728.2	712.6	347.8	712.6	719.6	697.0	699.1	341.2	699.1	706.1	683.4	667.9	325.9	667.9	674.9	652.2
N_2O Emissions (kg/MWh)	0.019	0.023	0.048	0.048	0.047	0.018	0.022	0.046	0.046	0.045	0.018	0.022	0.045	0.045	0.044	0.017	0.021	0.043	0.043	0.042
SO_2 Emissions (kg/MWh)	-	0.003	0.006	0.006	0.006	-	0.003	0.006	0.006	0.006	-	0.003	0.006	0.006	0.006	-	0.003	0.006	0.006	0.006

2.4 Economic Assessment

The economic performance of each sub-system was evaluated by calculating the Minimum Selling Price (MSP) of electricity. Furthermore, we also considered the economic feasibility of each project by calculating the electricity selling price (SP_{IRR}) which guarantees an IRR of 15% (Spath and Mann, 2000). In estimating the capital investment (CAPEX), a Class III costing approach was conducted due to the absence of detailed engineering quotations. Thus, costing methodologies- fully defined and used in past techno-economic assessments (Michailos et al., 2017; Rodríguez-Vallejo et al., 2021), such as bare module costs (Turton et al., 2018), lang factor and power factor (Sinnott, 2005) approaches were utilized in deriving CAPEX costs. In producing annual cash flows, region specific indicators aligned to Trinidad and Tobago were utilized while operating costs (OPEX) linked to raw materials, utilities and labor were assumed in accordance with market analysis and available costing data - given in **Table 3**. A detailed overview of the calculations used in estimating CAPEX and OPEX costs are given in **Supplementary Information**.

Table 3: Region-specific economic parameters, raw material, utilities and product costs.

Parameter (Unit)	Value
Working Capital (% of FCI)	15%
Plant Life (years)	20
Depreciation Method	Straight-line
Income Tax Rate	25%
Cost year for analysis	2020
Salvage Value	0
% spent in year 0	100%
Nominal Discount Rate[a]	6.76%
Operating hours (h/year)	8760
Natural Gas ($\$_{USD}$/MMBtu) (Henry Hub, 2021)	3.26
Process Water ($\$_{USD}$/kg) (Public Utilities Commission of Trinidad and Tobago, 2008)	1.52

CO_2 ($\$_{USD}$/kg) (Rodríguez-Vallejo et al., 2021)	10
Solar Electricity ($\$_{USD}$/MW) (Ray, 2020)	36.5
Wind Electricity ($\$_{USD}$/MW) (Ray, 2020)	40
Cooling Load ($USD/MJ) (Turton et al., 2018)	0.38
Heating Load ($\$_{USD}$/MMBtu) (Henry Hub, 2021)	3.26
Syngas ($\$_{USD}$/kg) (Nakyai et al., 2019)	0.8
Hydrogen ($\$_{USD}$/kg) (International Energy Agency, 2018)	1
SNG ($\$_{USD}$/MMBtu) (Henry Hub, 2021)	3.26
Oxygen ($\$_{USD}$/kg) (Zhang et al., 2020)	0.18

[a] where d_r is the real discount rate = 5.50 (Central Bank, 2021) and e is the inflation rate = 1.04 (Statista, 2021)

2.5 Data Analysis

To fully understand the potential of CC and hybrid power systems in leading the sustainable energy transition in Trinidad and Tobago, multiple decision criteria were used considering set KPIs defined from various attributes within the methodologies presented. Firstly, for each process system investigated, energy indicators such as fossil fuel and energy utilization was assessed through mass and energy balances supported by Aspen Plus simulations. Secondly, these mass and energy balances were further utilized in deriving set input and output flows which align to environmental burdens as well as raw material and utility flows linking to economic costs. Finally, from these KPIs, each sub-system was analysed and compared -with the goal to maximize resource and energy efficiency while minimizing electricity cost and environmental impact.

3. Results and Discussion

An overview of our results is discussed here across four main sections: Process Efficiency and Environmental Performance, LCIA, Economic Performance and Policy Agenda and Future Directions. Case-specific inventories were defined and correlated from mass and energy balances and aligned to each section through thermodynamics, environmental burden classification and lastly, CAPEX and OPEX estimations. By comparing key performance indicators (KPIs) and utilizing multiple decision criteria, a systems approach was used to identify the most sustainable scenarios for the Trinidad and Tobago power sector. Detailed cost contributions and selling prices are given in **Supplementary Information**.

3.1 Process Efficiency and Environmental Performance

Figure 3A gives the process performance of each case considering various technologies stemming from conventional-gas based to RE and hybrid energy systems. The performance of each system was highlighted by estimating two KPIs (Mahabir et al., 2021b) - energy efficiency and gas utilization, given by **Eqs 6-7**:

$$\eta_{energy} = \frac{\sum_i^n \; m_{p,i} . NHV_{p,i} + P_{Grid}}{\sum_i^n \; m_{r,i} . \; NHV_{r,i} + P_{RE}} \tag{6}$$

$$\eta_{gas} = \frac{m_{CH4} . NHV_{CH4}}{P_{Grid}} \tag{7}$$

Where: $m_{r,p,CH4}$ is the mass flow (kg/s) of raw materials, products and natural gas, P_{RE} is the RE input power (MW), $NHV_{r,p,CH4}$ is the net heating value (MJ/kg) of raw materials, products and natural gas, and P_{grid} is the power output to the national electricity grid.

Energy efficiency deduces effective energy conversion from inputs to outputs over a given process while the gas efficiency gives an overview on efficient fossil-fuel utilization for electrical power production.

Our results illustrate a gradual shift towards greater energy and gas efficiency through the utilization of CC and Power-to-X over SC technologies. Considering firstly, conventional BAU systems, SC gas turbines run at an average energy efficiency of 24% -much lower than typical SC systems which have efficiency ratings up to 36% (Bauen, 2004)- owing to aged machinery that is currently being used locally. The inefficiencies of local IPPs to improve these systems link directly to power purchase agreements with state agencies, whereby ancient take-or-pay contracts are maintained (Lassourd, 2019). This in turn reduces the need to consider greater energy utilization, thus promoting wastage at high gas utilization upwards of 14 GJ/MWh. Through the decommissioning of half of the total installed SC capacity, CC technologies can produce the same net grid power while using half the natural gas- boasting 50% energy efficiency and reducing gas utilization to 7.2 GJ/MWh.

With the diversification of the power sector, production of downstream commodities through electrification via electrolysis was considered. This resulted in an observed reduction in energy efficiency and increase in gas utilization from CC technology owing to low energy efficiencies associated with electrolysis brought about by ionic losses during the conversion of chemical energy to electrical energy. Among the various power-to-X cases, H_2 and SNG production showed similar performance in energy efficiency, ranging from 45-49% while syngas generation gave marginally lower efficiencies, 44-47% when compared to that of CC (50-53%). Gas utilisation increased to 9.8 GJ/MWh with H_2 production, however with solar and wind energy implementation, a reduction to 9.4-9.2 GJ/MWh was achieved. Generally, both KPIs are improved with the incorporation of RE through a hybrid system-with gas utilization improving for both CC and power-to-X systems up to 52.7%/6.47GJ/MWh and 49.1%/8.8GJ/MWh respectively.

The environmental performance of each case is given in **Figure 3B**, highlighting case specific life cycle GHG intensities and annual GHG emission quotas. These results support our overall process performance, whereby SC systems give the highest CO_2 intensity and annual CO_2 emission quotas of 971kgCO_2-eq/MWh and 6.45 million tonne CO_2-eq/year. By transitioning to CC technologies, a 50% reduction in life cycle emissions can be realized-with a reduced CO_2 intensity and annual emission quota of 478 kgCO_2-eq/MWh and 3.17×10^6 tonne CO_2-eq/year. These results align well with previous work done on CC technologies (Spath and Mann, 2000). Furthermore, this reduction in life cycle GHG emissions directly aligns with Trinidad and Tobago's national commitments to the Paris Agreement-which outlines a 15% reduction in GHG emissions across the power, industrial and transport sectors (Under The United Nations Framework Convention On Climate Change, 2014). Also, our results illustrate the importance of renewables in promoting this reduction, with current RE penetration giving up to 55.4% reduction in GHG grid intensity and annual GHG emissions through hybridization. Although chemical electrification does provide some environmental benefits through avoided emissions, reductions (ranging from 16.5-31.9%) are much lower when compared to CC technologies.

Comparing the GHG performance of power-to-X cases, H_2 production gives the highest avoided emissions of 127.93kgCO_2-eq/MWh while syngas and SNG generation gives 30.88 and 16.54kgCO_2-eq/MWh respectively. Although the utilization of CO_2 from ammonia for both SNG and syngas manufacture avoids between 55.96 and 61.34 kgCO_2-eq/MWh, the productivity of both process systems as well as the energy penalties of SOEC outweighs the consolidated environmental benefits. Therefore, to achieve cleaner electrical energy generation hybridization of CC and RE technologies are needed, and the intervention of new power sector policies to promote this transition must be prioritized with utmost importance.

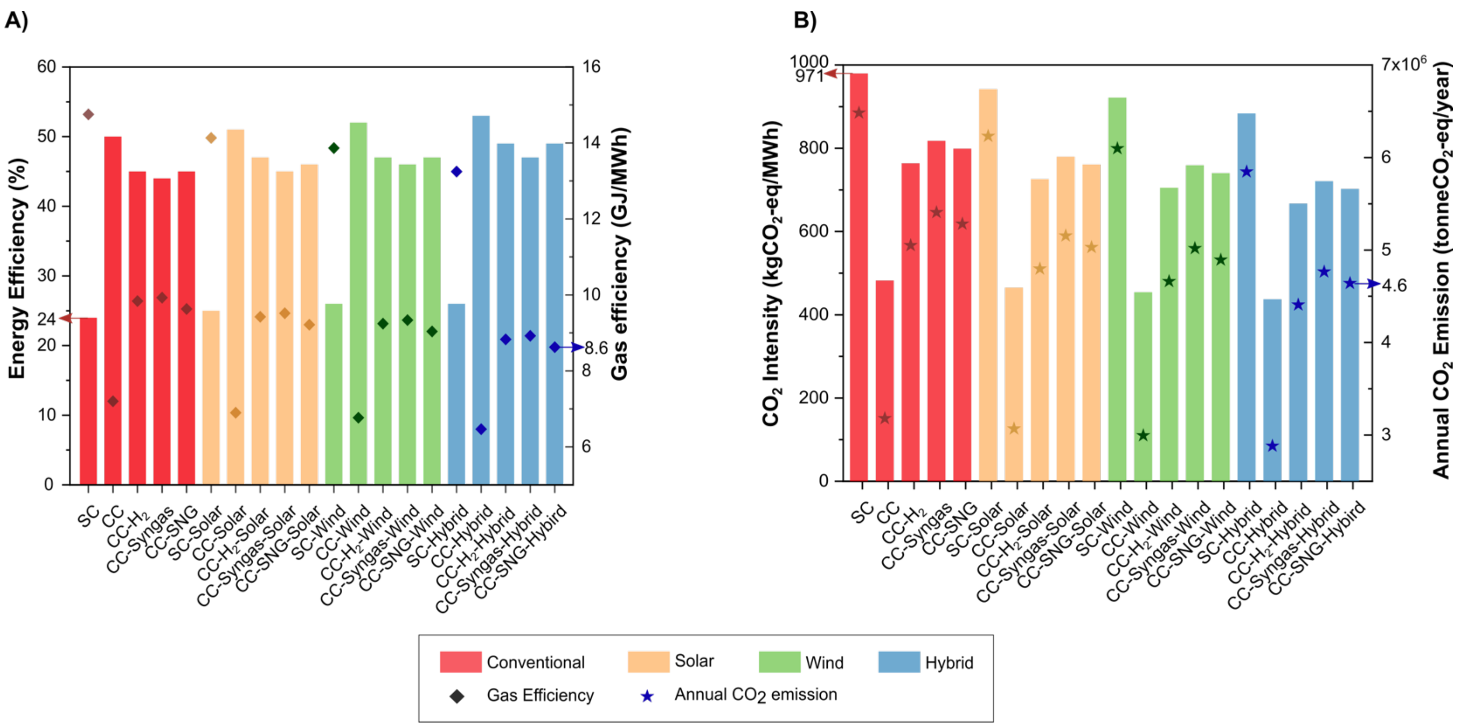


Figure 3: A) Overall model energy and gas efficiency profiles; B) Case-specific CO_2 intensity and annual GHG emission quotas.

3.2 LCIA

Here we report on case-specific environmental burdens across 17 impact categories, illustrated in **Figures 4 & 5**. The environmental impact associated with land system change was neglected due to the absence of biomass related feedstocks and processes within the process systems investigated. For the conventional-gas based cases (**Figure 4**), our results illustrate dominance associated with natural gas utilization across the majority of impact categories- with contributions >99% being observed. These environmental burdens were mainly attributed to fossil fuel extraction and depletion as well as combustion for combined heat and power. As such the release of toxic and precious metals such as Hg, Ni and V as well as GHGs-CO_2, CH_4 and N_2O, were emitted from the natural gas extraction and distribution processes. However, for global warming (GWP) and ozone depletion (ODP), process emissions such as CO_2 and SO_2 account for contributions between 62-81% respectively across cases. Comparing SC to CC technologies, our results showcase significant reductions (approximately 51%) in environmental burdens, and thus, illustrates the potential environmental benefits through increased resource and energy efficiency.

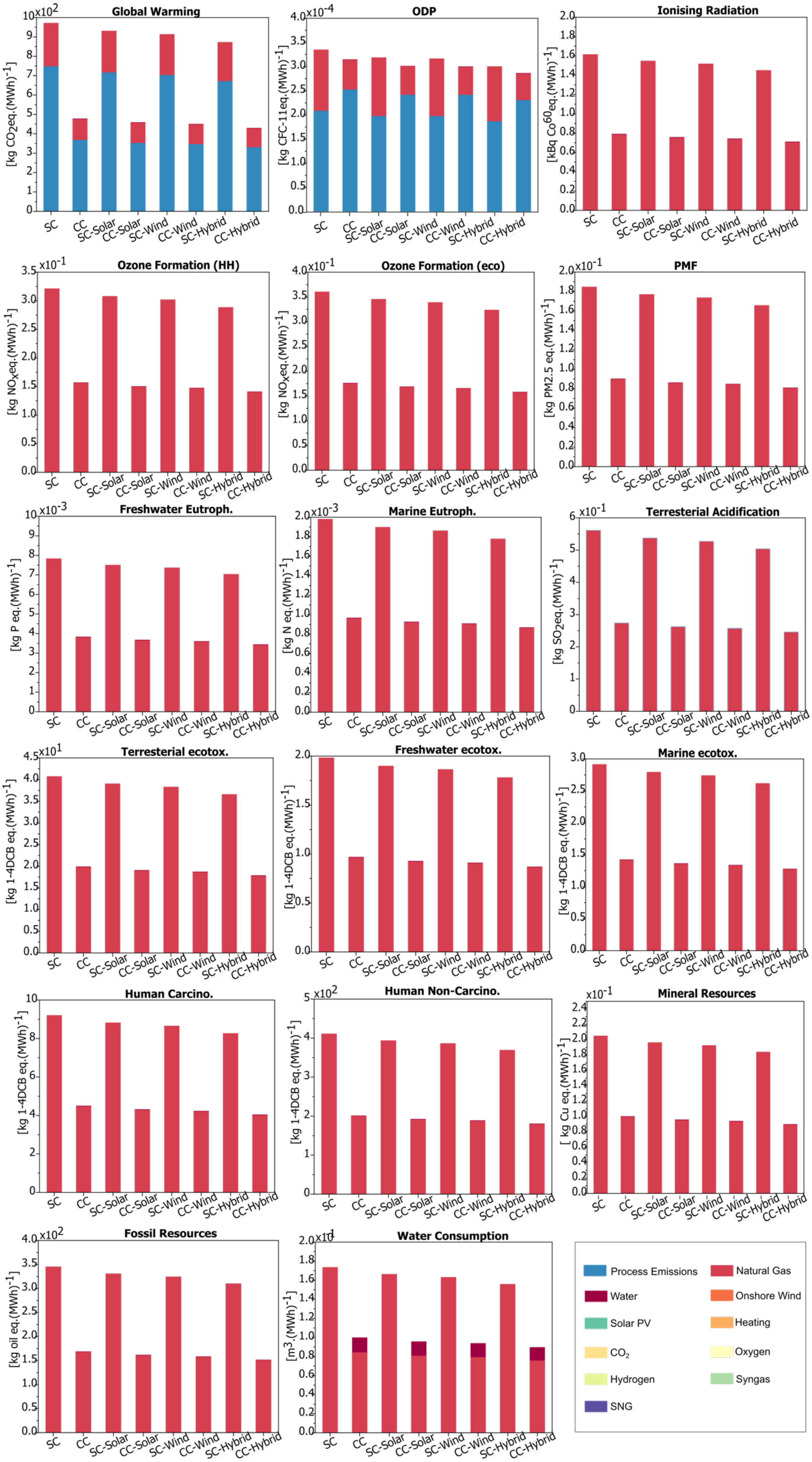

Global Warming
ODP
Ionising Radiation
Ozone Formation (HH)
Ozone Formation (eco)
PMF
Freshwater Eutroph.
Marine Eutroph.
Terresterial Acidification
Terresterial ecotox.
Freshwater ecotox.
Marine ecotox.
Human Carcino.
Human Non-Carcino.
Mineral Resources
Fossil Resources
Water Consumption
SC
CC
SC-Solar
CC-Solar
SC-Wind
CC-Wind
SC-Hybrid
CC-Hybrid
Process Emissions
Natural Gas
Water
Onshore Wind
Solar PV
Heating
CO₂
Oxygen
Hydrogen
Syngas
SNG

Figure 4: Characterized LCIA results for conventional-gas based power generation across 17 midpoint impact categories using the ReCiPe 2006 (H) methodology.

Similar burden comparisons were observed comparing conventional and power-to-X cases (**Figure 5**) for natural gas, solar and wind input flows. Among cases, natural gas dominates across terrestrial acidification (99%), human carcinogenic toxicity (77 - 98%), mineral resources (71 - 99%) and fossil resources (99%). Other similarities observed were for GWP and ODP, where process emissions accounted for the largest contributions (71-81%). However, CO_2 utilization from the ammonia process avoids up to 7% of the current total emissions. Solar environmental burden contributions were largely associated with terrestrial ecotoxicities (60%) and mineral resources (17%) due to the utilization of precious metals for the construction of the solar panels. Wind also contributes significantly towards freshwater ecotoxicity (22%), marine ecotoxicity (19%) and human carcinogenic toxicity (15%). The overall burden increases from solar (0.2 - 61%) and wind (0.1 - 22%) to the hybrid cases (0.3 - 65%) where both RE resources are consolidated, while burdens associated with heating load within syngas cases as well as water consumption contributed approximately 0.2% - 0.8% and 0.1- 54% respectively across impact categories.

The production of environmentally friendly by-products through electrification gives rise to significant avoided burdens within power-to-X cases (**Figure 5**). Among impact categories, the largest environmental benefits were observed across ionising radiation, freshwater eutrophication, marine eutrophication, human non-carcinogenic toxicity and water consumption-where > 100% reduction of environmental impact was observed. Avoided cryogenic oxygen production gave the largest avoided burdens across impact categories (8 – 100%), followed by avoided H_2 (6 – 14%) and syngas (3 – 9%) production from steam methane reforming and avoided natural gas extraction through the production of SNG (1.5-8%).

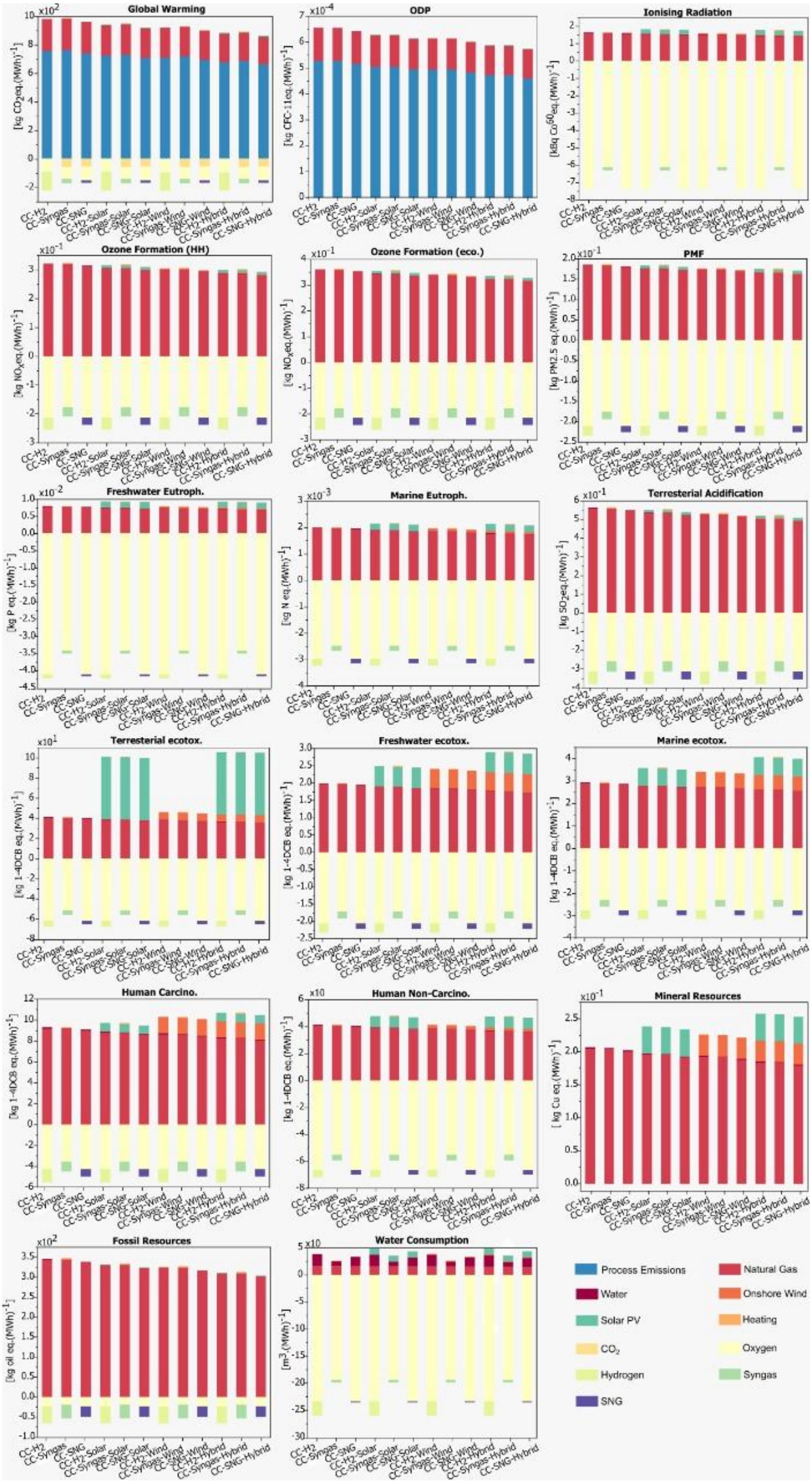

Global Warming
ODP
Ionising Radiation
Ozone Formation (HH)
Ozone Formation (eco.)
PMF
Freshwater Eutroph.
Marine Eutroph.
Terresterial Acidification
Terresterial ecotox.
Freshwater ecotox.
Marine ecotox.
Human Carcino.
Human Non-Carcino.
Mineral Resources
Fossil Resources
Water Consumption
CC-H2
CC-Syngas
CC-SNG
CC-H2-Solar
CC-Syngas-Solar
CC-SNG-Solar
CC-H2-Wind
CC-Syngas-Wind
CC-SNG-Wind
CC-H2-Hybrid
CC-Syngas-Hybrid
CC-SNG-Hybrid
Process Emissions
Natural Gas
Water
Onshore Wind
Solar PV
Heating
CO2
Oxygen
Hydrogen
Syngas
SNG

Figure 5: Characterized LCIA results for power-to-X cases across 17 midpoint impact categories using the ReCiPe 2006 (H) methodology.

3.3 Economic Performance

The economic feasibility of each case is assessed in this section as a function of MSP and SP_{IRR} as well as product prices. Furthermore, insights into the CAPEX and OPEX cost contributions associated with each project are also given. Lastly, a sensitivity analysis was studied to examine the potential implications of raw material and capital expenditure on financial competitiveness.

3.3.1 Influence of MSP and SP_{IRR} on Feasibility

Figure 6 illustrates the MSP and SP_{IRR} of electricity for each case as well as the product prices associated with power-to-X cases. For conventional gas-based systems (**Figure 6A**), a marked increase in SP_{IRR} from $\$_{USD}$62.60/MWh to $\$_{USD}$69.10/MWh (10.4% increase) was observed for CC technologies over SC, owing to the higher installed equipment costs associated with combined cycle power generation. These prices fall within the range of average global levelized costs of electricity (LCOE) derived from natural gas ($\$_{USD}$45-74/MWh) (Levelized Cost of Energy et al., 2021), but are still higher than local electricity prices due to domestic energy subsidies and low natural gas price (National Renewable Energy Laboratory, 2015). Additionally, RE penetration supports lower SP_{IRR}, with SC-Hybrid scenarios giving the lowest selling price among conventional cases; $\$_{USD}$60.82/MWh (a 2.8% decrease). The SP_{IRR} for each CC-RE scenario was found to be approximately 11.2% higher than its respective SC-RE cases while the MSP was marginally lower for CC scenarios, ranging from $\$_{USD}$54.85/MWh to $\$_{USD}$55.13/MWh across cases. For CC-RE cases (solar and wind), the MSP was found to be 34% and 10% higher than the global LCOE from solar ($\$_{USD}$41/MWh) and wind energy ($\$_{USD}$50/MWh) respectively(Levelized Cost of Energy et al., 2021). However, with increased RE penetration the MSP becomes more competitive with global prices. Although SC cases were marginally more competitive than CC, its lower MSP gives a higher margin for government subsidies to maintain affordable power for the national community.

Figure 6B-D gives the selling prices for the power-to-X cases utilizing CC and RE, with and without subsidization. In considering a desirable SP_{IRR} for power-to-X cases, we acknowledged the CC technology as the main incurred expenditure in providing electrical power. Thus, an upper limit on SP_{IRR} was maintained at that of the CC conventional case- $\$_{USD}$69.10/MWh. As such, in the unsubsidized cases, the product prices for each power-to-X case was estimated as a function of this maximum SP_{IRR}. Our results show a major increase in product prices when compared to current BAU costs. For H_2, unsubsidised prices were over 250% higher than the subsidised price ($\$_{USD}$1.00/kg). Future projection based on expected learning rates for green hydrogen production done by IRENA (International Renewable Energy Agency, 2021) indicates a future average green hydrogen price of $\$_{USD}$1.00/kg by 2030 - making unsubsidised H_2 production uncompetitive.

Without subsidy, syngas and SNG prices increased by 80% (from $\$_{USD}$0.80/kg) and >1000% (from $\$_{USD}$3.26/kg) respectively with "green" syngas and SNG prices standing at $\$_{USD}$0.86/kg (Fu et al., 2010) and $\$_{USD}$19.40-28.60/MMBtu (Becker et al.,2018) - illustrating the infeasibility of commodity sales for local downstream industries. Nevertheless, unsubsidized commodity prices decrease in favour of increased RE penetration- with reductions ranging from 8.7% ($\$_{USD}$3.78-3.45/kg) for H_2, 2.7% ($\$_{USD}$1.50-1.46/kg) for syngas and 7.7% ($\$_{USD}$ 40.83-37.70/MMBtu) for SNG.

Additionally, the effect of government subsidies to offset associated high product costs were considered. Here, product prices were maintained at current BAU prices while effects on the MSP and SP_{IRR} were investigated. For all cases, the MSP and SP_{IRR} increased by 60.3-191.3% and 38.0-61.1% respectively. In some cases, the MSP surpassed that of the SP_{IRR} for current power generation (SC cases)- illustrating that there is little to no margin for government subsidies to aid in affordable power consumption without significant national debt. Thus, to promote feasibility within power-to-X cases, carbon taxes and other forms of externalities will need to be considered at largely unrealistic values (González-Garay et al., 2019) to encourage the incorporation of electrolytic H_2, syngas and SNG within the current downstream petrochemical sector. Given that these policies do not yet exist and there are no laws on imposing such in the future, it is clear that power-to-X cases will need to re-evaluated as a proposed pathway for decarbonization efforts. Ultimately, a CC transition coupled with RE penetration gives the greatest advantage, both economically and environmentally, in securing affordable and clean energy through increased energy and resource efficiency.

3.3.2 OPEX AND CAPEX Contributions

Figure 7A-B gives case specific CAPEX and OPEX contributions respectively. Considering CAPEX costs, the highest ($\$_{USD}$ 3053 MM) was determined for the CC-syngas case where the electrolyser contributed the most (62.5%) to the total capital expenditure- while the power plant contributed 37.3% whereas the syngas contribution was negligible (<1%). Conversely, for the CC-SNG case- with a CAPEX of $\$_{USD}$ 1733 MM, the power plant gave the greatest contribution (65.6%), while the electrolyser contributed to 32.1% and the SNG plant contribution was negligible (<1%). The CAPEX for the CC-H_2 case amounted to $\$_{USD}$ 1694 MM and was attributed mainly to the power plant (67.1%) and the electrolyser (32.9%). For both the SC and CC cases, significantly lower CAPEX ($\$_{USD}$ 359 MM & $\$_{USD}$ 892 MM respectively) were found- with the power plant as the sole contributor.

Upon analysis of OPEX contributions, natural gas dominated as the largest contributor (51-91%) followed by fixed costs (8-39%) while the cumulative contributions of process water and carbon dioxide were marginal (< 2%). The highest wind and solar electricity contributions were 6.2% and 4% for the CC-wind and CC-solar cases respectively. Also, specifically for the various syngas cases, there was a negligible (<1%) heating load. Generally, both the conventional and power-to-X systems showed similar fixed cost contributions (27-40%) with significantly lower contributions (8-9.5%) to the operating expenses observed for SC systems over all other cases.

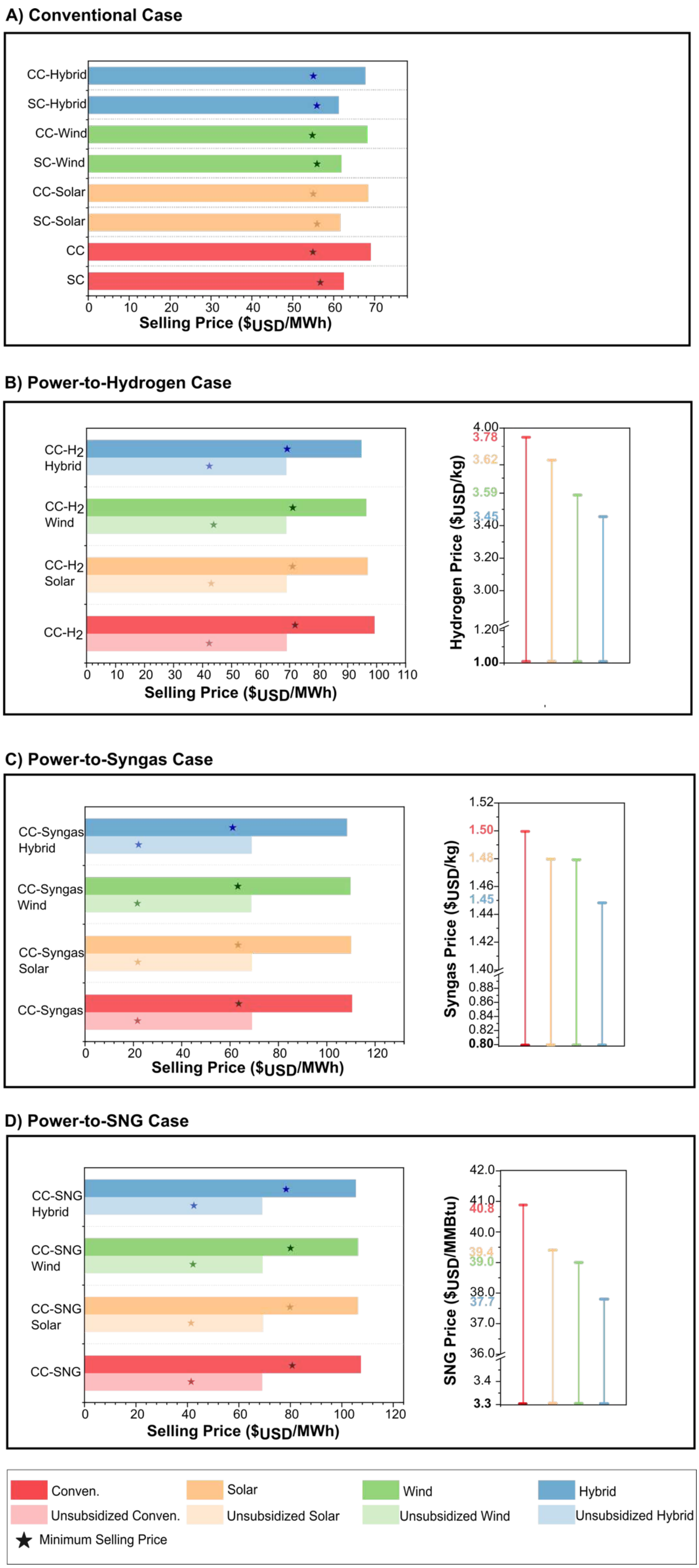

A) Conventional Case
CC-Hybrid
SC-Hybrid
CC-Wind
SC-Wind
CC-Solar
SC-Solar
CC
SC
0 10 20 30 40 50 60 70
Selling Price ($USD/MWh)
B) Power-to-Hydrogen Case
CC-H2 Hybrid
CC-H2 Wind
CC-H2 Solar
CC-H2
0 10 20 30 40 50 60 70 80 90 100 110
Selling Price ($USD/MWh)
Hydrogen Price ($USD/kg)
4.00
3.78
3.62
3.59
3.45
3.40
3.20
3.00
1.20
1.00
C) Power-to-Syngas Case
CC-Syngas Hybrid
CC-Syngas Wind
CC-Syngas Solar
CC-Syngas
0 20 40 60 80 100 120
Selling Price ($USD/MWh)
Syngas Price ($USD/kg)
1.52
1.50
1.48
1.46
1.45
1.44
1.42
1.40
0.88
0.86
0.84
0.82
0.80
D) Power-to-SNG Case
CC-SNG Hybrid
CC-SNG Wind
CC-SNG Solar
CC-SNG
0 20 40 60 80 100 120
Selling Price ($USD/MWh)
SNG Price ($USD/MMBtu)
42.0
41.0
40.8
40.0
39.4
39.0
38.0
37.7
37.0
36.0
3.4
3.3
Conven.
Solar
Wind
Hybrid
Unsubsidized Conven.
Unsubsidized Solar
Unsubsidized Wind
Unsubsidized Hybrid
Minimum Selling Price

Figure 6: Scenario specific economic indicators MSP and SP_{IRR} for A) Conventional; B) H_2; C) Syngas; D) SNG cases-with unsubsidized power-to-X product prices.

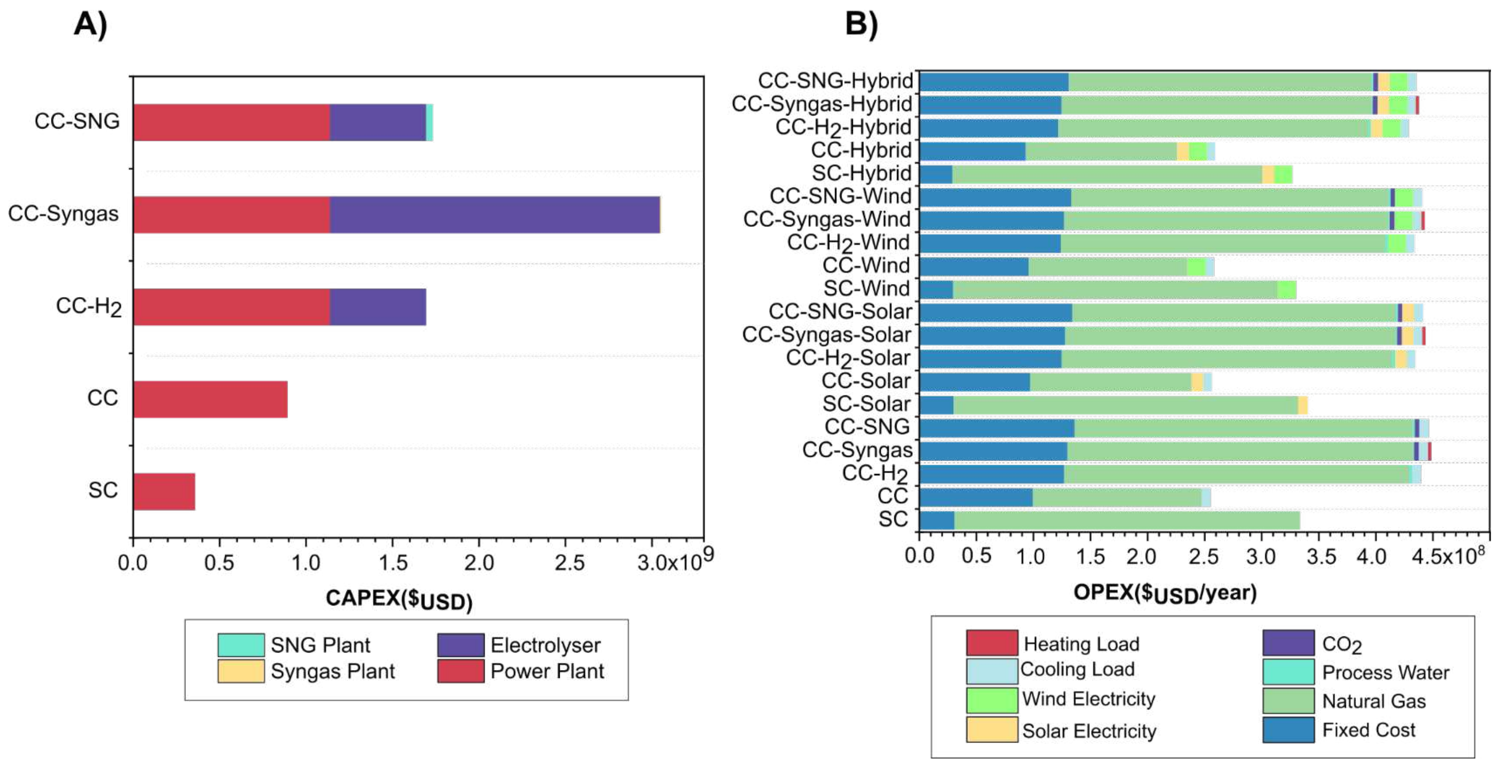
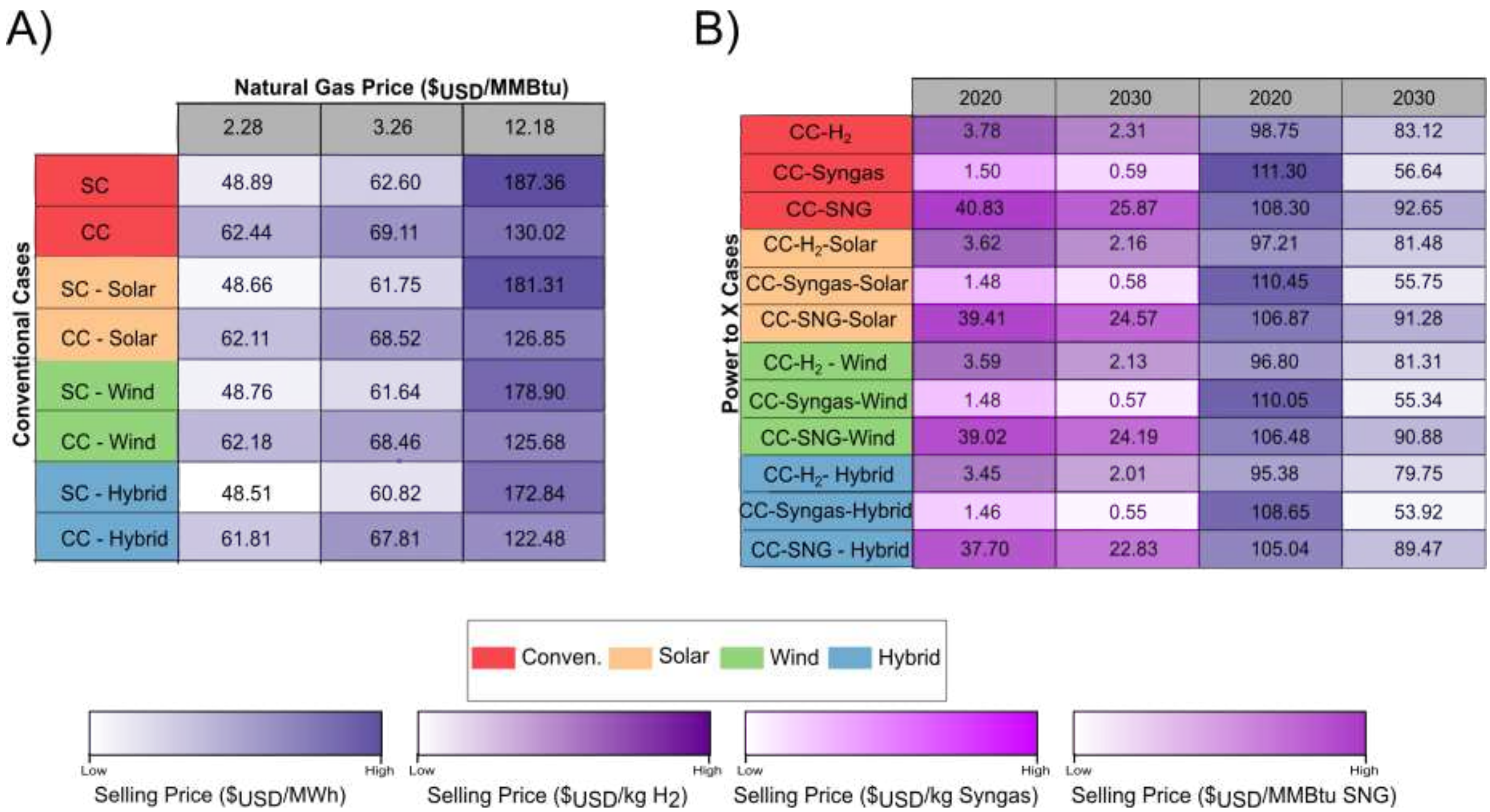


Figure 7: Case specific CAPEX (A) and OPEX (B) contributions.

3.3.3 Sensitivity Analysis

A sensitivity analysis was performed to judge the future financial competitiveness of each case. Firstly, for the conventional SC and CC cases, the cost of natural gas was varied considering a low, current and high Henry hub price range (Henry Hub, 2021) (**Figure 8A**). For the conventional SC system at a natural gas price of 2.28 $\$_{USD}$/MMBtu, the SP_{IRR} of electricity (approximately 49 $\$_{USD}$/MWh), directly aligns to the current average electricity price in Trinidad and Tobago (National Renewable Energy Laboratory, 2015). This directly supports literature on government natural gas subsidies for power generation (Ministry of Energy and Energy Industries, 2021a). Generally, SC systems were the more competitive technology only when natural gas prices were low. However, as local natural gas reserves decrease, future SP_{IRR} will most likely be linked directly to the global natural gas market- increasing SC electricity prices by as much as 283%. Nevertheless, with a hybrid CC-RE transition, higher-end electricity prices can reduce by as much as 98%.

Shifting attention to power-to-X cases (**Figure 8B**), sensitivities were mainly carried out on future (2030) electrolyser costs and stack lifetime. CAPEX for electrolysers is mainly dependent on stack costs. Given that learning rates for electrolyser and membrane technologies are expected to increase by 11-12% by 2030 along with developments in catalyst technology, CAPEX for PEM and alkaline technologies are expected to decrease. Furthermore, stack lifetime is expected to increase to 110,000 hours (120% increase) and 80,000 hours (300% increase) for PEM and SOEC systems respectively. As a result, CAPEX for both systems are likely to reduce to 200 and 300 $\$_{USD}$/kWh respectively by 2030 (International Renewable Energy Agency, 2020b). Taking these costs into consideration, our results illustrate a reduction in unsubsidized product costs in 2030- with H2 prices decreasing by 42% from 3.78 to 2.01 $\$_{USD}$/kg; syngas by 63% from 1.50 to 0.55 $\$_{USD}$/kg and SNG by 40% from 40.83 to 22.83 $\$_{USD}$/MMBtu. These reductions align with global metrics for commodity prices as the projected unsubsidized cost of H_2 lies between 1.40 - 2.30 $\$_{USD}$/kg (Hydrogen Council, 2021). For subsidized products, assuming little to no change in BAU prices, SP_{IRR} decreases by 14.4-50.3% across all cases from 111.30 to 53.92 $\$_{USD}$/MWh. As overall annualized costs for electrolysis in the future reduces, greater economic viability is expected- with future power-to-X markets aligning closer to BAU operations. Nevertheless, only syngas emerges as a future viable power-to-X system due to its economic competitiveness (SP_{IRR} <BAU price) compared to all other commodities.


A)

Conventional Cases	Natural Gas Price ($USD/MMBtu) 2.28	3.26	12.18
SC	48.89	62.60	187.36
CC	62.44	69.11	130.02
SC - Solar	48.66	61.75	181.31
CC - Solar	62.11	68.52	126.85
SC - Wind	48.76	61.64	178.90
CC - Wind	62.18	68.46	125.68
SC - Hybrid	48.51	60.82	172.84
CC - Hybrid	61.81	67.81	122.48

B)

Power to X Cases	2020	2030	2020	2030
CC-H_2	3.78	2.31	98.75	83.12
CC-Syngas	1.50	0.59	111.30	56.64
CC-SNG	40.83	25.87	108.30	92.65
CC-H_2-Solar	3.62	2.16	97.21	81.48
CC-Syngas-Solar	1.48	0.58	110.45	55.75
CC-SNG-Solar	39.41	24.57	106.87	91.28
CC-H_2 - Wind	3.59	2.13	96.80	81.31
CC-Syngas-Wind	1.48	0.57	110.05	55.34
CC-SNG-Wind	39.02	24.19	106.48	90.88
CC-H_2- Hybrid	3.45	2.01	95.38	79.75
CC-Syngas-Hybrid	1.46	0.55	108.65	53.92
CC-SNG - Hybrid	37.70	22.83	105.04	89.47

Figure 8: Economic sensitivities (SP_{IRR}) for conventional (A) and power-to-X (B) cases as a function of natural gas market prices, electrolyser CAPEX and stack lifetime.

3.4 Policy Agenda and Future Directions

Currently, there are ten (10) national policies that link to the prevention of environmental burden (National Environmental Policy, 2018). Among them, the national climate change policy (Solaun et al., 2015) outlines strategies for active decarbonization by 2030 within the petrochemical, transport and power generation sectors of Trinidad and Tobago. For the power sector, the largest power plant on the island employs SC systems (Point Lisas Power Station, 2021), at reduced energy efficiency and high fossil fuel utilization. Promoting a transition to more efficient power generation would accompany a reduction in natural gas consumption, which is currently constrained by existing take-or-pay power purchase agreements (Energy Chamber of Trinidad and Tobago, 2018). Thus, there is little to no motivation for IPPs to consider making changes that warrant energy efficient gains and reduced CO_2 emissions. To maintain affordable and clean power consumption-an important sustainable development goal (SDG 7) (Sustainable Development Goals, 2021), decisions need to be made to effectively meet national and international climate change commitments under the Paris Agreement. Currently, Trinidad and Tobago possess an unfavourable figure of less than 1% of RE penetration compared to its regional SIDS community (National Renewable Energy Laboratory, 2018). Most papers summarizing policy instruments for RE deployment in Trinidad and Tobago cannot account for fossil fuel subsidies which could work against RE expansion (Kersey et al., 2021; Khan and Khan, 2017).

Through multiple decision criteria and systems thinking, our results provide much needed guidance within the local sustainability space- illustrating CC technologies to promote higher energy and resource efficiency, reducing CO_2 emissions while providing significantly cheaper electrical energy over expensive power-to-X projects. Furthermore, RE penetration proves to be highly sustainable-simultaneously reducing environmental and economic burdens. Thus, to promote a sustainable energy transition, existing power purchase agreements (Ferrey and Laurent, 2015) need to be reconsidered, providing IPPs with opportunities to diversify current process operations-increasing resource efficiency and RE potential (Kersey et al., 2021). Secondly, governmental action plans need to be deployed swiftly to meet 2030 targets. Among them are ambitious decarbonization strategies, which can be expedited through imposed externalities (such as carbon taxes) (Solaun et al., 2021) on the largely GHG emitting petrochemical sector- while rewarding incentives for energy efficient technological solutions (Ministry of Energy and Energy Industries, 2021b). Lastly, feed-in-tariffs and open access grid compatibility (Ministry of Energy and Energy Industries, 2021c) needs to be prioritized to further manage reduced energy wastage nationwide.

4. Conclusion

Our study considers a shift towards greater resource and energy efficient process engineering, in promoting sustainable operations of the Trinidad and Tobago power sector. Here, 20 cases were investigated, reflecting BAU power generation as well as RE penetration and electrification of the national petrochemical industry through power-to-X processes. Overall, our results indicate a CC transition as the best alternative for current power generation- with increased energy efficiency of up to 50% and reduced gas utilization of approximately 7.2 GJ/MWh, accompanying 50% reduction in net life cycle GHG emissions. Although power-to-X systems do favor enhanced environmental benefits through avoided burdens, CC systems proved to be the more economically feasible technology- with lower overall SP_{IRR}. Additionally, considering a sustainable energy transition, RE technologies fully supports reduced environmental and economic burdens. Ultimately, among all cases investigated, hybridization of CC and RE technologies proved to be the most beneficial in assuring future clean and affordable energy for the nation.

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