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ABSTRACT

The sugar industry is considered a high-energy-demand and wasteful industrial sector in many developing countries. Such a high energy demand can undermine the sugar industry's economic and environmental aspects. Shifting from a linear economy model to a circular economy (CE) can help this industrial sector solve the current economic and environmental crises, decrease dependencies on fossil-based energies, increase circularity, and save considerable resources. However, such a transition necessitates comprehensive pre-feasibility studies to avoid problem shifts. Herein, we compared some novel waste-to-energy (WtE) technologies from a life cycle assessment (LCA) point of view; (a) integrated supercritical water gasification (SCWG) at 700 °C with solid oxide fuel cell (SOFC), (b) integrated SCWG at 700 °C with combined cycle gas turbine (CCGT), (c) cogeneration (Boiler), (d) integrated fixed-bed gasification combined cycle (IFXBGCC), and (e) integrated fluidized-bed gasification combined cycle (IFLBGCC). Iran, as a developing country with high dependencies on fossil resources and less CE implementation, was selected as a case study. Scenarios were compared using a functional unit (FU) of thermal management of 1 tonne of bagasse. SCWG is found to be an environmentally superior approach when hydrogen production is the primary function of the system. Otherwise, using boiler and steam turbine is is still the best approach to generate heat and electricity from bagasse. Direct combustion in the boiler showed considerable savings in climate change, i.e., 469 kg CO_2 eq saving/FU. The LCA results showed that bagasse to energy throughout direct combustion is a promising pathway to generating clean energy; in addition to helping industries earn more income, and contribute to sustainable development.

1. Introduction

Global annual sugar production reaches 183.2 million tonnes, 80 % of which is from sugarcane, and the rest is from sugar beet (USDA-FAS, 2022; ISO, 2019). Brazil, India, Thailand, China, Pakistan, and Mexico are the world's leading sugar producers (Aguilar-Rivera, 2022). Sugar production contributes significantly to the socioeconomic growth of developing countries and emerging economies (Solomon et al., 2020); for instance, in 2018, the global sugarcane export value was approximately 23 billion dollars (Udompetaikul et al., 2021). However, this sector also generates a tremendous amount of biowaste of different types, whose management is a severe challenge in these countries (Ungureanu et al., 2022). The mismanagement of biowaste from this sector has reportedly imposed considerable environmental impacts (Raza et al., 2021). The valorization of biowaste from the sugar industry into biofuels and value-added products not only can solve their current mismanagement problem in developing countries (Meghana and Shastri, 2020), but also help them shift into the circular economy (CE). A shift from the linear economy to CE can contribute more to socioeconomic developments in such developing countries, save more fossil fuels and resources, and mitigate considerable environmental impacts (OECD G20, 2021).

It was observed from a comprehensive literature review that cogeneration, gasification, anaerobic digestion, and fermentation of sugar industry's biowastes have been well studied from technical, environmental, and economic points of view (Table 1). Waste to energy (WtE) technologies have reportedly demonstrated notable

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Nomenclature

CCGT	Combined cycle gas turbine
CLCA	Consequential life cycle assessment
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CCS	Carbon capture storage
DALY	Disability-adjusted life years
HC	Hydrocarbon
FU	Functional unit
IGCC	Integrated gasification combined cycle
H_2SO_4	Sulphuric acid
BAU	Business-As-Usual
H_2	Hydrogen
PSA	Pressure swing adsorption
NaOH	Sodium hydroxide
LCA	Life cycle assessment
LHV	Lower heating value
SSPs	Shared socio-economic pathways
GW	Global warming
SCWG	Supercritical water gasification
SOFC	Solid oxide fuel cell
P_2O_5	Phosphorus pentoxide
K_2O	Potassium oxide
CE	Circular economy
USD	United States dollar
GE	General Electric
SG	Steam generator
IFXGCC	Integrated fixed-bed gasification combined cycle
IFLGCC	Integrated fluidized-bed gasification combined cycle
CGE	Cold gas efficiency
NRI	Niroo Research Institute
MBOE	Million barrels of oil equivalent
PLCA	Prospective life cycle assessment
IAM	Integrated assessment model

environmental and economic benefits (Chen et al., 2022; Alao et al., 2022). However, the technologies studied so far also suffer some shortcomings and drawbacks. For instance, the energy recovery through thermal treatment is not so efficient since bagasse has a high moisture content. On the other hand, anaerobic digestion and fermentation are slow processes whose hydrolysis takes a long time to be completed, increasing the plants' total capacity and investment rate. Supercritical water gasification (SCWG) has been proposed for such types of bio-wastes to overcome the above-mentioned shortcomings and drawbacks (Okolie et al., 2020; Adar et al., 2020). SCWG is a promising clean technology that can immediately decompose biomass with high moisture content into H_2, CH_4, CO_2, and CO at supercritical conditions (374 °C and 22.1 MPa) without prior drying (Cao et al., 2020; Guo and Jin, 2013; Yakaboylu et al., 2015; Lee et al., 2021). SCWG's main product is hydrogen, known as the cleanest energy in the 21st century (Rana et al., 2019; Zhang et al., 2019). Hydrogen combustion is CO_2 free, without other toxic gases (Sharma et al., 2020). Accordingly, it can play a pivotal role in the future energy market (Tacuri et al., 2022; David et al., 2022), and have undeniable roles in industrial and transportation sectors (Wang et al., 2024). It should be noted that so far, no research has evaluated the environmental impacts of hydrogen production from sugarcane bagasse via the SCWG pathway.

The hydrogen, generated through the SCWG process, can then be combusted in fuel cells or combined cycle gas turbines (CCGT) to be converted into other forms of energy, e.g., electricity. Solid oxide fuel cell (SOFC) is the most promising distributed power generation technology (up to 1 MW) as they are incredibly highly efficient, low pollutant, without moving parts, highly reliable, low maintenance seeker, and flexible in fuel (Zhang et al., 2017). On the other hand, CCGT is a process in which fuels are combusted in a gas turbine, and the turbine's exhaust gases are used to generate power in a steam turbine, achieving high thermal efficiency (International Energy Agency, 2019). Accordingly, the integration of SCWG with SOFC and CCGT seem promising WtE technology working at the downstream of the sugar industry in developing countries and emerging economies to treat bio-wastes, including sugarcane bagasse. Our comprehensive literature review demonstrated that such integrated technologies have not been studied from the environmental points of view. While SCWG has been proposed for bagasse, to the best of our knowledge, no research has evaluated the environmental impacts of hydrogen production from sugarcane bagasse via the SCWG pathway. This study aims to fill this gap. Despite the potential of the integration of SCGW with SOFC and CCGT, their environmental implications remain largely unexplored. This study, therefore, significantly contributes to the existing literature by undertaking a comprehensive assessment of the environmental impacts of these technologies. This assessment extends in addition to the conventional cogeneration in boilers and includes both fixed-bed and fluidized-bed gasification processes. The findings of this study are expected to provide valuable insights into the environmental sustainability of above-metnioned WtE technologies.

To fill the above-mentioned scientific gaps, the primary goal of this study was set to employ the life cycle assessment method (LCA) as early environmental sustainability guidance to account for the environmental impacts of various WtE technologies in the sugar industry. In this context, Iran's sugar industry sector was selected as a case study, and sugarcane bagasse was used as feedstock for our assessment. The case study was chosen on the basis that Iran's sugar production industry is one of the oldest, energy-demanding (i.e., 1.4 times of global average and about 2.5 times of average in developed countries (Naseri et al., 2020)), and wasteful industries, which urges transition to CE (Hosseinzadeh and Moghaddas, 2017). Although all the assessment done herein is based on a case study, the results will be of interest of other developing countries and also other similar waste/residual streams.

2. Materials and methods

LCA is a system modeling tool for quantifying the environmental impacts of processes and products through their life cycles (Rödger et al., 2020). LCA in the present work was conducted using OpenLCA 1.10.3 software package. The guidelines and recommendations adopted by ILCD handbook and the ISO 14040/44 standard were followed (Wolf et al., 2011; Weidema, 2014). The following sub-sections discuss the four steps of LCA (goal and scope, life cycle inventory, life cycle impact assessment, and interpretation) in detail.

2.1. Goal and scope

This study was conducted as early environmental sustainability guidance/pre-feasibility to identify the most environmentally friendly gasification system/configuration to produce renewable electricity and other types of bioenergy from sugarcane bagasse. Hence, the goal was to perform a comparative study between some novel gasification systems to assess and compare their environmental impacts, identify the hotspots, and find opportunities for further improvements. According to the ILCD handbook (European Commission - Joint Research Centre - Institute for Environment and Sustainability, n.d.), this study falls into the Macro/Meso level decision context (i.e., situation B) since it can have policy implications and some consequences on other systems out of its

Table 1
An overview of previous studies conducted to investigate various aspects of sugar industries' biowaste management.

Product	Feedstock	Technology	Scope			Country	LCA specification			Year	Key funding	Ref
			Tech.	Env.	Econ.		FU[a]	LCIA	Context			
Electricity	Bagasse	Cogeneration	–	✓	–	India	1 MWh surplus electricity	ReCiPe 2016 midpoint (H)	Attributional with system expansion	2021	Using by-products of sugarcane could reduce the overall GWP by 13–15 %.	(Hiloidhari et al., 2021a)
Electricity	Bagasse, cane trash	• Direct combustion • Gasification • Anaerobic digestion	–	✓	–	Iran	1 kWh surplus electricity	CML baseline	Attributional	2020	Direct combustion in boiler have better performance	(Mohammadi et al., 2020)
Electricity	Bagasse	Cogeneration	✓	✓	–	India	1 kWh surplus electricity	ReCiPe 2016 midpoint (H)	Attributional with system expansion	2021	Modern cogeneration technology and the use of renewable energy-based micro-irrigation could be beneficial.	(Hiloidhari et al., 2021b)
Electricity	Bagasse	Cogeneration	–	✓	–	Brazil	1 MWh surplus electricity	EDIP	N/A	2014	Dust from the straw burning prior harvesting has great impact.	(Lopes Silva et al., 2014)
Electricity	Bagasse	Cogeneration	–	✓	✓	Jamaica	Sugar mill electricity demand for a year	ReCiPe midpoint (H)	N/A	2018	Bagasse electricity has economic, environmental, and social benefits.	(Contreras-Lisperguer et al., 2018)
Electricity	Bagasse	Cogeneration	–	✓	–	Cuba	1000 kWh electricity per day	Eco-indicator 99	N/A (system expansion)	2013	Human health is affected by inorganic compounds in the cogeneration process.	(Pérez Gil et al., 2013)
• Electricity • Paper	Bagasse	• Landfill gas • Anaerobic digestion • Incineration • Pulp production	–	✓	–	Thailand	1 tonne of bagasse	EDIP 97	N/A	2009	Anaerobic decomposition option gives the best environmental performance.	(Kiatkittipong et al., 2009)
Ethanol	Juice	Fermentation	–	✓	–	Brazil	• 1 kg sugarcane • 1 liter ethanol • 1 J ethanol	Energy analysis: • Energy analysis • Fossil fuel embodied energy	N/A	2010	Large-scale ethanol production presents low renewability.	(Pereira and Ortega, 2010)
Ethanol	• Juice • Molasses	Fermentation	–	✓	–	Mexico	1 GJ ethanol	IPCC	N/A	2011	Ethanol from direct juice has the lowest emissions of GWP.	(García et al., 2011)
Ethanol	Molasses	Fermentation	✓	–	–	Nepal	–	IPCC	–	2009	Ethanol from molasses could promote sustainability while meeting energy demand and security.	(Khatiwada and Silveira, 2009)
• Electricity • Ethanol	Bagasse	• Cogeneration • Fermentation	✓	–	✓	Brazil	–	–	–	2017	84 % of sugarcane bagasse for 2G ethanol and the rest for electricity is the best option.	(De Souza et al., 2017)
• Electricity • Ethanol • Methanol	• Bagasse • Molasses	• Cogeneration • Fermentation • Syngas of gasification	–	✓	✓	India	1000 kg sugarcane	CML and ReCiPe	N/A	2019	Combined power and alcohol production is more environmentally.	(Joglekar et al., 2019)
Ethanol	• Agave juice • Molasses	Fermentation	✓	✓	✓	Mexico	1 MJ ethanol	Midpoint ReCiPe 2016	N/A (system expansion)	2021	The most harmful stages were cultivation and fermentation.	(Parascanu et al., 2021)
• Electricity • Heat	Bagasse	Gasification	✓	–	✓	Iran	–	–	–	2021	Optimum configuration of the total external utility consumption is conducted.	(Rahimi et al., 2021)
Ethanol	• Sugarcane molasses • Sugar beet molasses	Fermentation	✓	✓	–	Iran	1 l ethanol	Midpoint ReCiPe	Attributional and consequential	2021	Sugarcane molasses had a higher environmental impact compared to the sugar beet.	(Zaki Dizaji et al., 2021)

(continued on next page)

Table 1 (*continued*)

Product	Feedstock	Technology	Scope			Country	LCA specification			Year	Key funding	Ref
			Tech.	Env.	Econ.		FU[a]	LCIA	Context			
Electricity	Bagasse	Cogeneration	–	✓	–	Mauritius	1 GWh of electricity delivered to consumer	CML World 1992 and Eco-Indicator 99	Attributional	2015	GWP is 29 kg CO_2 eq/MWh.	(Brizmohun et al., 2015)
• Electricity • Ethanol	• Bagasse • Molasses	• Cogeneration • Fermentation	–	✓	–	Australia	• 1 kWh electricity • 1 MJ ethanol	Impact 2002+	Attributional with system expansion	2011	Expansion of the system is attractive for identifying co-products.	(Renouf et al., 2011)
• Steam and electricity • Ethanol • Fertilizer	• Bagasse • Molasses • Vinasse	• Cogeneration • Fermentation • Returning to farm	–	✓	–	Thailand	• 1 tonne raw sugar • 1 tonne refined sugar • 1000-liter ethanol • 1 MWh electricity	ReCiPe midpoint (H)	N/A	2017	Using residues throughout the whole chain could reduce environmental impacts.	(Silalertruksa et al., 2017)

[a] FU: functional unit.

decision context (e.g., electricity market). Therefore, a consequential LCA was conducted as instructed.

The functional unit (FU) was then chosen as the management of 1000 kg bagasse with different gasification systems described in the following sub-sections. Due to the fact that electricity is the primary product/function of the system and can be used in the sugar industry and/or sold into the national electricity grid, a second FU was also considered; 1 kWh net electricity (i.e., after subtracting the internal electricity demand of gasification systems). The second FU would allow us to compare the environmental impacts of bagasse-based electricity with the current electricity mix in the national grid.

The gasification systems/configurations studied herein can be used for any sugar industry worldwide despite variations in the characteristics of the sugarcane bagasse. To enable broader utilization of the results, the counterfactual system (current management of bagasse in Iran which might be different in other countries) is evaluated separately as scenario 0, and the findings are presented in the supplementary materials. However, to be more specific, the geographical boundary was narrowed to Iran during the system modeling and the selection of suppliers from background systems. Nevertheless, the findings of this study will have a broader interest than the selected geographical region. The temporal boundary targeted the year 2030 as the minimum timeframe needed to scale up the process and run the facility.

The system boundary started from the point that sugarcane bagasse was delivered to the gasification plant for further processes. As discussed above, the system boundary for the counterfactual system is presented separately. The gasification of sugarcane bagasse results in more outputs than electricity so we had a multifunctional system. In order to address the issue of multifunctionality, system expansion with substitution was employed to circumvent allocation problem. As a result, the system was given credit by substituting the products' marginal counterparts as instructed by ILCD handbook.

In the following sub-section, the gasification systems/configurations are described in detail.

2.2. *Life cycle inventory (LCI)*

Data from different sources were used to compile LCI for this research. Two types of inventory data were used in the current study, as did in any other LCA study: foreground and background data. In the foreground system, data is derived from technical reports, literature reviews, and infrastructure suppliers to determine each scenario's material flow, energy flow, waste streams, and emissions. In order to model the background processes, including the production of auxiliaries, materials, chemicals, and energy carriers, the ecoinvent database was employed. The following describes each scenario (Sc) in details and the data used for this study. Table 2 summarizes the inventory data related to the scenarios.

2.2.1. *Scenario development*

Four novel gasification configurations were adopted in this study and compared with a conventional boiler system. The primary product of all systems was electricity. The generated electricity and systems' by-products (i.e., methane and power) were used to meet the plant's internal demand, and then the surplus was considered as the plant's product. However, except Sc1, the generated heat within the system cannot be recycled and used to meet the plant's internal heat demand due to mismatching of pressure and temperature. In two scenarios, i.e., Sc1 and Sc2, bagasse is first converted to hydrogen through SCWG process, and then the generated hydrogen is used either in SOFC (Sc1) or CCGT (Sc2). In Sc3, bagasse is directly combusted in a boiler to generate heat and electricity. In Sc4 and Sc5, the generated syngas by fixed-bed and fluidized-bed reactors is used in an integrated gasification combined cycle (IGCC). In Table 3, all scenarios are summarized.

Table 2
Life cycle inventory data for LCA modeling of 1000 kg bagasse management.

Unit process	Item	Sc1	Sc2	Sc3	Sc4	Sc5	Unit
Mixer	Bagasse	1000	1000	1000	1000	1000	kg
	Electricity consumption[a]	44	44	–	–	–	kWh
	Make-up deionized water	363.32	363.32	–	–	–	kg
High pressure metering pumps	Electricity consumption[a]	155.56	155.56	–	–	–	kWh
Furnace	Direct emissions	Table SI-6	Table SI-8	–	–	–	g
Reactor & preheater	Heat consumption[a]	2203.61	1528.03	–	–	–	kWh
	Direct emissions	Table SI-6	Table SI-8				g
Cooler	Electricity consumption[a]	36.82	36.82	–	–	–	kWh
Pressure swing adsorption	Electricity consumption[a]	28.04	28.01	–	–	–	kWh
	CO	65.54	65.54	–	–	–	kg
Low pressure liquid gas separator	CO_2	797.90	797.90	–	–	–	kg
Solid oxide fuel cell	Electricity consumption[a]	24.57	–	–	–	–	kWh
	Air	3010	–	–	–	–	kg
Combined cycle gas turbine	Decarbonized water	–	676.12	–	–	–	kg
	Soft water		20.26				kg
	Electricity consumption[a]	–	3.31	–	–	–	kWh
	NO_x	–	372.4	–	–	–	g
	Air	–	213.56	–	–	–	kg
Boiler	Electricity consumption[a]	–	–	47.14	–	–	kWh
	Tap water	–	–	2340	–	–	kg
	Direct emissions	–	–	Table SI-10	–	–	g
Gasifier	Heat consumption[a]	–	–	–	326.83	275.46	kWh
	Electricity consumption[a]	–	–	–	61.38	55.09	kWh
	Tap water	–	–	–	150.4	157.5	kg
	Direct emissions	–	–	–	Table SI-12	Table SI-14	g
	NaOH	–	–	–	0.4	0.4	kg
	H_2SO_4	–	–	–	3	3	kg
	Dolomite	–	–	–	–	10	kg
	Zeolite powder	–	–	–	–	2	kg
Integrated gasification combined cycle	Decarbonized water	–	–	–	631.12	679.78	kg
	Soft water	–	–	–	18.92	20.37	kg
	Direct emissions	–	–	–	Table SI-12	Table SI-14	g
Avoided electricity		459.51	206.02	411.19	399.02	440.74	kWh
Avoided heat		–	353.41	840.28	517.25	633.56	kWh
Avoided phosphorus pentoxide (P_2O_5)		1.36	1.36	1.36	1.36	1.36	kg
Avoided potassium oxide (K_2O)		2.81	2.81	2.81	2.81	2.81	kg

[a] Internal source.

Table 3
A summary of the different scenarios (SCWG: supercritical water gasification, SOFC: solid oxide fuel cell, CCGT: combined cycle gas turbine, IFXVGCC: integrated fixed-bed gasification combined cycle, IFLBGCC: integrated fluidized-bed gasification combined cycle).

Scenario	Technology	SCWG operation temperature (°C)
Sc1	SCWG + SOFC	700
Sc2	SCWG + CCGT	700
Sc3	Cogeneration (Boiler)	–
Sc4	IFXBGCC	–
Sc5	IFLBGCC	–

2.2.1.1. Supercritical water gasification (SCWG). Temperature, pressure, reaction time, and concentration are among the factors that influence SCWG (Lu et al., 2012). The output of the process varies based on these parameters and feedstock (i.e., bagasse) characteristics. It has been reportedly observed that there is a direct relationship between process temperature and the amount of hydrogen produced (Cao et al., 2018; Safari et al., 2016). It has been found that pressure would not have significant effects on the carbon conversion efficiency under supercritical water environment (Basu and Mettanant, 2009; Lu et al., 2006). Hence, recent studies are performed at constant pressure while investigating the impacts of other parameters. Ebrahimi-Nik (2012) increased reaction time by up to 4 h under similar conditions, but it did not have a significant effect on bagasse conversion ratio. Accordingly, the effect of reaction time seemed to vary with biomass type and reaction conditions. On the contrary, Cao et al. (2018) reported that increasing reaction time had a positive effect on hydrogen generation. Barati et al. (2014) reported a reverse relationship between bagasse concentration and the amount of hydrogen production. In a study on the SCWG of bagasse, Safari et al. (2016) concluded that the relationship between biomass concentration and hydrogen production was first direct (up to a concentration of 20 %) and then turned into the inverse relationship. Following a comprehensive literature review a process temperature of 700 °C was chosen for process modeling and environmental impact assessment. Table 4 summarizes Iran's bagasse's elemental composition and syngas' components after SCWG at 700 °C temperature.

Further details of process simulation and modeling, assumptions, and calculations of each scenario are discussed below.

2.2.1.2. Integrated supercritical water gasification and solid oxide fuel cell

2.2.1.2.1. Sc1. In this scenario bagasse and deionized water are first mixed to generate a slurry. The mixture is then pumped into a heat exchanger for preheating. This heat exchanger receives its heat from an internal source (hydrogen-rich syngas). Next, water and bagasse slurry are sent to a preheater, followed by the process's main reactor. Since the internal heat production (i.e., the heat of SOFC) is not sufficient to meet the heat demand of the process, a furnace is needed to combust internally produced biomethane and hydrogen. The required air for this process is supplied using an air blower. The exhaust gas from the furnace is circulated to increase the water temperature in the preheater and reactor. At the next step, hydrogen-rich syngas is directed to the heat exchanger to decrease its temperature. Then hydrogen rich-syngas is transferred to a cooler followed by a high-pressure separator; gases are separated from water when the mixture is cooled down (Boukis and Katharina Stoll, 2021). The hydrogen-rich gas, which contains hydrogen, methane and carbon monoxide, is separated from the liquid (CO_2 is dissolved in water at this stage) in a high-pressure separator and enters the pressure swing adsorption (PSA). In this process, hydrogen

Table 4
Iran's bagasse's elemental composition and syngas' components after SCWG at 700 °C temperature (Sheikhdavoodi et al., 2015).

Elementary composition					Operation conditions				Syngas components (mol/kg)			
C	O	H	N	S	Temperature (°C)	Pressure (MPa)	Reaction time (min)	Sugarcane bagasse (wt%)	H_2	CH_4	CO_2	CO
46.40	47.82	5.69	1>	0.09	700	25	15	9 %	30.53	7.22	18.13	2.34

gas reaches a purity of 99 %, and the other two flows, i.e., CH_4 and CO, are directed to the furnace. The separated liquid is fed into a low-pressure gas-liquid separator to separate CO_2 in a scrubbing column filled with pall rings (Boukis and Katharina Stoll, 2021). The remaining water is recycled within the system, and CO_2 is released into the atmosphere (i.e., considered a biogenic emission). During SCWG process, the heat demand is covered by methane combustion and SOFC heat. The remaining heat is supplied by burning hydrogen, and the remaining hydrogen is fed into the SOFC. This type of fuel cell is commonly perceived as a pollution-free technology because the combustion is avoided. On the other hand, it is a high-temperature fuel cell operating at 600 °C to 1000 °C and generating power with efficiencies of about 40 %–60 % (Mehmeti et al., 2016). Moreover, as this fuel cell typically operates at high temperatures (usually above 800 °C), its high-grade heat waste can be recycled in power generation systems (Choudhury et al., 2013). Consequently, the heat from SOFC is used to meet the heat demand of SCWG (all calculations and data related to the SCWG and SOFC are shown in the Supplementary file “SI-3”). Fig. 1 depicts the detail process flow diagram and mass balance within the integrated SCWG and SOFC for Sc1.

2.2.1.3. Integrated supercritical water gasification and combined cycle gas turbine

2.2.1.3.1. Sc2. Within this scenario, the remaining hydrogen, after providing the internal heat demand of the process, is fed into a CCGT to generate power with high thermal efficiency (International Energy Agency, 2019). On the other hand, in a combined cycle configuration, the generated steam is also utilized to drive the steam turbine generator for electricity production (Zhang et al., 2022). Fig. 2 displays the integrated SCWG and CCGT for Sc2. All calculations, related to this scenario, are reported in the Supplementary file “SI-4”.

The following assumptions were used for process modeling (Ortiz-Imedio et al., 2021):

- One gas turbine and one steam turbine are used in CCGT.
- Engine speed in the gas turbine is 3000 rpm.
- Fuel/air mass ratio in the gas turbine is kept at 1.5 (λ = 1.5).

The gas turbine that can be run with a high percentage of hydrogen is a high technology (Öberg et al., 2022). General Electric (GE) has gas turbines that can use fuels with more than 90 % hydrogen (Goldmeer, 2019). One of these gas turbines is 6B.03 which can operate on a wide range of non-standard gas or liquid fuels, including over 90 % hydrogen. Also, net heat rate of this turbine is reported as 6940 kJ/kWh (net heat rate is the amount of heat input required to generate one unit of electricity (Ghenai and Amine Hachicha, 2017)) all data, calculations, and energy balance of Sc2 are provided in detail in the Supplementary file “SI-4” and Fig. SI-5.

2.2.1.4. Combustion in boiler

2.2.1.4.1. Sc3. Based on this scenario, a boiler is used for cogeneration. The process flow diagram for cogeneration at 60 bars and 480 °C is demonstrated in Fig. 3 (Ocampo Batlle et al., 2021). The use of cogeneration in the sugar industry is a prevalent method to produce heat and electricity from sugarcane bagasse with acceptable environmental and economic performance (Silalertruksa and Gheewala, 2020). Accordingly, bagasse was directly combusted in the boiler in our process design to generate steam. The steam runs the turbine to generate electricity and heat. A steam-to-bagasse ratio of 2 kg/kg was used to determine the energy value (Lopes Silva et al., 2014). The overall efficiency of the boiler was assumed to be ~85 % (Chauhan et al., 2011; Javalagi et al., 2010), with thermal and electrical efficiency of 55 % and

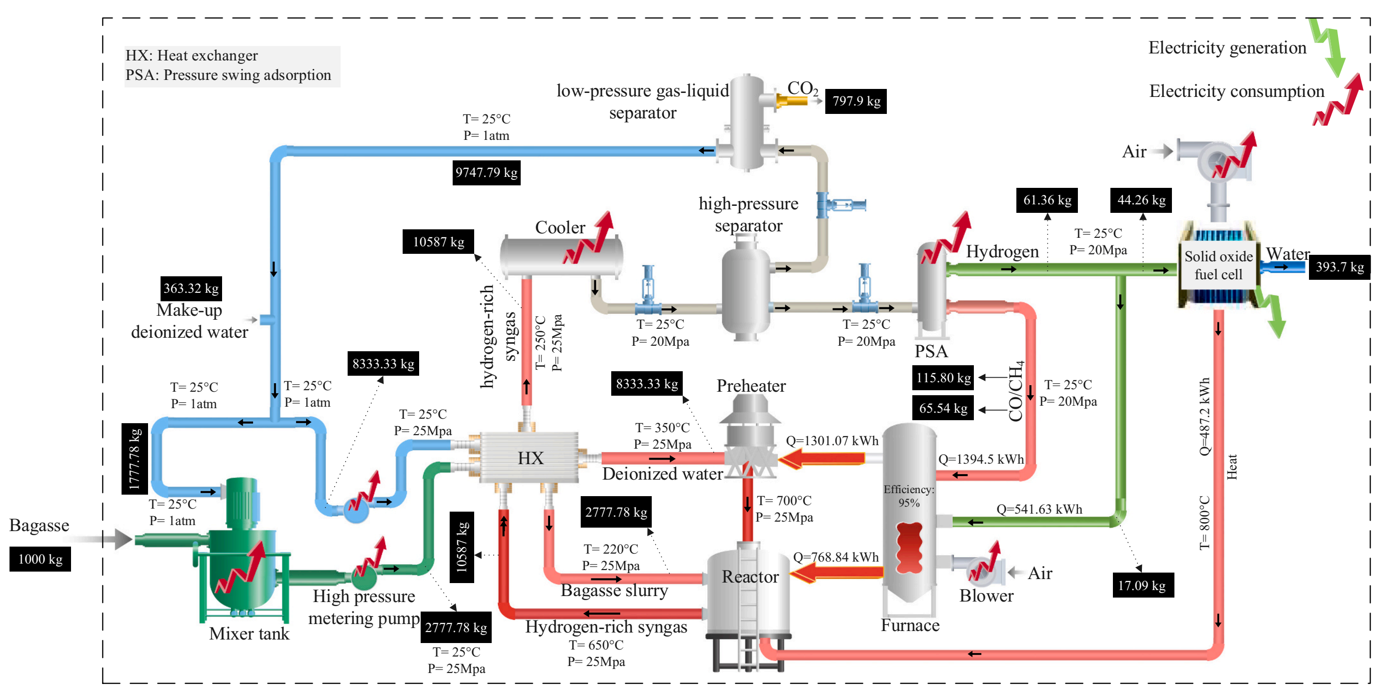

Fig. 1. Process flow diagram and mass flow in Sc1 which represents critical water gasification at 700 °C integrated with solid oxide fuel cells.

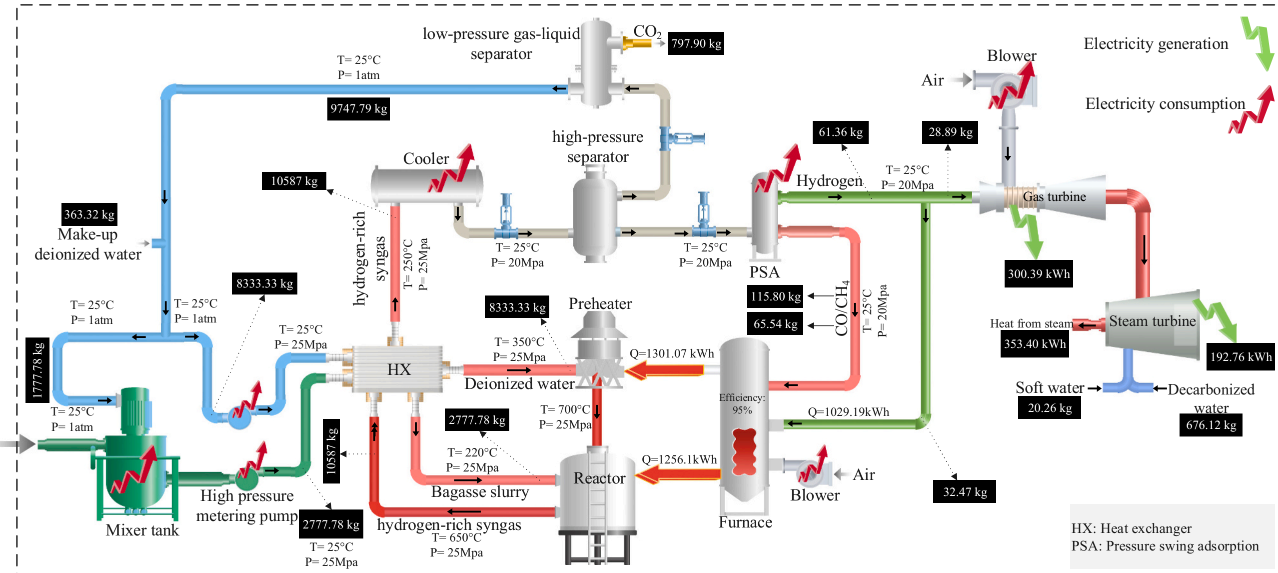

Fig. 2. Process flow diagram and mass flow in Sc2 which represents critical water gasification at 700 °C integrated with combined cycle gas turbine.

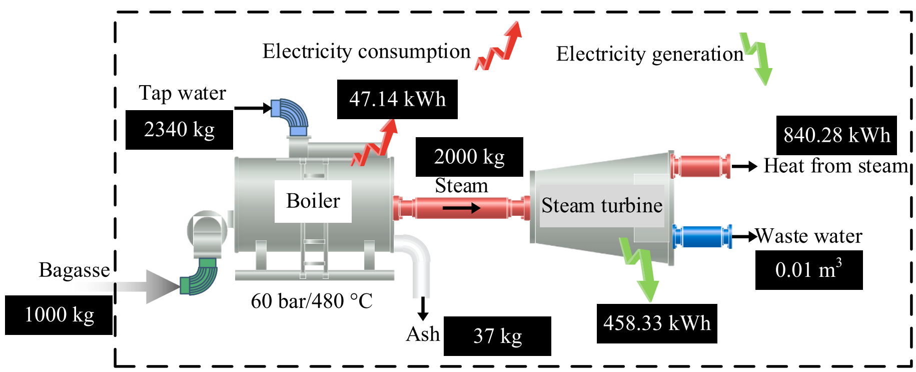

Fig. 3. Process flow diagram and mass flow in Sc3 which represents cogeneration.

30 %, respectively. Further details of process design are provided in the Supplementary file “SI-5”.

2.2.1.5. Integrated fixed-bed gasification combined cycle (IFXBGCC)

2.2.1.5.1. Sc4. In this scenario, as shown in Fig. 4, bagasse is combusted in a fixed-bed gasifier to produce syngas. The produced syngas is then ignited in a combined cycle to generate heat and electricity using a gas and steam turbine. In Sc6 and 7, data are mainly compiled from the literature and previous studies and partly from the ecoinvent database as a secondary dataset. Regarding to this scenario, the bagasse moisture content is first reduced to 10–15 %. The energy demand of the gasification process is estimated at 0.06 $kWh_{el}/N\ m^3$ and 1.15 $MJ_{thermal}/N\ m^3$ to meet the energy demands of the pumps, air compressor, gas cleaning, moisture content reduction, and gasifying. A gas cleaning process is considered after gasification to remove impurities from syngas. The impurities, such as tars and sulphur species, are separated using sulphuric acid (H_2SO_4) and sodium hydroxide (NaOH) (Mohammadi et al., 2020; Chan et al., 2019). Within the scrubbing system, water is also used, which has been accounted for in the LCI. The generated heat within the scenarios is first used to meet the enteral heat demand, and then the surplus is assumed as net output energy.

The efficiency of the gasification process is commonly expressed as cold gas efficiency (Lestander et al., 2022), which is measured by the following formula (Jayathilake and Rudra, 2017):

$$\text{Cold gas efficiency} = \frac{V_{syngas} \times LHV_{syngas}}{LHV_{biomass}} \times 100 \quad (1)$$

where V_{syngas} represents syngas yield N m^3/kg feedstock, LHV_{syngas} stands for the lower heating value of syngas (MJ/N m^3), and $LHV_{biomass}$ indicates the lower heating value of biomass on a dry basis in MJ/kg. The CGE of biomass is typically between 50 % and 80 % (Daniel et al., 2012). Following the findings of Niroo Research Institute (NRI), a 65 % CGE was assumed for the fixed-bed gasification, and an LHV of 5.4 MJ/kg was used for the produced syngas (Mohammadi et al., 2020). The overall energy efficiency of the gas and steam turbine (i.e., to convert syngas to heat and electricity) was assumed to be 85 % (55 % for heat and 30 % for electricity generation) (Mohammadi et al., 2020). Detailed data and calculations are available in the Supplementary file “SI-6.”

2.2.1.6. Integrated fluidized-bed gasification combined cycle (IFLBGCC)

2.2.1.6.1. Sc5. The difference between scenarios 4 and 5 is that a part of the space inside the reactor is filled with ineffective and refractory grains, so-called bed. The bed materials used in the fluidized bed process combines 83 % dolomite and 17 % zeolite (Mohammadi et al., 2020). Also, this scenario needs 0.05 kWh electricity and 0.9 MJ heat per N m^3 syngas generated (Mohammadi et al., 2020), and the CGE of fluidized-bed gasification is considered 70 % (Mohammadi et al., 2020). The Supplementary file “SI-7” contains data and calculations about this scenario.

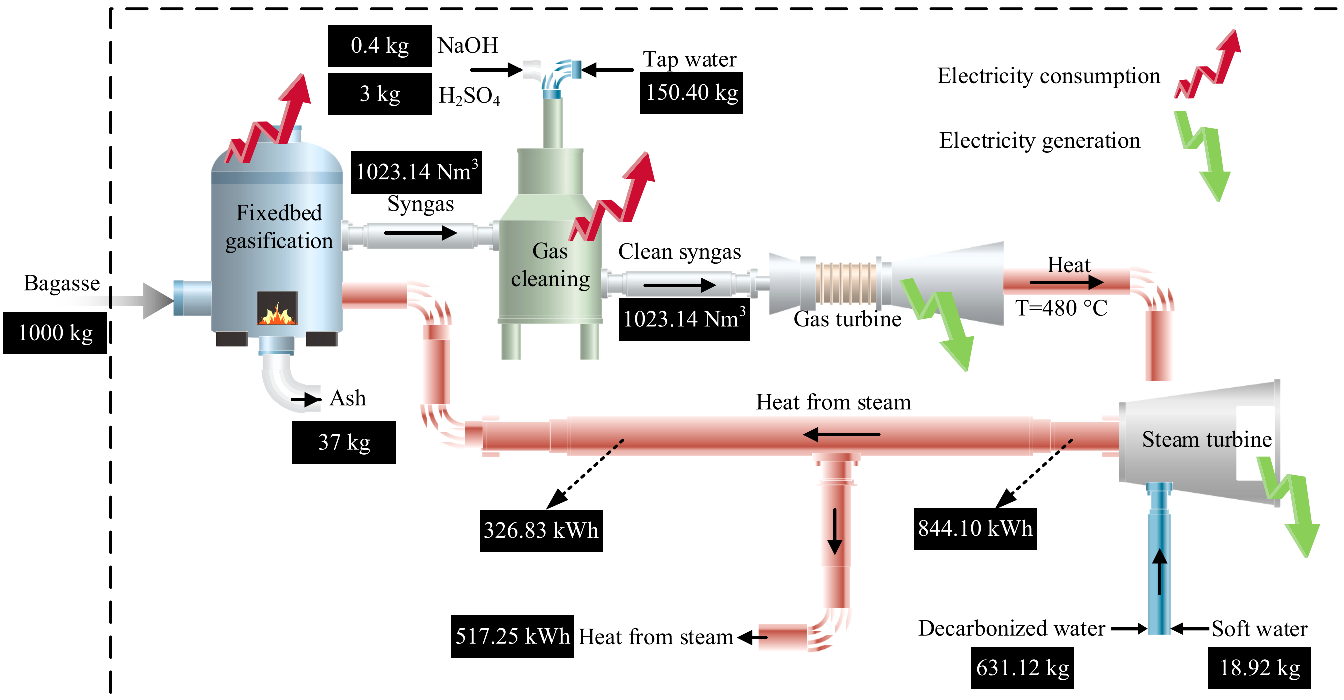

Fig. 4. Process flow diagram and mass flow in Sc4 which represents integrated fixed-bed gasification combined cycle.

2.2.2. *Pollutant emissions from unit processes*

In the developed scenarios, bagasse and some other fuels, e.g., hydrogen and methane as a by-product of SCWG and syngas, are combusted for heat and power generation, which result in the emission of different gaseous pollution. It should be noted as said earlier, hydrogen combustion produces no CO_2 or other toxic emissions (Sharma et al., 2020). The emission of methane, carbon monoxide, and carbon dioxide from bagasse and other biomass-based fuels were considered as biogenic while that of fossil fuels were considered non-biogenic emissions. The Supplementary file shows emissions related to all scenarios in Tables SI-6, SI-8, SI-10, SI-12, and SI-14.

2.2.3. *Marginal data and system expansion*

To deal with the multifunctionality problem, system expansion with substitution was used as described in the ILCD handbook (European Commission - Joint Research Centre - Institute for Environment and Sustainability, n.d.) to give credit to the system's cofunctions. As this is a consequential LCA (CLCA) study, marginal technologies shall be identified and used for process modeling and crediting purposes. To identify marginal processes and technologies for the geographical and temporal boundary of the current study, the 5-step procedure proposed by Weidema et al. (1999) was followed. Accordingly, marginal heat and electricity were identified for Iran (see details in SI-11). Natural gas has been the most significant contributor to Iran's total final energy consumption since 2003, followed by crude oil (Solaymani, 2021). Consequently, natural gas-based heat and electricity were considered as marginal options: Heat, from steam, in chemical industry (steam production, as energy carrier, in chemical industry) and electricity, high voltage (electricity production, natural gas, and combined cycle power plant). It should be highlighted that when the LCA results were evaluated based on our second FU, as described in the goal and scope section, i.e., 1 kWh net electricity, credit was not given to electricity as it constituted the primary function of the system. Hence, all scenarios could be compared on the same basis/function.

Ash is one of the systems' outputs. It can be reportedly used as soil conditioner in agricultural lands, e.g., sugarcane farms, to improve soil fertility (Chauhan et al., 2011). Van Langenhove et al. (2009), reported that 2.69 tonnes of ash from bagasse could substitute 0.1 tonne P_2O_5 and 0.21 tonne K_2O. Accordingly, the produced ash in all scenarios received credit by substituting marginal phosphorus pentoxide (P_2O_5) and potassium oxide (K_2O) fertilizers.

2.3. *Life cycle impact assessment (LCIA)*

In the present study, the environmental impacts of the developed scenarios at both midpoints (impact categories) and endpoints (damage categories) were assessed using the ReCiPe2016 (H) method. This is an ISO and ILCD compliant LCA study. ISO has no preference for using specific LCIA method over others. The suggestion is to use the most relevant LCIA method that can fully cover all the impacts caused by the exchange of elementary flows between biosphere and technosphere. Accordingly, this method was selected as it covers a wide range of impact categories and three endpoint categories to also cover impacts on areas of protection. Three endpoints, i.e., human health, ecosystem quality, and resource scarcity, and one midpoint, i.e., global warming (GW), are selected for interpretation. In contrast, the results of other impact categories are reported in the Supplementary SI-13. Since normalization and weighting are two optional steps in LCIA according to ISO14040, the normalized and weighted results have not been reported herein. Interpretation is, finally, the last step of LCA during which results are presented considering goals, scope, inventory of inputs and outputs, and assessment method. LCIA and the results of LCA are discussed in the next sections.

3. Results

In the following sub-sections, the findings of this study are reported in detail. It should be noted that the negative values represent environmental savings, and the positive values show the induced impacts. The sum of these negative and positive numbers indicates the net environmental savings or impacts. The results are shown at both midpoint and endpoint levels and discussed in detail in the following section.

3.1. Global warming (GW) and other midpoint indicators

Sc1 (SCWG + SOFC) was demonstrated by the findings to produce the highest electricity (i.e., 459.51 kWh/FU) among all investigated scenarios; however, it has been achieved at the cost of consuming all internal heat generation. The total energy recovery was the highest in Sc3, where 411.19 kWh of electricity/FU and 840 kWh of heat/FU were recovered. Scenario 5 (i.e., 440.74 kWh_{el} and 633.35 kWh_{th}) had the second highest energy recovery followed by Sc 4 (i.e., 399.02 kWh_{el} and 517.25 kWh_{th}). Accordingly, Sc3 outperformed other scenarios in 14 out of 18 impact categories investigated (Table 5).

As shown in Table 5, all five scenarios developed and investigated in this study were environmentally friendly (i.e., climate neutral) in the GW impact category. However, Sc3 (bagasse combustion in boiler) showed the best environmental performance with the highest net saving, i.e., −469 kg CO_2 eq per tonne of bagasse treated. In all scenarios, the avoided impacts achieved by substituting the marginal counterparts of the systems' products (i.e., electricity, heat, and ash) could dominate the induced impacts, resulting in net savings. As displayed in Fig. 5A, Sc3 received the highest credit (−292 kg CO_2 eq/FU for heat production and −175 kg CO_2 eq/FU for electricity production) since the process configuration in this scenario led to the highest electricity generation.

As shown in Fig. 5B, the last three scenarios had the highest induced impacts (the highest for Sc5, followed by 4 and 3). In other words, the boiler unit in scenario 3 and the gasifier in scenarios 4 and 5 dominated the induced impacts in the GW impact category. This is due to tap water consumption (see details in Fig. SI-9) and zeolite powder (Details in Fig. SI-10) in the boiler and gasifier, respectively. Over 77 % of the induced impact in the first two scenarios is related to the mixer unit, while the furnace had the least induced impacts (Tables SI-6 and SI-8).

The higher heat recovery from SOFC in Sc1 caused lower hydrogen to be needed for combustion compared to Sc2 (see SI-3 and SI-4 section). Put it all together, Sc1 had the highest electricity recovery, so that it received the highest credit from the substitution of marginal electricity. It should be noted that Sc1 received the highest credit from the substitution of electricity (−195 kg CO_2 eq/FU) (see Table SI-18). Sc1 had the lowest induced impacts among all scenarios investigated herein. An induced impact from the mixer unit process can be also observed in the first two scenarios (Fig. 5B). Such an induced impact originates from the production of deionized water in the background system. More specifically, this impact rooted from the electricity demand for tap water production process (see Fig. SI-8). SCWG consumes deionized water, which is the same for both Sc1 and 2. It is worth mentioning that since the energy demand of all unit processes are supplied internally, any background emissions from energy production have not contributed to the GW impact category.

In scenario 2, induced impact originated from the mixer, furnace, and CCGT. As illustrated in Fig. 5B, a significant share of the induced impacts originates from the mixer. The furnace uses hydrogen and methane, and emissions from the methane combustion constitute 22 % of the induced impact in this impact category. However, the avoided impact from the substitution of heat and electricity was significant enough to compensate for the induced impacts and result in such significant net savings. In this scenario, the avoided heat and electricity contributed to 57 % and 40 % of total savings, respectively. It should be highlighted that all scenarios had the same amount of ash production. Hence, the saving from applying ash as soil amendment was the same for all scenarios, i.e., −3.96 kg CO_2 eq/FU. Further information is provided in SI-11.3.

The contributional analysis of Sc3 demonstrated that all induced impact from the boiler originates from tap water production. To be more specific, this unit consumes the highest amount of tap water (Table SI-8). As mentioned earlier and shown in Fig. SI-9, electricity consumption for ultrafiltration tap water production contributed most to the total induced impact of 1.83 kg CO_2 eq/FU. This scenario received the highest credit from the substitution of heat (−292 kg CO_2 eq/FU).

Regarding the last two scenarios, IFLBGCC (Sc5) showed a lower GW impact than IFXBGCC (Sc4); −396 kg CO_2 eq/FU vs. −350 kg CO_2 eq/FU. Induced impact in Sc4 and 5 are the highest among all scenarios. The IGCC dominated the induced impact in Sc4, while the gasifier dominated Sc5 (Fig. 5B). The induced impact caused by the fluidized-bed gasifier (Sc5) was estimated at 13.1 kg CO_2 eq per tonne of bagasse treated. The breakdown analysis showed that the background emissions from dolomite and zeolite powder production dominated this unit process by 92.1 % (Fig. SI-10). The total induced impact in Sc4 was 3.48 kg CO_2 eq/FU, while in the fixed-bed gasifier unit, which had the most contribution, the induced impact was estimated at 1.03 kg CO_2 eq/FU. The induced impact from IGCC is rooted in direct emissions of syngas combustion (99 %). Although Sc5 had a higher induced impact than Sc4, it received more credit from the substitution of heat and electricity. This is due to the fact that Sc5 had higher cold gas efficiency causing higher heat and electricity to be recovered from the process (calculations and further

Table 5
The color-mapped environmental impacts of five assessed scenarios at midpoint level (impact categories). Results of the counterfactual system is shown as Sc0 in the SI.

Impact category	Unit	Sc1	Sc2	Sc3	Sc4	Sc5
Global warming	kg CO_2 eq	-198.01	-213.39	-469.13	-349.66	-395.52
Stratospheric ozone depletion	kg CFC11 eq	-0.0001	0.0000	-0.0001	-0.0001	-0.0001
Ionizing radiation	kBq Co-60 eq	-0.16	-0.88	-1.99	-1.41	-2.12
Ozone formation, Human health	kg NOx eq	0.13	0.49	0.24	1.28	1.34
Fine particulate matter formation	kg $PM_{2.5}$ eq	0.03	0.05	-0.09	0.07	0.09
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.12	0.49	0.22	1.26	1.33
Terrestrial acidification	kg SO_2 eq	0.11	0.20	-0.15	0.32	0.36
Freshwater eutrophication	kg P eq	-0.0062	-0.0102	-0.0180	-0.0123	-0.0025
Marine eutrophication	kg N eq	-0.0005	-0.0008	-0.0016	-0.0011	-0.0006
Terrestrial ecotoxicity	kg 1,4-DCB	-42.85	-43.39	-64.49	-43.32	19.11
Freshwater ecotoxicity	kg 1,4-DCB	-0.54	-0.72	-1.32	-0.94	-0.26
Marine ecotoxicity	kg 1,4-DCB	-0.81	-1.03	-1.86	-1.33	-0.34
Human carcinogenic toxicity	kg 1,4-DCB	-0.39	-0.72	-1.32	-1.01	2.27
Human non-carcinogenic toxicity	kg 1,4-DCB	-18.46	-20.45	-34.21	-24.58	-3.45
Land use	m^2a crop eq	-0.91	-1.06	-1.54	-1.08	0.46
Mineral resource scarcity	kg Cu eq	-0.23	-0.24	-0.33	-0.29	-0.06
Fossil resource scarcity	kg oil eq	-74.52	-77.93	-171.05	-129.07	-147.02
Water consumption	m^3	-0.63	0.70	1.77	0.45	0.81

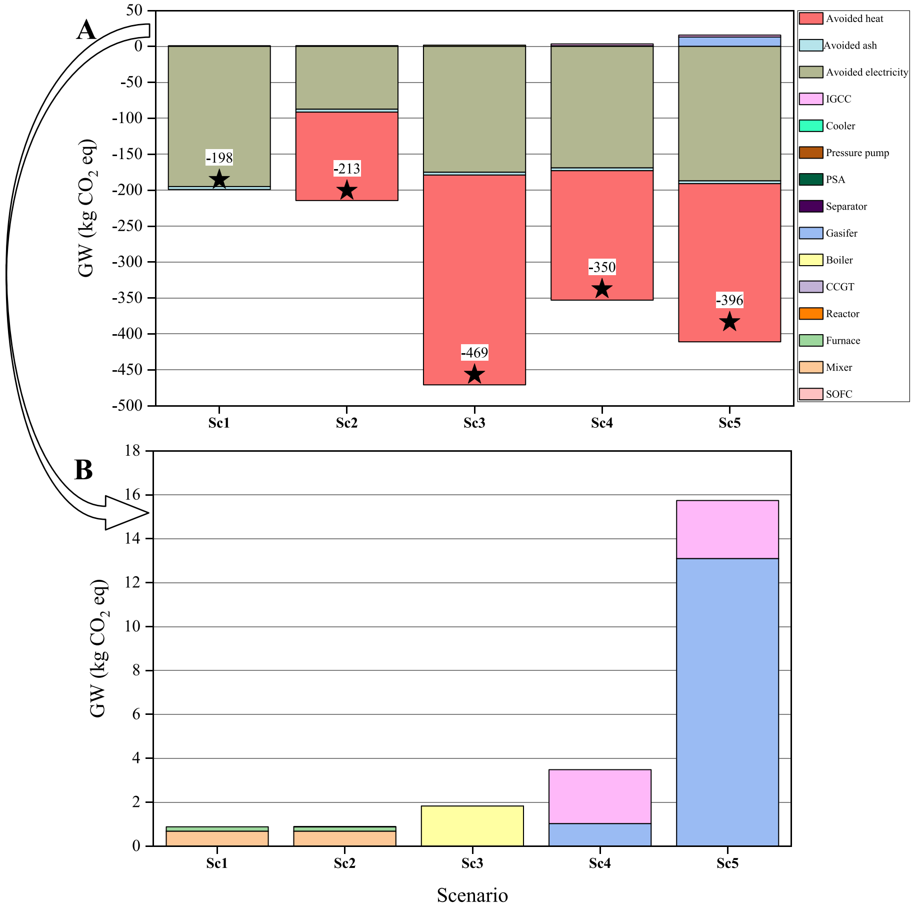

Fig. 5. A: Contributions to global warming for different scenarios (stars show net value). B: Comparison of developed scenarios in global warming induced impact. (GW: global warming, IGCC: integrated gasification combined cycle, PSA: pressure swing adsorption, CCGT: combined cycle gas turbine, SOFC: solid oxide fuel cell.). Note: Results of the counterfactual system is shown as Sc0 in the SI.

information are provided in SI-6 and SI-7 sections).

3.2. Human health damage category

The damage category of human health reflects environmental impacts from the impact categories of human toxicity, global warming, water use, ozone depletion, and formation and particulate matter (see Fig. SI-30). As evident from Fig. 6, all scenarios led to environmental savings in this damage category, meaning that the net results are negative for all scenarios. Scenario 3 received the highest credit from the substitution of heat and electricity among all scenarios (i.e., −5.34E−4 DALY/FU), and Sc5 was placed in the second rank with a net saving of −2.98E−4 DALY/FU; although Sc5 had the highest induced impacts among all scenarios. What contributed most to the induced impacts of Sc5 are gasifier and IGCC by 55.5 % and 44.5 %, respectively.

The induced impacts in Sc1 are attributed to the furnace, reactor, and mixer unit processes, where the furnace has dominated the induced impacts by 81.77 %. The induced impact from the furnace is rooted in background emissions from direct emissions from methane combustion (see Table SI-6). More specifically, among the direct emissions, NO_x emissions from methane combustion have dominated the impacts on human health. In Sc1 lower amount of hydrogen is needed to supply the heat demand of the process compared to Sc2 (see Figs. SI-2 and SI-3); as a result, all hydrogen is used for electricity generation, and this scenario received the highest credit from the substitution of electricity. On the other hand, Sc1 had the lowest induced impact, but due to the substitution of heat in other scenarios (in scenario 1 all the heat produced by SOFC is utilized by SCWG; therefore, there is no surplus heat, so the system would not be given credit for surplus heat production), Sc1 was not the best option in this damage category. Regarding Sc2, the contribution of mixer and furnace units are the same as Sc1, but the induced impact from CCGT originates from NO_x emissions which are emitted during hydrogen combustion in gas turbine (94.3 %), as well as decarbonized and soft water by 5.39 % and 0.16 %, respectively (see Fig. SI-11).

Following Sc1, Sc3 had the lowest induced impact. Only the boiler exists in this scenario, and all the induced impact herein is attributed to the boiler. The breakdown analysis demonstrated that 20.2 % of the induced impact in Sc3 is related to water consumption, i.e., "tap water", and the rest is associated with NOx emissions from bagasse combustion (Table SI-10 and Fig. SI-12).

In the last two scenarios, although the induced impacts in IFLBGCC were more than those of IFXBGCC (17.77E−5 vs. 12.04 DALY/FU), higher cold gas efficiency led to higher net heat and electricity production and larger avoided impacts and net savings. In both scenarios, avoided heat contributed most to the net savings (51 % of total savings in Sc4 and 54 % in Sc5). The induced impact in these scenarios corresponds to the gasifier and IGCC. In the gasifier of Sc5, zeolite powder production was the main reason for the higher induced impact by 50.82 % (see Fig. SI-13). Within the gasifier of Sc4, 81.1 % of all induced impacts are attributed to bagasse combustion, 10 % to sulphuric acid production, 7.4 % to sodium hydroxide production, and the rest to the tap water (tap water production by ultrafiltration led to the highest contribution to tap water which causes an increase in malnutrition). Furthermore, in Sc4 and Sc5, the induced impacts in the IGCC were estimated at 7.34E−5 and 7.9E−5 DALY/FU, respectively. Direct

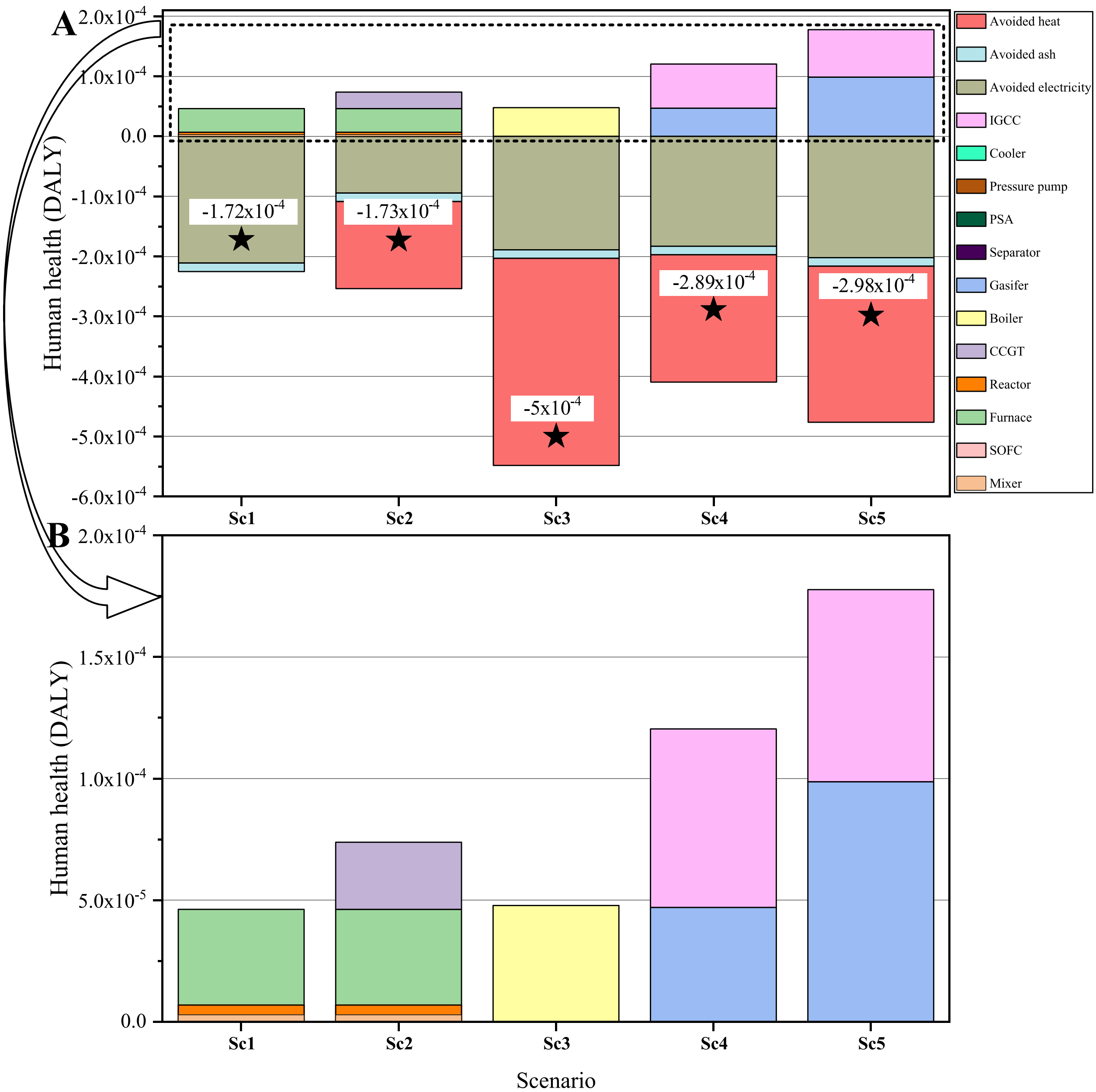

Fig. 6. A: Contributions to Human health damage category of different scenarios (stars show net value). B: Comparison of developed scenarios in Human health induced impact. (DALY: disability-adjusted life year, IGCC: integrated gasification combined cycle, PSA: pressure swing adsorption, CCGT: combined cycle gas turbine, SOFC: solid oxide fuel cell.). Note: Results of the counterfactual system is shown as Sc0 in the SI.

emissions from syngas combustion in the gas turbine were the most significant contributor to the IGCC (96 % of induced impact in both scenarios) (see Tables SI-12 and SI-14).

3.3. Ecosystem quality

The ecosystem damage category aggregated impacts from eutrophication potential, land use, acidification, water consumption, toxicity potential, ozone formation, and global warming (Bare et al., 2019). The breakdown analysis and net impacts on ecosystem quality are shown in Fig. 7A. As a result, Sc3 and Sc5 had the highest net savings, ranked first and second with net savings of −1.32E−6 and −8.44E−7 species·year/FU, respectively. The credits received by the substitution of heat had the highest contribution in both scenarios, and the substitution of electricity was the highest in Sc1. The induced impacts of all scenarios are shown in Fig. 7B. Among all unit processes, the IGCC had the highest induced impacts.

In scenario 1, 95.2 % of the total savings were contributed to the substitution of marginal electricity in the market. On the other hand, the unit process of the furnace dominated the induced impacts in this scenario (6.5E−8 species·year/FU). Such an induced impact is rooted in direct emissions from methane combustion. The detailed analysis of Sc1 showed that the direct emissions, specifically NO_x emissions, were the major contributors in Sc1 (see Tables SI-6 and SI-8). It should be noted that the performance of the mixer and furnace are the same in scenarios 1 and 2.

In scenario 2, the saving impacts caused by the avoided electricity and heat production reached −2.65E−7 and −3.82E−7 species·year/FU, respectively. Induced impacts in this scenario were rooted in the mixer, gasifier reactor, furnace, and CCGT. More specifically, deionized water is consumed during the mixing operation, imposing an induced impact of 7.75E−7 species·year/FU. The use of water from nature (see

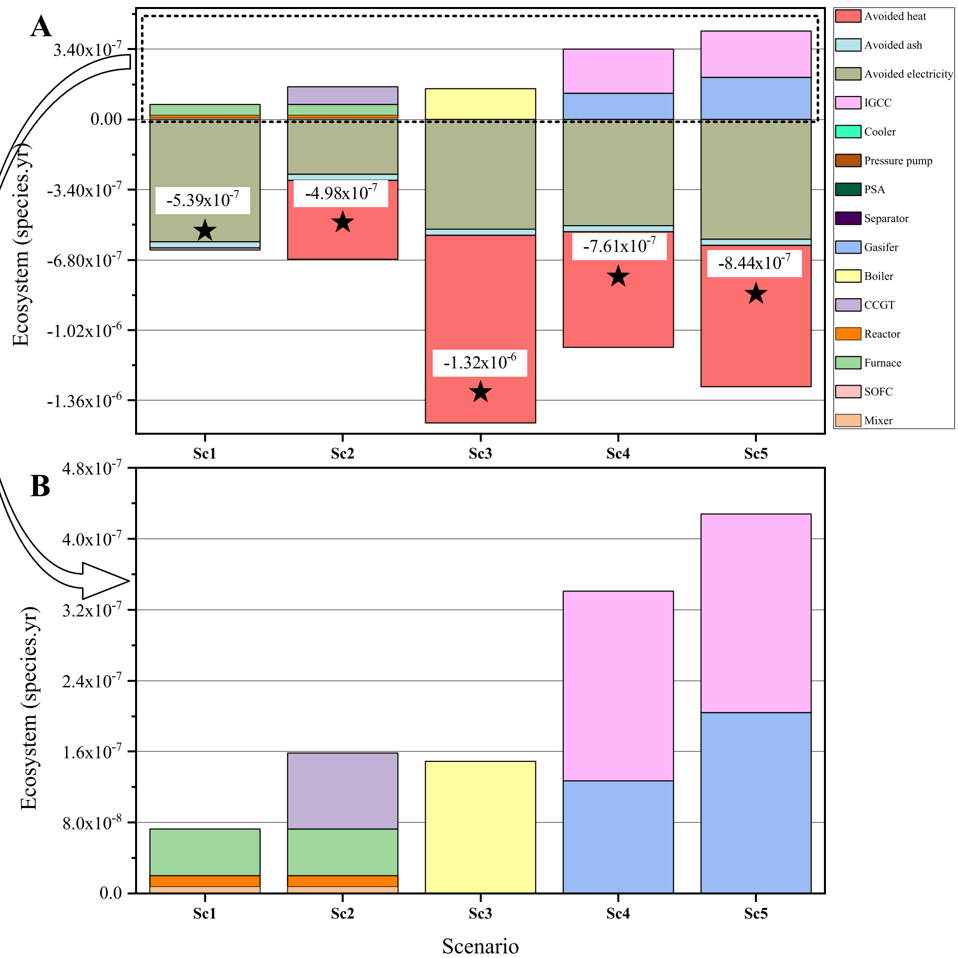

Fig. 7. A: Contributions to ecosystem quality damage category for different scenarios (stars show net value). B: Comparison of developed scenarios in Ecosystem quality induced impact. (IGCC: integrated gasification combined cycle, PSA: pressure swing adsorption, CCGT: combined cycle gas turbine, SOFC: solid oxide fuel cell.). Note: Results of the counterfactual system is shown as Sc0 in the SI.

Fig. SI-14) has the highest impact on deionized water in this damage category. The reason is that, in the long term, the use of water can result in numerous effects on the ecosystem, including death and migration of organisms, loss of habitats and species diversity, salination, soil degradation, and groundwater contamination. In the CCGT unit process, NO_x emission and water consumption dominated the induced impacts. It has been well documented that NO_x emission is a major contributor to the ecosystem damage category (de Vries, 2021); this is why the scenarios with higher NO_x emissions had a higher induced impact (Sc1 vs. Sc2, see Tables SI-6 and SI-8). NO_x is the sole emission from hydrogen combustion in the gas turbine in the CCGT unit process. Therefore, 48 % of the induced impacts are related to the CCGT unit process in Sc2 (see Fig. SI-15 for more details).

Scenario 3 had the best performance among all scenarios. This scenario received the highest credit from the substitutions of heat and electricity, −9.08 and −5.31 species·year/FU, respectively. Induced impacts in the scenario are related to the boiler (1.49 species·year/FU) and it was rooted in NO_x emissions and tap water (see Tables SI-9 and SI-10).The contribution of NO_x was 75.1 %, and the rest was associated with tap water. To be more specific, lake water from nature was the dominant parameter (see Fig. SI-16).

Likewise, Sc4 and Sc5 highly benefited from substituting marginal heat and electricity. On the other hand, Sc4 and Sc5 had higher induced impacts compared to other scenarios. The induced impacts in Sc4 and Sc5 are associated with two unit processes; IGCC and gasifier. The induced impacts from Sc4's gasifier amounted to 1.27E−7 species·year/FU, with 87.7 % contribution from the direct emissions (more importantly, NO_x emissions) caused by bagasse combustion (see Figs. SI-17 and SI-18). In S5, zeolite powder, used as bedding materials in the fluidized-bed reactor, imposed a significant impact, amounting to 2.04E−7 species·year/FU. To be more specific, in the gasifier of Sc5, 53.9 % of the impact was attributed to direct emissions, while 37.2 % was rooted in the background emissions from zeolite powder production. The induced impacts from the IGCC unit process were almost the same for Sc4 and 5 (2.14E−7 vs. 2.24E−7 species·year/FU). In both scenarios, 96 % of the induced impacts in the IGCC were contributed to direct emissions from syngas combustion (see SI-6 and SI-7 section).

3.4. Resources scarcity

The midpoint characterization factors for resource scarcity damage category are mineral resource and fossil resource (see Fig. SI-30). Similarly to human health and ecosystem quality, all five scenarios were found to be environmentally friendly in the resources damage category (Fig. 8A). However, scenarios 3, 4, and 5 had the highest savings in the resources damage category, with a net saving of −60.52, −52.45, and −45.77 USD2013/FU, respectively. The induced impacts are depicted in Fig. 8B. In the scenarios 1 and 2, deionized water consumption in the mixer unit had a major contribution to the induced impacts (more details are shown in Fig. SI-19). The contribution of CCGT was also negligible while originating from decarbonized and soft water consumption (see Fig. SI-20). All induced impacts in boiler of Sc3, is associated with the consumption of water. As illustrated in Fig. 8B, Sc5 had high induced impacts in gasifier as such impacts are rooted in the

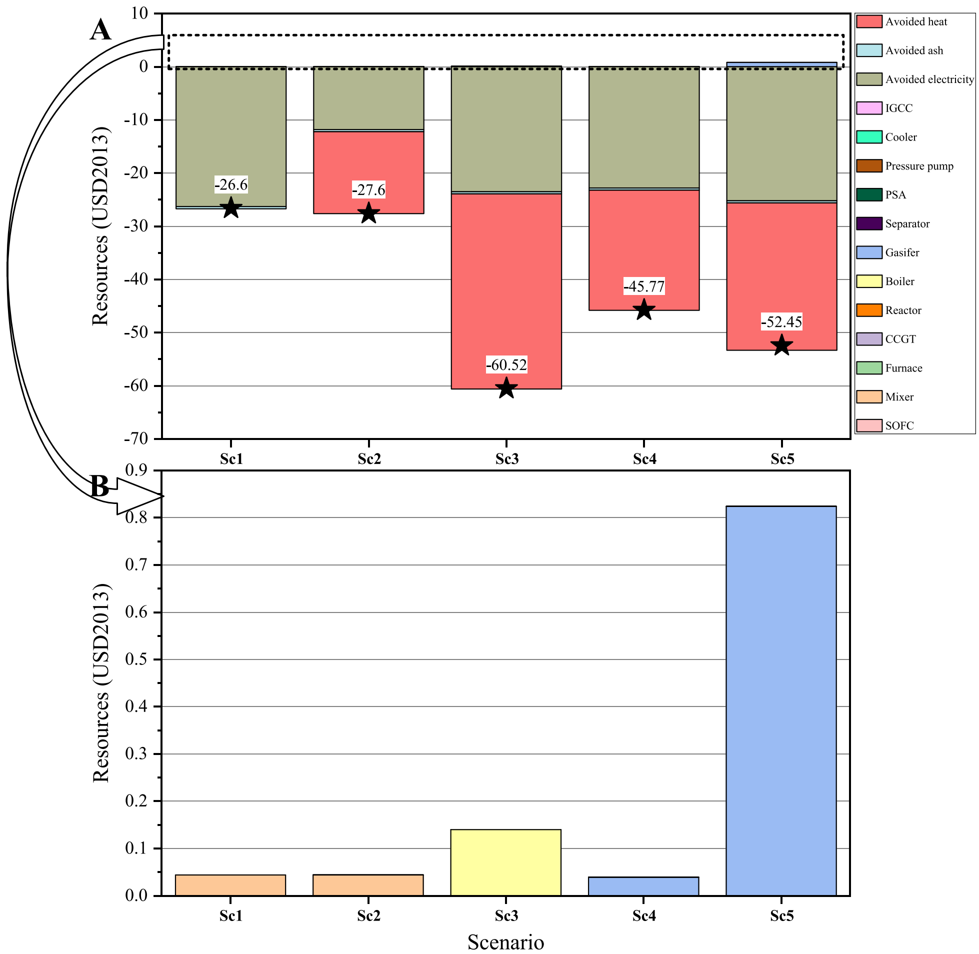

Fig. 8. A: Contributions to Resources scarcity damage category for different scenarios (stars show net value). B: Comparison of developed scenarios in Resources scarcity induced impact. (USD: United States dollar, IGCC: integrated gasification combined cycle, PSA: pressure swing adsorption, CCGT: combined cycle gas turbine, SOFC: solid oxide fuel cell.). Note: Results of the counterfactual system is shown as Sc0 in the SI.

consumption of zeolite powder (see Fig. SI-21 for Sc5 and Fig. SI-22 for Sc4).

4. Discussion

Several minor/major uncertainties can affect the final results of every LCA study (Rafiee et al., 2016). For example, substituting heat and electricity for their marginal counterparts significantly affects the overall results. However, Iran lacks district heating or proper infrastructure to deploy such recovered heat. If such a substitution could not be possible in the short term, what would be the environmental impacts of all scenarios assessed herein? Some sensitivity analyses are considered to understand to what extent our primary assumptions and modeling approach can affect the LCA results.

The sensitivity analysis was conducted to investigate the impact of heat substitution on the overall results achieved herein. As described earlier, excess heat from process received high credit; however, district heating network does not exist in Iran, the generated heat can be used within the sugar industry (Chauhan et al., 2011; Javalagi et al., 2010). As can be seen in Table 6, the least sensitive damage category was resource scarcity, whereas the most sensitive damage category was human health. Furthermore, Sc3 had the highest sensitivity to the deployment of the heat generated, where 62 % of the savings in this impact category can be lost. Since Sc1 had no surplus heat, the environmental saving in this scenario cannot be affected. Scenario 2 was also significantly affected because the net heat recovery was more than the net electricity generation in this scenario. As shown in Table 6, the extent of changes in all damage categories was also significant, while scenarios are affected differently. In the damage categories of human health and ecosystem quality, Sc5 had the highest sensitivity, with an 87 % and 81 % reduction in the savings achieved, respectively. The results

Table 6
The sensitivity analysis compares global warming and three damage categories to the baseline scenarios.

Indicator	Scenario	Changes %
Global warming	Sc1	–
	Sc2	57.5 %
	Sc3	62.2 %
	Sc4	51.4 %
	Sc5	55.8 %
Human health	Sc1	–
	Sc2	83.8 %
	Sc3	69 %
	Sc4	73.4 %
	Sc5	87 %
Ecosystem quality	Sc1	–
	Sc2	76.5 %
	Sc3	68.7 %
	Sc4	73.4 %
	Sc5	81 %
Resource scarcity	Sc1	–
	Sc2	56.1 %
	Sc3	60.6 %
	Sc4	49.3 %
	Sc5	52.7 %

show the importance of using the generated heat within the sugar industry. It would be beneficial to explore potential infrastructure changes or technologies that could enhance future heat recovery and utilization in Iran. It is also important for policymakers and industry leaders to think about strategies for maximizing heat recovery within the sugar industry, given its significant potential for reducing the current environmental impacts.

A second FU was also selected in this study as 1 kWh net electricity production from the thermal treatment of baggage (data related to this section is provided in the SI-12 section). Choosing the second FU makes it possible to compare the environmental impacts of 1 kWh of electricity generation through various scenarios investigated in this study and compare the results against electricity generation from other sources. Fig. 9 shows the results of environmental impacts related to scenarios, marginal electricity of Iran (further information about marginal electricity is discussed in SI-11.1 section) and electricity generation from different resources. Accordingly, the environmental impacts of electricity from bagasse were compared against five electricity sources: Elec-1: natural gas combined cycle power plant, Elec-2: natural gas conventional power plant, Elec-3: electricity from oil, Elec-4: electricity from 1 to 3 MW wind turbine, Elec-5: electricity from hydro run-of-river. As shown in Fig. 9, the electricity production from bagasse in all scenarios were noticeably more environmentally friendly that dominant electricity production sources in Iran (i.e., natural gas combined cycle power plants, natural gas conventional power plant, and electricity from oil). Hydropower also considerably contributes to Iran's electricity grid but its constraint by geographical location and climatic conditions. The environmental impacts of electricity generation in Sc2 to Sc5 could outperform hydropower in climate change and all damage categories investigated. Scenario 1 in which no surplus heat was generated was still a more environmentally alternative to natural gas combined cycle power plants, natural gas conventional power plant, and electricity from oil but it could not compete renewable electricity sources such as wind electricity. However, it is worth mentioning that the amount of bagasse needed to generate 1 kWh net electricity is different among all scenarios (see SI-12 section). For instance, Sc1 needs 1.68 kg of bagasse to generate 1 kWh net electricity, while the amount for Sc2 is 4.82 kg (see Tables SI-19 and SI-21).

Although SOFC is considered a clean technology because it only produces ash as a byproduct, in Sc1 the conversion of hydrogen to electricity by SOFC exhibits the worst performance. This is due the fact that the plant configuration had high internal power and heat demand. More specifically, all heat production in Sc1 was internally used causing that no surplus heat to be generated. Therefore, Sc1 could not receive any credit from heat generation as did other scenarios. Scenario 1 is more superior when hydrogen production is the main objective. Otherwise, our results showed that using boiler and steam turbine was the best approach to generate heat and electricity from bagasse.

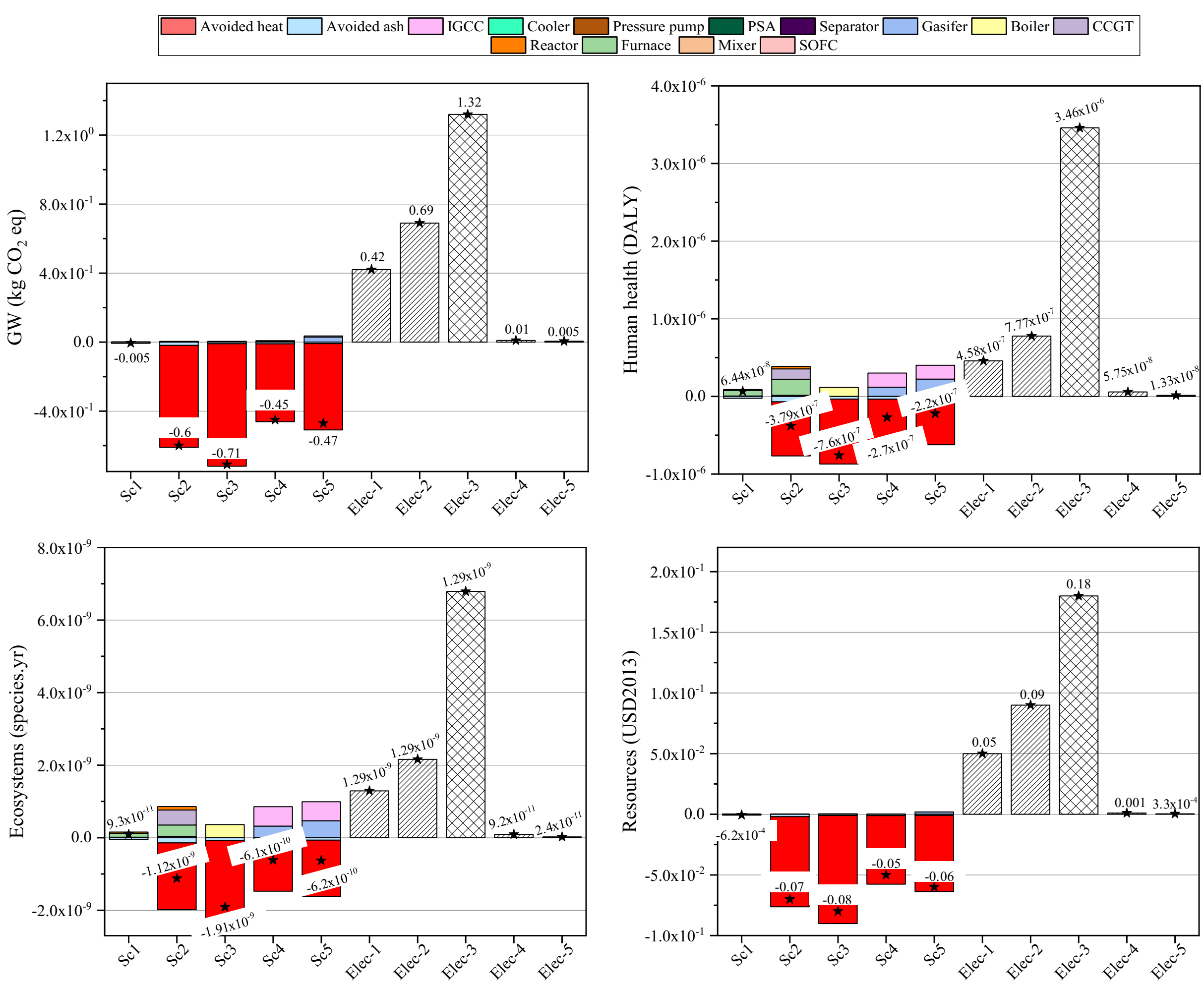

Fig. 9. Contribution of the developed scenarios and electricity of Iran in Global warming, Human health, Ecosystem quality, and Resource scarcity (FU = 1 kWh net electricity) (PSA: pressure swing adsorption, CCGT: combined cycle gas turbine, SOFC: solid oxide fuel cell, GW: global warming, DALY: disability-adjusted life year, USD: United States dollar, IGCC: integrated gasification combined cycle, Elec-1: natural gas combined cycle power plant (marginal of Iran), Elec-2: natural gas conventional power plant, Elec-3: electricity from oil, Elec-4: electricity from 1 to 3 MW wind turbine, Elec-5: electricity from hydro run-of-river).

In the sugar industry, the conventional methods of electricity generation, such as gasification, are in full commercial use, utilizing sugarcane bagasse as the source (Bruno et al., 2021). In Iran, large amounts of sugarcane bagasse can be used as the source for electricity production (Dibazar et al., 2023). In other words, 2.4 million tonnes of bagasse is annually produced in Iran (Mohammadi et al., 2020), and if it is used for electricity generation following Sc3 configuraion, it can generate 986.86 GWh electricity per year. However, the share of renewable sources in Iran's energy basket, i.e., mainly biomass, is low (Solaymani, 2021). Through using robust regulations and plicies, such as removing direct subsidies for energy or providing incentives for renewable energy generaion, the government can facilitate such transiton toward greener energy market (Moshiri et al., 2015). As a result, there can be optimism in the future that government policy reforms on energy and technology development will lead to the generation of electricity from sugarcane bagasse, which would contribute to phasing out Iran's fossile energy sources.

Numerous studies worldwide have explored the environmental impacts of generating electricity from sugarcane bagasse. However, direct comparision among these studies is challanging since the LCA results may differ due to differences in data quality, and methodological chooses. Thus, it is important to consider all these factors when LCA results from various sources are compared.

There is no doubt that fossil-sourced electricity, e.g., from coal and oil, has significantly higher environmental impacts. According to Spath et al. (1999), an average coal-fired plant in the United States produces about 1.022 kg CO_2/kWh_{el}. As compared to coal-based electricity, bagasse electricity emits 6 to 10 times fewer greenhouse gases (Hiloidhari et al., 2021a). The following are some examples of the LCA results regarding the generation of electricity from bagasse.

The study conducted by Ramjeawon (2008) indicated that the combustion of bagasse to generate 1 kWh of electricity produced 0.03 kg CO_2 eq. Mohammadi et al. (2020) investigated three methods for generating electricity (combustion, gasification, and anaerobic digestion), and found that they produced 0.2, 0.38, and 0.35 kg CO_2 eq/kWh_{el}, respectively. An analysis conducted in Brazil (Lopes Silva et al., 2014) determined that the global warming potential of generating, transmitting, and distributing electricity from bagasse is 0.14 kg CO_2 eq/kWh_{el}. Brizmohun et al. (2015), found that power generated from bagasse emits 0.029 kg CO_2 eq/kWh_{el}. According to Silalertruksa et al. (2017), bagasse-based electricity generation emits 0.038 kg CO_2 eq per kWh_{el}. Another study conducted by Renouf et al. (2011) indicates that bagasse-derived electricity emits 0.26 kg of CO_2 eq per kWh_{el}. Based on the present study, the GW impact category ranges between −0.005 and −0.71 kg CO_2 eq/kWh_{el}. The reason for this is that CLCA was used in this study, and the system received credit for avoiding heat and fertilizers. Therefore, the results of this study should be considered independently.

4.1. Prospective LCA

With the rapid shift to sustainable development in the sugar industry, both the foreground and background systems are expected to change. The changes could lead to enhanced technology efficiency, improvements in recycling systems, and reductions in energy losses. In addition, alterations to the energy mix could have an impact on the background system.

Since the current existing ecoinvent database is static, it may not fully reflect these dynamic changes. To accurately evaluate future scenarios, it is essential to consider different time frames, including short-term and long-term perspectives, such as the horizons of 2030, 2050, and 2100. In order to address this issue, prospective life cycle assessment (pLCA) can be performed, which evaluate the environmental performance of current and emerging technologies in the future (Langkau et al., 2023; Thonemann et al., 2020). As a result, the potential environmental impacts of future technologies are better understood and the development of these technologies is guided.

Besides this, shared socio-economic pathways (SSPs) refer to projected socioeconomic changes of the world up to the year 2100 that are based on climate change scenarios. The scenarios are used to determine greenhouse gas emissions associated with different climate policies (Riahi et al., 2017). By integrating SSPs and the ecoinvent database, pLCA can be enhanced in terms of providing a comprehensive, dynamic assessment of the sustainability of technologies. To simplify this process, a tool called "Premise" has been already developed which integartes shared socio-economic pathways into ecoinvent database. The purpose of Premise is to generate prospective inventory databases for pLCA through the integration of scenarios generated by integrated assessment models (IAM). As a result of the projections provided by the IAM, transformations are applied to energy-intensive activities in the ecoinvent database (Sacchi et al., 2022). As a result of this approach, the environmental performance of technologies can be assessed in a more dynamic and future-oriented manner.

4.2. Implication and limitation

Establishing clear planning and regulatory pathways in developing countries and emerging economies is essential to the development of different technologies for converting bagasse (and other biowastes) into energy. Sustainability is not only determined by the conditions of an industry, but also by the broader conditions of a country, including legislation, institutions, policy frameworks, and financing, which constitute all aspects of governance in the country (Salazar et al., 2023). A major obstacle to the development of renewable energy technologies in developing countries like Iran is the economic and financial conditions (Oryani et al., 2021). By providing financial supports and other relevant regulations such as green tax and incentives, the development of green technologies may be facilitated in future. On the other hand, investors will be able to purchase and install the necessary equipment and infrastructure at a more cost-effective price, taking advantage of all relevant financial supports to increase electricity production and optimize the use of heat and electricity on-site (Bin et al., 2023; Abdul et al., 2021). Collectively, these measures contribute to the efficient and sustainable use of bagasse for energy production.

Furthermore, using sugarcane bagasse for energy generation has significant economic benefits and can help to shift into circular bioeconomy (Ungureanu et al., 2022). Besides providing a renewable source of energy, the process also allows for the utilization of residual streams or waste flows from sugarcane production process (Ajala et al., 2021). Additionally, bagasse-based heat and electricity cogeneration can provide financial relief to sugarcane millers in sugar factories (Kabeyi and Olanrewaju, 2023). There is also the possibility of generating additional revenue through the export of excess electricity to the grid.

Several limitations identified in this study should be addressed and overcome in future research. As an example, advanced technologies such as SCWG and gas turbines that utilize hydrogen are still in the process of maturation (Cecere et al., 2023; Guti, 2022). There is the potential for these technologies to enhance efficiency and undergo significant transformations, with the possibility that further improvements in efficiency may be made in the near future.

Moreover, there is no district heating infrastructure in Iran (Abbaspour et al., 2022). While this infrastructure is not present at present, it may develop in the future, which could have a significant impact on the feasibility and efficiency of the technologies under study.

Furthermore, this study considered that hydrogen produced by SCWG is converted into electricity. However, it may be more beneficial to use hydrogen for other purposes rather than generating electricity in the future. The study did not take into account possible uses in the transportation, heating, or petrochemical sectors.

Although this study offers a comparative analysis of different WtE technologies, it does not take into account potential technological advancements or policy changes which might have an impact on the sustainability and environmental impacts in the future. As discussed in Section 4.1, future studies could take into account the dynamic factors for a more comprehensive analysis.

5. Conclusions

The potential for generating electricity from sugarcane bagasse is a promising solution that can provide additional value to the sugar production process while addressing the challenges associated with bagasse disposal. Furthermore, the heat generated can be utilized as energy in various industries, such as sugar factories. Accordingly this study employed life cycle assessment method (LCA) as early environmental sustainability guidance to account for the environmental impacts of various WtE technologies in the sugar industry. According to the results, Scenario 3 (direct combustion in a boiler with a steam turbine) outperformed the other scenarios in all damage categories. For scenarios involving hydrogen production (Scenarios 1 and 2), it is recommended to operate at temperatures higher than the specified range, such as 600 °C or 650 °C. In Scenario 1, despite being a clean technology, the SOFC falls short due to plant's high internal heat and power demand. The substitution of heat from various technologies emerged as a critical hotspot. Fluidized-bed gasification exhibited greater impact savings compared to fixed-bed gasification, except in the human health impact category. In subsequent research, it would be beneficial to address and overcome certain barriers and limitations. It is anticipated that a period of 5 to 10 years will be required for such technologies to be fully developed and for the energy produced to be utilized. Within this timeframe, technologies such as SCWG, fuel cells, and gas turbines have the potential to improve efficiency and undergo significant transformations. Also, the infrastructure for using district heating may be implemented in Iran. Consequently, future modeling of WtE technologies introduces an element of uncertainty in the results. This uncertainty could be further explored using probabilistic uncertainty models in future investigations. Future research could focus on developing sustainability assessments that incorporate environmental, social, and economic factors in order to provide a more comprehensive understanding of the subject. In this way, the sustainability of each WtE technology could be viewed from a triple-bottom-line perspective. The sugar industry would also benefit from exploring the potential of emerging technologies such as artificial intelligence and machine learning in optimizing energy use and waste management.

CRediT authorship contribution statement

Amin Sadeghi Sheshdeh: Conceptualization, Data collection, Formal analysis, Methodology, Software, Writing - original draft. **Mohammad Reza Sabour:** Conceptualization, Supervision, Writing - review & editing. **Fateme Mohammadi:** Data collection, Software, Investigation. **Jin Hui:** Validation, Writing - review & editing. **Morten Birkved:** Funding acquisition, Writing – review & editing. **Benyamin Khoshnevisan:** Conceptualization, Supervision, Data validation, Writing – review & editing.

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

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2023.12.014.

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