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The greenhouse gas performance and climate change mitigation potential from rice straw biogas as a pathway to the UN sustainable development goals

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A B S T R A C T

Rice, as a main crop, contributes to food security in Asia. However, its by-product, rice straw, poses challenges as it is often disposed of unsustainably. This research investigates the environmental performance of a 1000 m^3 rice straw biogas pilot plant in Laguna, Philippines. A lifecycle assessment identified the climate change impact of the biogas system, straw burning and soil incorporation. In addition to GWP100, the global temperature potential's dynamic climate effects were assessed, including integrated radiative forcing and instantaneous temperature effects. The timeframe of the biogenic emission fluxes of rice production is particularly relevant as the sequestered CO_2 during plant growth is partly released as methane and CO_2, depending on the straw management practices. Straw burning had the highest net emission impact. However, straw incorporation has the highest short-term radiative forcing and temperature increase. The biogas system provided significant short- and long-term GHG emission reduction of up to 68 % when biogas replaced burning or soil incorporation and the use of fossil fuels. Still, considerable uncertainties remain about fugitive methane emissions, handling and post-processing of the digestate. While single GHG emission figures on a GWP100 basis are useful for informing decision-making, this single-metric approach limits understanding of rice production's short- and long-term impacts. Additionally, our assessment emphasises the necessity for governance frameworks that promote sustainable practices in rice farming, as banning rice straw burning may result in less favourable outcomes from soil incorporation, whereas integrating biogas offers a solution benefiting rice-growing communities and global sustainability efforts.

1. Introduction

Rice production and unsustainable rice straw disposal are key contributors to global greenhouse gas emissions (GHG). Globally, rice production releases about 30 million tonnes of methane (CH_4) annually, about 8 % of global CH_4 [1] and about 2 % of global GHG emissions [1,2]. While CH_4 is the dominant GHG in rice production in flooded paddy fields, significant environmental impact arises from unregulated rice straw burning in the fields after harvest. This is particularly apparent in Asia, leading to significant health and environmental pollution problems [3]. In Asia, about 650–700 Mt of rice straw are produced annually [4,5]. Most of Asia's 200 million rice growers are small-scale farmers with less than 1 ha of farmland and low income [6]. Utilising rice straw for energy and facilitating energy access for rural communities could offer a valuable low-carbon bioenergy source.

The Philippines is one of the main rice-producing countries globally and rice production is a key economic activity for about 2 million farm households [7,8]. Rice is grown in small-scale systems in the Philippines, with 1.4 ha as the average rice farm size [7]. About 19 Mt of rice are produced annually in the Philippines [5] in two crop cycles of 4–6 months each. On average, one tonne of rice produces about 1 t of straw [4]. Traditionally, rice farming was dominated by labour-intensive manual land and crop management practices. Most of the straw was burned for quick disposal and to allow land preparation for the following crop [9]. However, straw burning causes significant environmental and health impacts as various air pollutants (carbon dioxide, carbon monoxide, particulates, dioxins, furans) are released [10,11]. In recent years, straw burning has significantly reduced, and straw incorporation is the

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most common straw management option. This change in straw management is encouraged by national and local authorities to stop rice straw burning in line with legislation that prohibits the burning of straw [9,12,13].

Additionally, a rapid uptake of semi-mechanised crop management and mechanised harvest practices with combine harvesters could be observed. The most used combine harvesters in the Philippines cut the straw about 30–40 cm above ground, with the stubbles remaining in place and the cut and threshed straw being spread on the field in windrows. With the scattered distribution of straw in the field, farmers started to incorporate the straw and stubbles during the following land preparation.

For several reasons, using rice straw as low-carbon energy could be an attractive option in rice growing. Reducing the amount of organic matter from flooded paddy fields can reduce methane emissions produced during the anaerobic decay of the straw. Similarly, reducing the burning of straw would reduce environmental and health impacts. Producing biogas from rice straw can provide communities with a sustainable alternative to straw burning and incorporation and offer access to a renewable energy source. This potentially displaces fossil fuel use, leading to further emission reduction.

However, challenges associated with implementing new technology innovations in rice-growing communities were identified during an earlier project phase that focused on utilising rice straw for energy use [14,15]. This research investigates the environmental performance and GHG emission trade-offs of biogas production from rice straw compared to current rice straw management practices. The assessment is based on the activities and implementation of a rice straw biogas pilot plant in the Philippines.

This research aims to conduct a lifecycle assessment (LCA) to evaluate the GHG emission profile of different rice straw management options and the potential of reducing emissions from rice supply chains by introducing biogas production. Focus is given to straw management as straw is a main source of CH_4 emissions. The straw management options investigated are straw burning, incorporation, and removal with biogas production. A central assessment element is expanding the system boundaries, including avoiding emissions from straw decay, fossil fuel use, biogenic GHG fluxes, and temporal climate change impacts.

Integrating biogas in the rice production supply chains results in changes in straw management. It provides a renewable energy source that can displace fossil fuel use. This has counterfactual impacts on the overall system, and understanding this wider emission impact is important to evaluate the sustainability of rice straw biogas.

Additionally, the biogenic GHG fluxes and temporal impact of GHG emissions are important. The timeframe of carbon sequestration during plant growth and release during straw management is very short, within 4–6 months. However, there is a potential change in GHG type in rice cultivation depending on the straw management approaches. Sequestered CO_2 during biomass growth might be released as CH_4, with a 28-times higher climate change effect for a 100-year time horizon. Additionally, with a different atmospheric lifetime, CH_4 shifts the timing of the peak temperature impact. This will have a temporal impact on the atmospheric GHG balance and climate change effects. The temporal climate change impact of the different straw management options and biogas use will be assessed to capture this impact and inform decision-making on climate change mitigation measures.

The research was part of the Innovate UK-funded Energy Catalyst Round 4 project "Rice Straw to Biogas" to set up, test and assess a biogas facility for anaerobic digestion of rice straw [16].

2. Material and method

2.1. Description of case study area and biogas facility

The biogas pilot facility assessed in this environmental impact assessment is based in the barangay San Francisco, municipality of Victoria, Laguna province in the Philippines (see Fig. 1). Rice is a main agricultural crop in Laguna, with about 14–16 thousand hectares of rice paddies [7]. Rice is grown twice a year in a dry and wet cropping season; about 5 million hectares of rice are grown annually [7]. The average rice yield is about 4 t ha^{-1}, totalling about 20 million tonnes of rice each year [7,17]. With this, about 0.7 t to 1.4 t of straw (green) per tonne of rice [18], about 14 t to 28 t of rice straw amount annually.

As for most of the Philippines, in Laguna, rice is grown on a small scale, with a typical rice farm size of about 1.5 ha–2 ha [19–21]. The rice fields are divided by narrow irrigation canals and dykes [20,21]. An increase in the mechanisation of rice production has been observed in recent years. However, walk-behind semi-mechanised devices dominate land and crop management [22]. Still, the use of combine harvesters has seen a rapid uptake in replacing hand-harvest and semi-mechanised threshing. The detailed agricultural practices are described in section 2.2.

The biogas facility is a dry digestion batch system with two 500 m^3 reactors built from a PVC liner. The digester includes internal irrigation hoses and a sump pump to circulate the leachate in the digester. The biogas is collected in a PVC bladder. Gas blower fans are used to move the biogas from the digester to the gas bladder via pipes. The biogas from the storage gas bladder can then be filled into other containers (gas bags, compressed gas bottles) or be directly used in a 3.5 kW biogas CHP unit. The resident time of the straw, as this is a batch system, is about 4–6 months, depending on the biogas production.

2.2. Rice production

Rice production in the Philippines can be characterised by semi-mechanised production, including manual and mechanised activities, mainly using walk-behind 2-wheel tractors.

Land preparation includes primary and secondary tillage, ploughing and harrowing, and levelling as the third tillage activity. These three activities are commonly done by using a walk-behind 2-wheel tractor. Once the paddy field is prepared, seedlings, which have been grown in a small, separated seed bed, are transplanted. While mechanised transplanting devices exist, most transplanting is still done by hand. The application of fertiliser and, where required, plant protection is applied also manually. This semi-mechanised rice production approach is considered for all rice straw management systems.

Additionally, rice requires irrigation. While many paddy fields are connected to the national irrigation network, this is maintained poorly, and most farms run private diesel-driven pumps to ensure the right amount and timing of irrigation. This is particularly important during the dry season.

2.3. Rice straw management systems

For this research, three different rice straw management systems have been assessed: straw burning, straw incorporation, and straw removal with biogas production.

For all rice straw management systems, similar upstream rice production practices to the point of rice harvest were assumed. For rice harvest, 3 different ways of harvesting were considered as these will partly influence the straw management and are described in detail for each rice straw management system.

2.3.1. Rice straw burning

Following the rice production as described in section 2.2, the rice is harvested considering two different options: manual cutting and threshing with a stationary diesel-fuelled thresher in the field, harvesting with a walk-behind reaper (semi-mechanised) and threshing with a stationary diesel-fuelled thresher in the field. Following the threshing, the rice is collected in 50 kg sacks and carried by labour to the roadside for transport to the farm or storage. For both harvesting options, straw accumulates in a heap in the field, and a common method to dispose of

Fig. 1. R2B pilot facility in San Francisco, Laguna, Philippines. The picture shows the two 500 m^3 digesters (Left: digester covered with grey canvas and digesting rice straw. Right: preparation of digester with rice straw bales).

the straw is in-field burning.

2.3.2. Rice straw incorporation

Following the rice production described in section 2.2, the rice is harvested considering two options: harvesting with a walk-behind reaper (semi-mechanised) and threshing with a diesel-driven thresher in the field; combine harvesting, including cutting and threshing at the same activity. In the case of reaping with diesel-driven threshing in the field, the rice is collected in 50 kg sacks and carried by labour to the roadside for transport to the farm or storage. The straw accumulates in a heap in the field and needs to be spread manually to disperse it for easier incorporation during tillage.

In the case of combine harvesting, the rice plant is cut, threshed, and grain and straw separated. The straw is blown out from the combine harvester in scattered windrows. This way, the straw is dispersed for incorporation during the following land preparation. The uptake of combine harvesting has resulted in increasing incorporation as the already scattered straw is easier to incorporate and difficult to burn.

2.3.3. Rice straw removal and biogas

Following the rice production described in section 2.2, the rice is harvested using a combine harvester. It is then baled with a tractor-pulled baler. The bales are collected at the road site and transported to the nearby biogas facility with an average of 10 km round trip distance with an empty return. At the biogas facility, 300 m^3 straw is manually loaded in the digester; about 12 t of cow manure and 40 m^3 of water are added. As a batch system left, the digester is kept closed for 4–6 months with regular pumping to circulate the leachate and using a blower to remove the produced biogas and store it in a gas bladder. At the end of the digestion process, all gas is emptied from the digester by blowing it into the gas bladder, the leachate is collected for the next batch in an earth pool, the digester is opened, and the digestate is removed with a small bulldozer and stored onsite for aerobic composting and air drying to produce a horticultural compost. The composting process will take another 4–8 weeks, resulting in a compost that can be used for different purposes. In this case study, compost was not returned to rice fields but sold to local horticultural enterprises.

Three options for biogas use were considered: electricity generation using the onsite 3.5-kW CHP unit, domestic cooking with the biogas, and operating an irrigation pump. The specifications for the different types of energy generation and use are provided in Table 4 as part of the LCA inventory.

2.4. GHG and climate change impact

2.4.1. Lifecycle assessment

An attributional LCA was conducted with the goal of evaluating the dynamic climate impact of the 3 different rice straw management options in the Philippines: straw burning, straw incorporation, and straw removal with biogas production in the described biogas pilot plant. The scope was all rice production and post-harvest activities, including increased or displaced energy and material use emissions. Particular focus was given to post-harvest activities within the control of the farmers.

The LCA followed the ISO Standard 14040:2006 and 14044:2006 [23,24] and was conducted using SimaPro 9.5 using the Ecoinvent 3.9.1 database and the ILCD 2011 Midpoint + V1.11/EC-JRC Global, equal weighting [25]. An attributional mid-point assessment was suitable to achieve the goal and scope of the LCA and allow a comparison between the emission profiles of the different straw management options and biogas uses and their counterfactuals.

The main impact category assessed was Global Warming Potential (GWP100). The final unit of measurement was kilograms of CO_2 equivalent (eq) mass per tonne of rice straw; this included fossil and biogenic CO_2, CH_4 and N_2O emissions as main GHGs. The functional unit was one tonne of rice straw.

The LCA scope included land preparation, tillage, crop establishment and management, fertiliser and herbicide application where relevant, harvest and rice straw management, transport and biogas production and use.

To allow an easier comparison of results, two levels of system boundaries were considered, which are also illustrated in Fig. 2. The first system boundary includes rice production, straw management, and biogas use. It can be argued that the fertiliser input is reduced in the case of straw incorporation because straw returns nutrients to the soil. However, farmers in the fieldwork location did not change fertilisers or other agrochemical applications by changing straw management. The system boundary is then expanded to the biogas use counterfactual, including avoided emissions from straw removal and biogas production and use compared to alternative straw management options and alternative fuel uses for electric production, domestic cooking, or irrigation.

The lifecycle inventory for rice production, harvest and post-harvest activities of the three straw management options and biogas production is presented in Table 1, 2, 3 and 4.

2.4.2. GHG emissions impact from biogas use

Rice production is one of the main emitters of CH_4, and a share of these emissions relates to decaying biomass containing the carbon

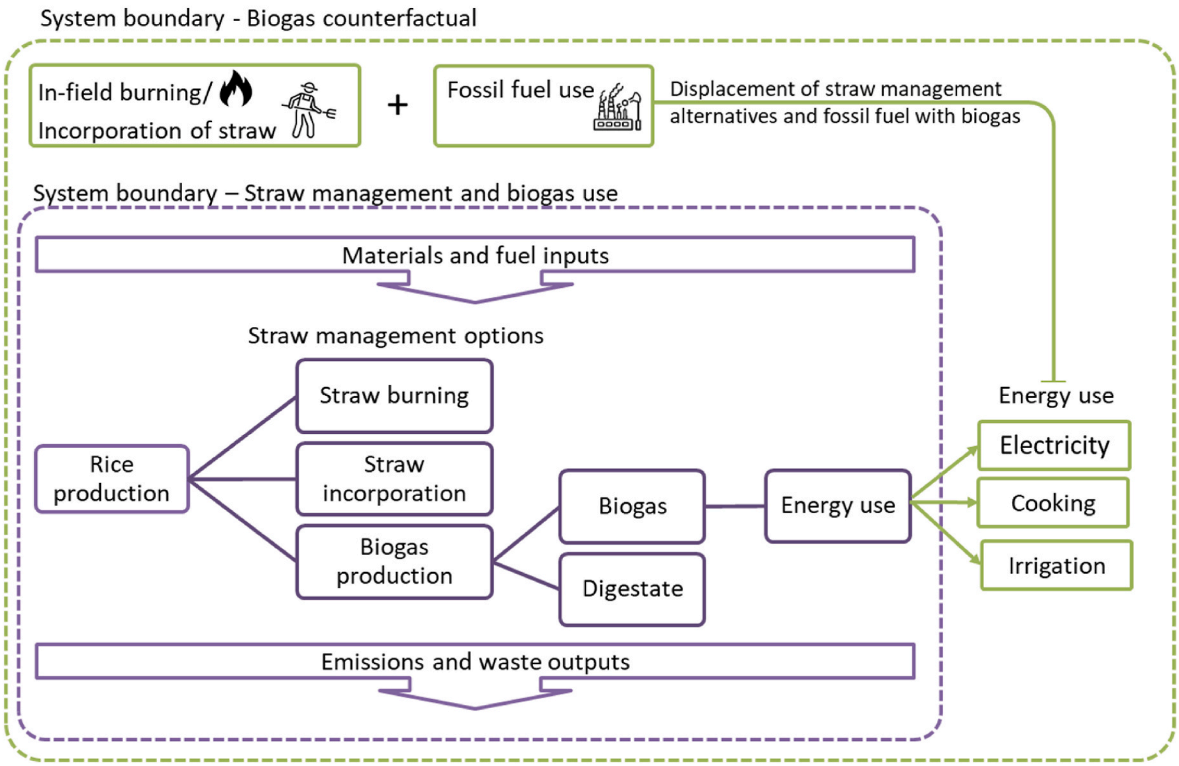


Fig. 2. System boundary for rice straw management with the expansion of boundaries referencing the final energy use.

Table 1
Lifecycle inventory rice production.

Item	Unit	Value
Rice yield		
Yield rice straw	t ha^{-1}	3
Yield rice grain [26]	t ha^{-1}	4
Straw: grain ratio [3,4]		0.8
Dry matter rice straw (pilot plant) [3]	%	80
Land preparation		
Ploughing (diesel) [27]	l ha^{-1}	7
Harrowing (diesel) [27]	l ha^{-1}	7
Levelling (diesel) [27]	l ha^{-1}	7
Rice production		
Seeds [28]	kg ha^{-1}	75
Pumping (diesel) [27,29]	l ha^{-1}	200
Fertiliser NPK 15-15-15 [26,30]	kg ha^{-1}	167
Fertiliser Urea [26,30]	kg ha^{-1}	100

previously sequestered as CO_2 from the atmosphere. This means while CO_2 is sequestered during rice growth, CH_4, as a stronger climate change forcer, is subsequently released. The net emission for each rice straw management option was included in the evaluation to capture this change of forcing impacts.

The net GHG emissions are the sum of all biogenic and fossil-based emission flows as described in Equation 1

$$E_{GHG} = (CO_2 + CH_4 + N_2O)_{in} + (CO_2 + CH_4 + N_2O)_{out}$$

Additionally, the emissions impacts of the final use of biogas and GHG savings from replacing fossil fuels were assessed.

Additionally, the GHG emission profiles of the three biogas use options for the fossil fuels currently used have been calculated. Fossil fuel use builds the reference scenarios for the three different biogas uses, which are as follows: electricity provision from grid electricity, domestic cooking using bottled LPG, and irrigation pumping with diesel.

The GHG results for each fossil fuel reference case were subtracted from the GHG emissions or the corresponding biogas option to calculate the GHG emission reduction. Additionally, the GHG emissions from the straw management were included as the rice straw still needs to be managed when fossil fuel is used. The reduced emissions were calculated following Equation 2

$$E_{red} = E_{Biogas} - E_{fossil} - E_{straw}$$

Table 2
Lifecycle inventory rice harvest for different levels of mechanisation and different rice straw management options.

Item	Unit	Rice straw burning		Rice straw incorporation		Rice straw removal and biogas
		Manual	Semi-mechanised	Semi-mechanised	Combine harvester	Combine harvester
Reaper (petrol) [27]	l ha^{-1}	n/a	7	7	n/a	n/a
Mobile thresher (diesel) [27]	l ha^{-1}	12	12	12	n/a	n/a
Combine harvester (diesel) [27]	l ha^{-1}	n/a	n/a	n/a	15	15
Bailing (diesel) [27,31]	l ha^{-1}	n/a	n/a	n/a	n/a	13
Bales (pilot plant)	p ha^{-1}	n/a	n/a	n/a	n/a	205
Bale [31]	kg p^{-1}	n/a	n/a	n/a	n/a	14.5
Bales per trailer (pilot plant)	p	n/a	n/a	n/a	n/a	30
Round-trip straw transport (pilot plant)	km	n/a	n/a	n/a	n/a	10
4-wheel tractor (diesel) [32]	kg tkm^{-1}	n/a	n/a	n/a	n/a	8

Table 3
Lifecycle inventory for pilot plant biogas facility (onsite measurements).

Item	Unit	Value
Biogas facility inputs		
Size digester	m^3	500
Total load (rice straw)	m^3	300
Batch retention time	days	180
Straw loss (wet basis)	t	35
Straw bales (wet basis)	t	58
Straw bales	p	4000
Manure	t	12
Water	m^3	40
Pumping of leachate (electricity)	kWh per day	8
Blower to remove biogas (electricity)	kWh per day	0.5
Loading and unloading digester (diesel)	l	50
Biogas facility outputs		
Biogas production	Nm^3	6600
CH_4 content	%	47 %
Calorific value biogas	kWh Nm^3	4.7
Energy per straw	kWh kg^{-1}	0.53
Digestate	t	63
Emission factor biogas combustion [33]	kg CO_2 $Nm^{3\ -1}$	1.8

Table 4
Devices for biogas use and energy generation and alternative fuels and emission intensity.

		Electricity	Cooking	Irrigation
Device		CHP 3.5 kW (Cummins C115D)	Domestic gas cooker	Irrigation diesel pump (900–1500 RPM)
Conversion efficiency	%	30 [34]	50 [35]	20 [36]
Alternative fuel		Grid electricity	LPG	Diesel
Emissions factors at application from fossil fuels	CO_2 eq kWh^{-1}	0.7	0.6	1.6
Emissions factors at application from biogas	CO_2 eq kWh^{-1}	0.7	0.4	0.7

2.4.3. Sensitivity analysis

Sensitivity analyses for bioenergy LCAs are often done for supply chain activities that are well understood, like transport and energy conversion efficiency [37]. The investigated rice straw biogas supply chain of the pilot plant includes stretches across agricultural and energy production and use activities subject to uncertainties and variations due to the nature of rice production and the operation of a newly set up biogas pilot facility. Particularly with biogas production, there is limited knowledge on impacts from fugitive emissions and emissions related to the storage of digestate.

In the Philippines, rice is produced in a wet and dry season, depending on the level and timeframe of paddy field flooding. This can significantly impact CH_4 and N_2O emissions [11,38,39]. The operations of the pilot facility showed that the quality and usability of the rice straw varies significantly between the wet and the dry season. During the dry season, the straw can be more easily harvested with less contamination compared to the wet season. At the same time, the straw will be drier, which can have a limiting impact on biogas production. Still, it might be challenging to mobilise all straw in an appropriate quality during the wet season. To capture possible variations during the dry and wet season, sensitivity analysis was conducted for each season in addition to assessing the annual average emissions as the baseline. The relevant inventory data is collated in Table 5.

In addition to seasonal variation, there are operational uncertainties. Biogas facilities have the risk of fugitive emissions from biogas slip during biogas production. Assessing fugitive emissions and minimising the impact is environmentally and commercially important as fugitive emissions reduce the emission savings benefit of biogas and, at the same time, reduce the amount of useable biogas.

Table 5
Lifecycle inventory field emissions for different rice straw management options [11,39].

Item	Unit	Rice straw burning	Rice straw incorporation	Rice straw removal with biogas production
CH_4 wet season	kg ha^{-1}	89	184	81
CH_4 dry season	kg ha^{-1}	51	130	41
CH_4 average	kg ha^{-1}	70	157	61
N_2O wet season	kg ha^{-1}	2.3	1.9	1.6
N_2O dry season	kg ha^{-1}	1.5	1.0	0.6
N_2O average	kg ha^{-1}	1.9	1.5	1.1

Values on the amount of fugitive emissions vary widely [40]. To understand the possible impact of fugitive emissions on the overall emission profile of a biogas facility, a sensitivity analysis was considered following existing literature values on biogas loss [40,41] using a default of 0.5 % fugitive emission and increasing them to 1 % and 3 %.

While the main share of volatile solids decomposes during anaerobic digestion, decomposing the left decomposable matter in the digestate can lead to additional emissions after biogas production. The GHG type and amount will depend on volatile solids, aerobic and anaerobic environment during storage, temperature, moisture content and microbial processes. As for fugitive emissions, there are large variations and uncertainties related to decomposing and composting emissions [42–44]. A sensitivity analysis was also conducted, assessing the impact of composting the digestate. This was based on existing literature values [42–44].

The sensitivity analysis for both fugitive and composting emissions was then combined to provide results on the overall impact of these two factors. The assumption for the sensitivity analysis is included in Table 6.

The assessment focused on GWP as an impact category. While other categories related to air and water pollution are of interest, the data available, particularly on straw burning and diesel-driven irrigation pumps, was limited, not allowing a comprehensive assessment and comparison and would have been subject to high levels of uncertainty.

2.5. GHG flux and temporal climate change impact

The timeframe of the biogenic emissions flux of rice straw is very short, with 4–6 months of growth followed by immediate straw management. However, the GHG type can change based on crop and straw management. CO_2 previously sequestered during biomass growth might get released as biogenic methane, with a different temporal climate change impact, as long-term forcers like CO_2 and short-term forcers like CH_4 have different timing and magnitude of climate change impacts. While GWP 100 is the main metric to assess climate change impacts to

Table 6
Sensitivity analysis for fugitive emissions and emissions from composting.

Item	Unit	Default	Medium	High
Fugitive emissions [40,41]				
Fugitive emissions as % of biogas production	%	0.5 %	1 %	3 %
Composting emissions [42,44]				
CH_4	kg t^{-1}	0.03	0.34	3.4
N_2O	kg t^{-1}	0.05	0.08	0.16
CO_2	kg t^{-1}	0	0	0.1

inform policy, it does not capture the timing and impact of different forcers. An assessment based on the mix of GHGs from the LCA was used to evaluate the climate impact and timeframe of the different rice straw management options. For this, a spreadsheet tool developed by Cooper et al. [44,45] was used to assess the global temperature potential's dynamic climate effects, including integrated radiative forcing and instantaneous temperature effects. This assessment included only the carbon sequestered in the straw and not the grain, as the fate and time frame of biogenic carbon release from the grain is uncertain and not within the scope of this study.

For simplicity, the temporal impact of a single-point emission release has been considered, assuming that all emissions are released simultaneously and only once and not a cumulative assessment. This allowed a simple comparison of the temporal climate change impact of the different straw management options. Of course, this is not the case in a real-world setting, as emissions occur at different stages and times of the supply chain. However, as the timeframe for one rice straw rotation is about 6 months, further disaggregation on, for example, a weekly basis would not have provided significantly different results.

3. Results

3.1. GHG emissions from rice production

Rice production has been assessed for three different harvest regimes: manual, semi-mechanised, and mechanised. The results are presented in Fig. 3. The total rice production and harvest emissions per tonne of rice straw are 143.1 kg CO_2 eq, 144.9 kg CO_2 eq and 144.6 kg CO_2 eq for rice production with manual, semi-mechanised and mechanised harvest. Crop production and management are the same for all three types of harvest, described in the method section, resulting in the same amount of emissions. The emissions related to harvest differ slightly as manual harvest only releases emissions during threshing, semi-mechanised harvest during harvesting and threshing, and mechanised harvest from using a combine harvester. The results show that emissions hardly change as introducing the reaper instead of hand harvesting has only a small impact. A similar impact can be observed with introducing a combine harvester as this replaces reaping and threshing, leading to a replacement and slight reduction in fuel requirements. The main share of emissions during rice production is from using diesel for pumping irrigation water and emissions from fertiliser use, including direct soil emissions.

3.2. GHG emissions from straw management

Fig. 4 presents the emission profiles of the three investigated straw management options: burning, incorporation and removal with biogas production and use. Rice sequesters 472 kg CO_2 eq per tonne of rice straw during growth. The emissions from the different crop production and management regimes vary slightly between 143.1 kg CO_2 eq and 144.9 kg CO_2 eq per tonne of rice straw, as described in the LCA results for rice production.

The most significant difference in the results is caused by the emissions related to the different straw management options. In the case of rice straw burning, a total of 514.7 kg CO_2 eq per tonne of rice straw is released. Of these emissions, 270.4 kg CO_2 eq is released mainly from biogenic CO_2 when burning the straw. An additional 244.3 kg CO_2 eq is released during the decay of stubbles and residues left in the field. These are biogenic carbon emissions, mainly $CH_{4,}$ as the residues decay under anaerobic conditions in the irrigated field. Carbon monoxide, volatile organic carbon (VOC), black carbon and other air pollutants during straw burning were not included due to a lack of data. However, such emissions, if included, would increase the GWP.

Regarding rice straw incorporation, 466.3 kg CO_2 eq per tonne of rice straw is released. These emissions are mainly CH_4 from the decay of the straw left and incorporated in the field. While the straw starts to decay before incorporation, the decay occurs after incorporating and flooding the field for the following crop.

In the case of straw removal and biogas production and use, 441.5–442.1 kg CO_2 eq per tonne of rice straw is released depending on the final biogas use. There are still emissions related to straw decay in the field as stubbles remain on site. Still, with a lower cut than in hand- or semi-mechanised harvest, biogenic field emissions are 196.5 kg CO_2 eq per tonne of rice straw. Additionally, activities linked to biogas production, such as baling and transporting the straw and energy use at the biogas facility, lead to fossil-based emissions, adding 41.9 kg CO_2 eq per tonne of rice straw. Once the biogas is used for energy generation, the biogenic CO_2 embedded in the biogas will be released back into the atmosphere. In the case of electricity generation or irrigation water pumping, another 203.1 kg CO_2 eq per tonne of rice straw is released. Domestic cooking with biogas will release 203.7 kg CO_2 per tonne of rice straw.

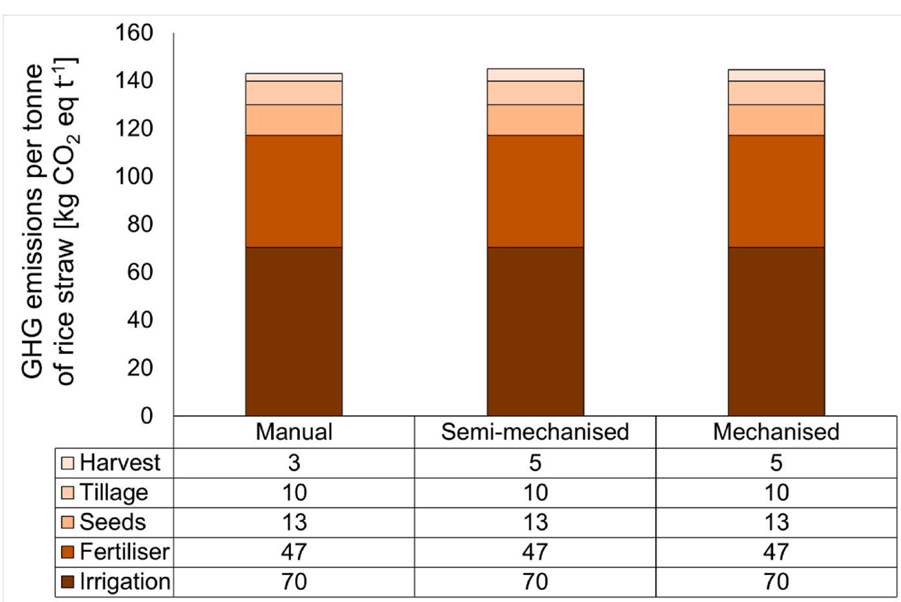


Fig. 3. Emissions from rice production and different harvest regimes.

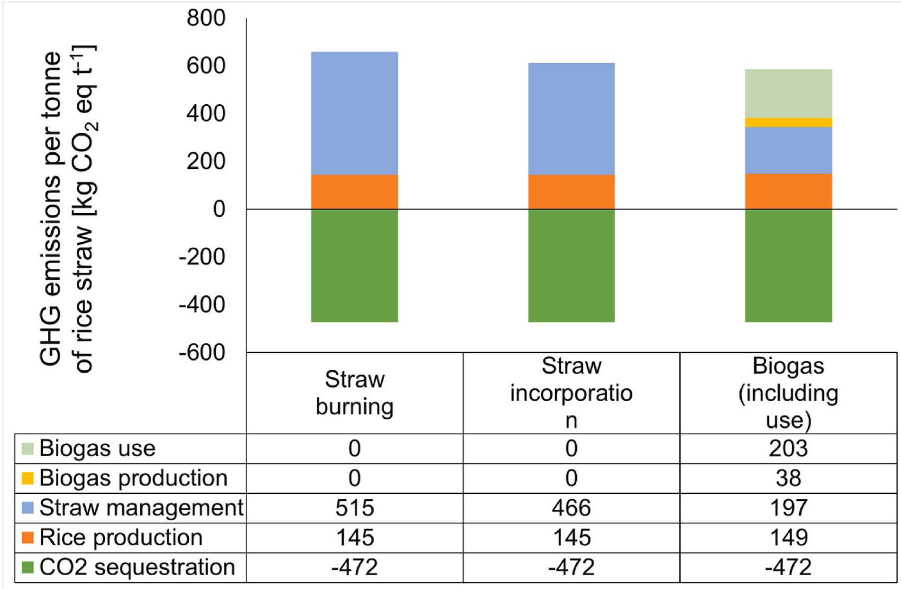


Fig. 4. Emissions from rice production with different straw management regimes.

3.3. GHG emissions from straw management

The GHG emissions of the value chain were calculated from the fossil-based supply chain and biogenic emissions from crop production, straw management and biogas use (see Equation 1). While rice is an arable crop with a short timeframe for biogenic CO_2 sequestration and release, the type of GHG released can vary for the different rice straw management options. During plant growth, the rice plant sequesters CO_2 from the atmosphere; the carbon embedded in the biomass is then released as biogenetic CO_2 and CH_4 during straw management. As the different types of GHGs have other climate change impacts during post-harvest activities and processes, the biogenic and fossil-based emission flows are included in the assessment of the three rice straw management systems. This consists of converting non-CO_2 emissions like CH_4 and N_2O into CO_2 eq. The GHG emissions from burning rice straw were 187.5 kg CO_2 eq and 185.7 kg CO_2 eq per tonne of rice straw for semi-mechanised and manual harvest, respectively. The incorporation of rice straw led to GHG emissions of 138.8 kg CO_2 eq and 139.2 kg CO_2 eq per tonne for mechanised and semi-mechanised harvest, respectively. Removing rice straw from the field and producing and using biogas resulted in GHG emissions of 114.0 kg CO_2 eq and 114.6 kg CO_2 eq per tonne of rice straw for domestic cooking and electricity generation or pumping for irrigation, respectively. As the variation of values for each rice straw management option are very similar, Fig. 5 represents the rounded value for the three management options, not including the different harvesting and biogas use alternatives.

3.4. Net GHG emission from biogas use and emission reductions

The assessment of the biogas use was based on the measured biogas production and characteristics from the pilot facility as presented in Table 3. 58 t of straw produced 6566 Nm^3 of biogas with a CH_4 content of 47 %. Based on this, 1 kg rice straw converts into 0.5 kWh. With a gas conversion efficiencies of 30 % for electricity, 50 % for cooking and 20 %

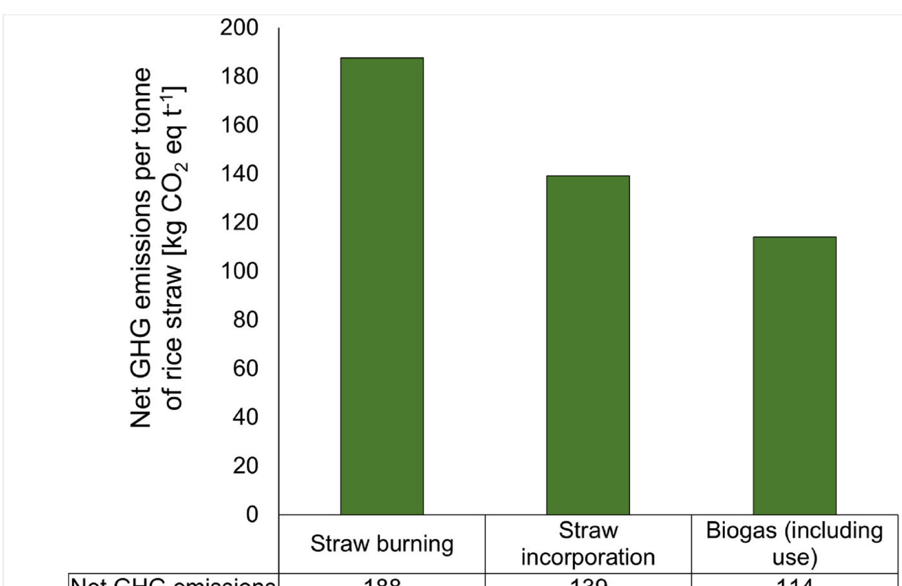


Fig. 5. Net GHG emissions of the different rice straw management options.

for pumping, also presented in Table 4, one tonne of rice straw can produce 158.7 kWh, 264.5 kWh and 105.8 kWh, respectively.

The expanded system boundary (Fig. 2) shows that the production and use of biogas avoids the emissions from burning or incorporating rice straw in the field. Additionally, biogas can displace conventional fuel use like grid electricity, LPG for cooking or diesel for irrigation water pumping. Based on the extended system boundary, the reduced GHG emissions, including the emissions from biogas and the emissions from avoided fossil fuel and straw burning or incorporation were calculated using Equation 2. The results are presented in Fig. 6 and Table 7.

Biogas from 1 tonne of rice straw can generate 159 kWh of electricity, resulting in 114 kg CO_2 eq. Compared to this, using the same amount of grid electricity would result in 117 kg CO_2 eq. Not burning the rice straw avoided 188 kg CO_2 eq per tonne of rice straw. Hence, biogas use for electricity generation results in 191 kg CO_2 eq reduced emissions. Rice straw incorporation leads to 139 kg CO_2 eq per tonne of rice straw. Hence, the reduced GHG emissions are 142 kg CO_2 eq per tonne of rice straw when straw incorporation is avoided, and grid electricity is replaced.

If biogas is used for domestic cooking, the GHG emission reductions are 242 kg CO_2 eq and 193 kg CO_2 eq per tonne of rice straw if straw burning or straw incorporation are avoided and LPG is substituted with biogas. In the case of pumping irrigation water with biogas, the reduced emissions are 247 kg CO_2 eq and 198 kg CO_2 eq per tonne of rice straw if straw burning or straw incorporation are avoided and diesel is substituted with biogas.

While all three biogas options have similar emissions, the replacements of LPG for cooking and diesel for pumping achieve the highest emission savings per tonne of rice straw. This is due to the higher emissions of the replaced fossil fuels. The different biogas options can achieve 63 %–68 % emission reductions in the counterfactual rice straw burning cases and 55 %–63 % emission reductions in the counterfactual rice straw incorporation cases.

Emissions per unit of energy produced are an important indicator for energy providers and policymakers in decarbonising the energy sector. Fig. 7 presents the GHG emissions converted to energy as the final unit of measurement. Electricity generation and pumping with biogas have with 0.7 kg CO_2 eq kWh^{-1} higher GHG emissions than cooking with 0.4 kg CO_2 eq kWh^{-1} due to the higher conversion efficiency of domestic cookstoves. However, the GHG emissions and emission reductions are highest for pumping with 1.8 kg CO_2 eq kWh^{-1} (75 %) and 2.1 kg CO_2 eq kWh^{-1} (71 %) for avoided straw burning and avoided straw incorporation emissions, respectively.

3.5. Sensitivity analysis

Sensitivity analysis was conducted to evaluate seasonal variations related to straw management and possible impacts from fugitive and composting emissions during biogas production. The results are illustrated with the red and black stars in Figs. 8 and 9.

3.5.1. Seasonal field emissions

In the case study region, rice is grown twice yearly, resulting in a wet and a dry harvest season. Considering the annual average from dry and wet seasons, in-field emissions contribute 37 %, 76 % and 34 % to the

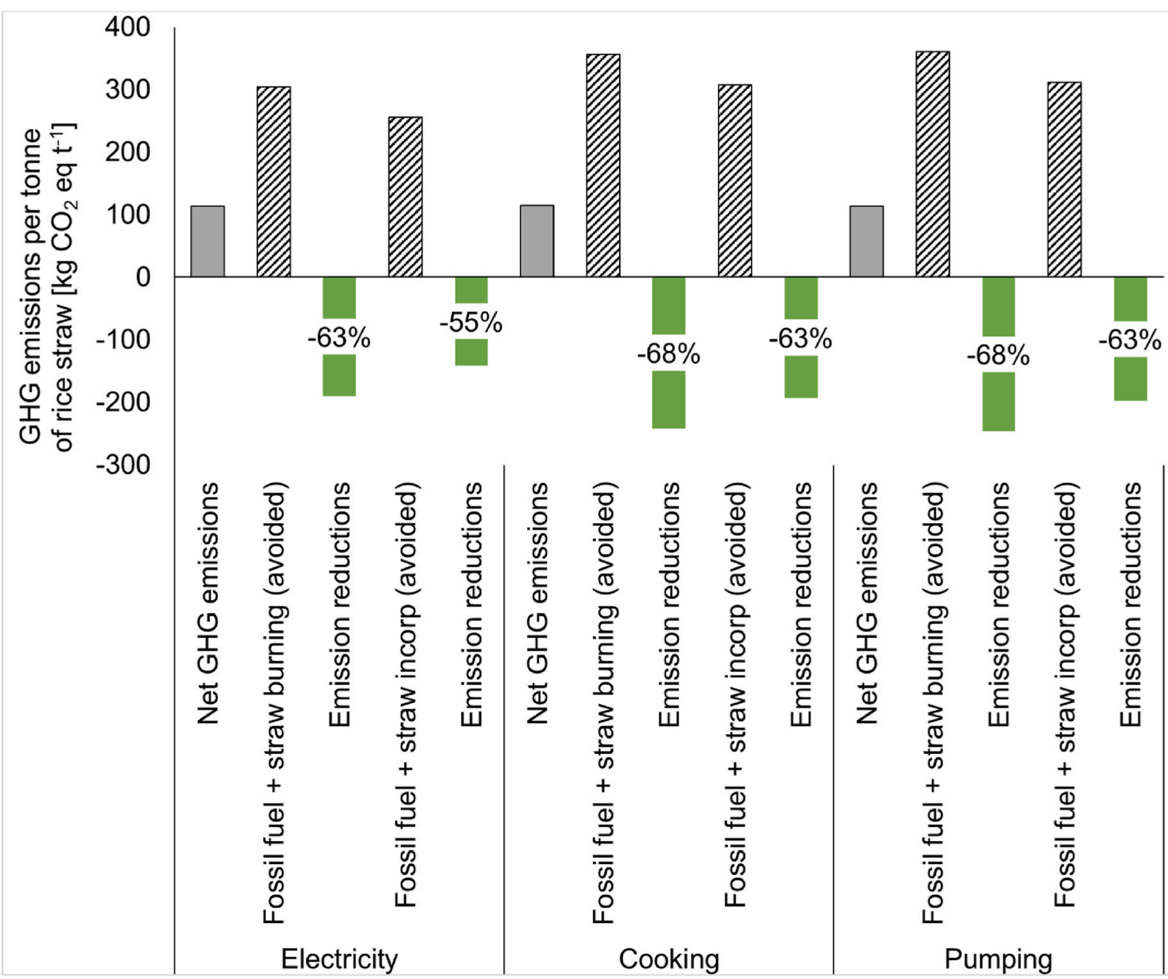


Fig. 6. GHG emission impact from biogas use, including reduced emissions per tonne of rice straw.

Table 7
Emission impact from biogas use, including avoided emissions as kg CO_2 eq.

	Electricity		Cooking		Pumping	
	Straw burning	Straw incorporation	Straw burning	Straw incorporation	Straw burning	Straw incorporation
Biogas use	114	114	115	115	114	114
Straw management emissions (avoided)	188	139	188	139	188	139
Fossil fuel emissions (avoided)	117	117	169	169	173	173
GHG emission reductions	**191**	**142**	**242**	**193**	**247**	**198**

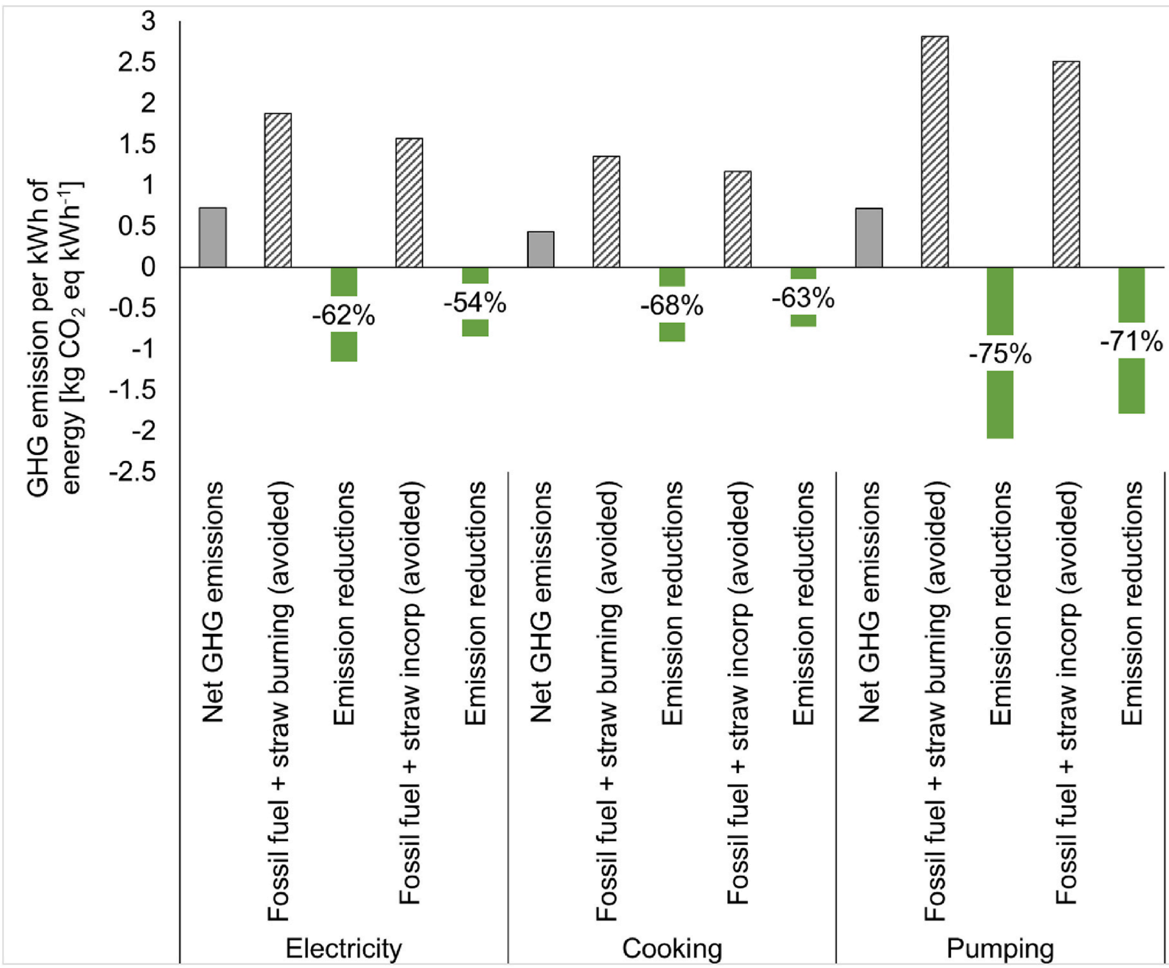


Fig. 7. GHG emission impact from biogas use, including reduced emissions per kWh.

overall emission profile in the cases of straw burning, straw incorporation and biogas, respectively. Emissions related to in-field straw decay are significantly larger during the wet season compared to the dry season [11,39]. Based on research by Refs. [11,39] and summarised in Table 5, in-field CH_4 emissions can be about 30 %–50 % and N_2O emissions about 35 %–63 % higher during the wet season compared to the dry season. Based on these variations, the sensitivity analysis showed that total supply chain emissions during the wet season are 28 % higher for rice straw burning, 33 % higher for rice straw incorporation and 27 % higher for biogas than in the dry season.

The impact of seasonal in-field emissions becomes even more apparent when looking at the GHG emissions of each straw management option, which are the sum of all biogenic and fossil-based emission fluxes. The wet season's GHG emissions exceed the dry season's emissions by 150 %, 352 % and 304 % in the cases of rice straw burning, incorporation and biogas, respectively. This can be explained by the significant release of CH_4 from decaying straw residues in the field.

The high emissions during the wet season emphasise the challenges of rice production and related methane emissions. During the wet season, the emission reduction from biogas was 32 % for straw burning and 17 % for incorporation. This shows the benefit straw removal for biogas production can deliver.

3.5.2. Emissions from biogas slip and composting of digestate

Table 6 presents the values considered for the sensitivity analysis of emissions related to fugitive emissions and digestate composting. Both sources of emissions are a release of biogenic carbon. They can reduce the emission benefits of biogas. As for seasonal variation, both sources of emissions are subject to high uncertainty. For simplicity, literature values [39,40] that showed high agreement on fugitive emissions and composting were used to investigate the sensitivity. The results are presented in Fig. 9 and show an increase of 0.3 % and 1.3 % of the GHG emissions if fugitive emissions increase to medium and high levels. The increase of composting emissions to medium and high levels resulted in a total increase of emission impact of 1.3 % and 7.4 %, respectively. When combining fugitive and composting emissions, the GHG emission

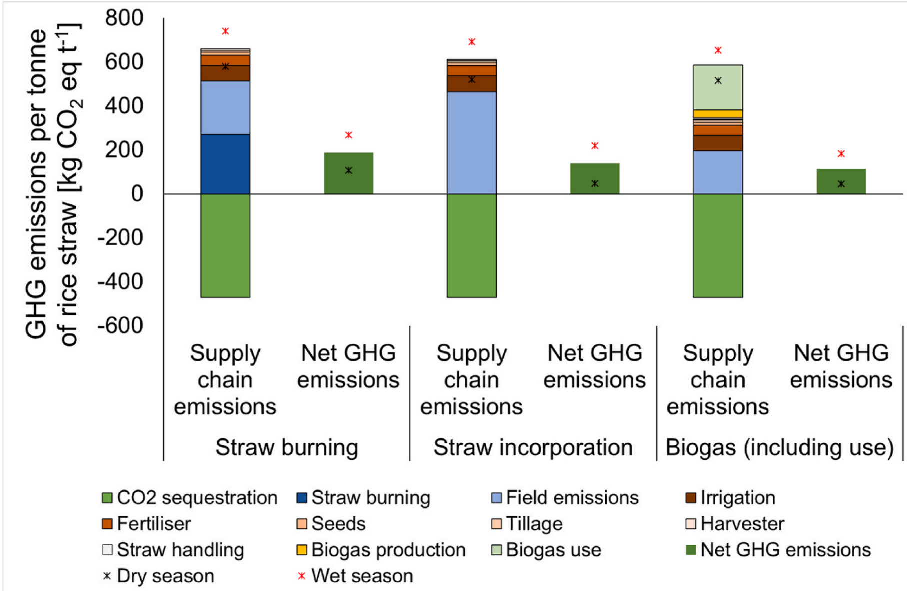


Fig. 8. Sensitivity analysis for seasonal variation of emissions (dry and wet season). GHG emission profiles of three rice straw management options, including biogenic, fossil-based supply chain emissions and net GHG emissions for each option.

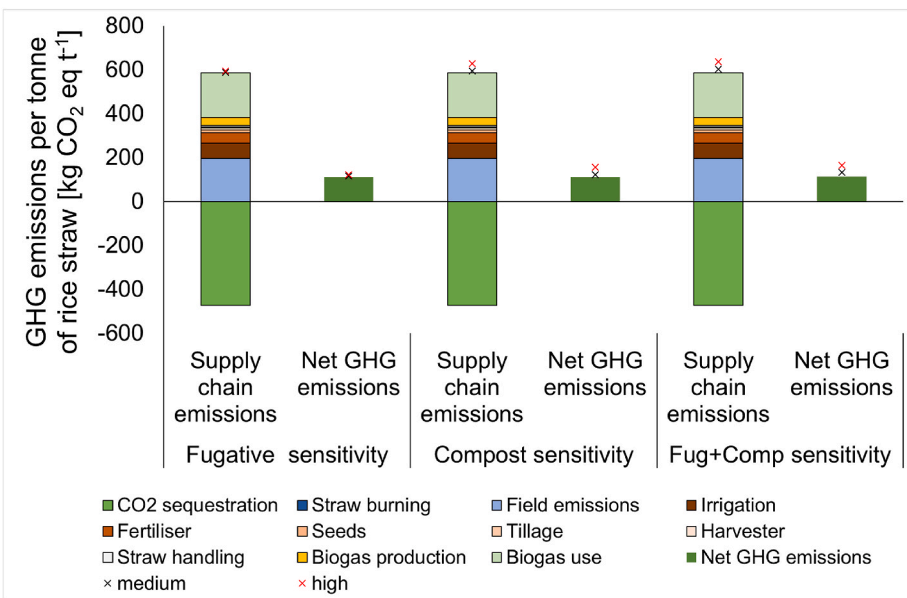


Fig. 9. Sensitivity analysis for biogas slip (fugitive emissions) and emissions from composting. GHG emission profiles of three rice straw management options, including biogenic, fossil-based supply chain emissions and net GHG emissions for each option.

impact of the biogas system would increase by 3.1 % at medium and 8.7 % at high levels. This shows the relevance of evaluating these emissions and implementing measures to improve biogas supply chain handling and operational practices and reduce avoidable risks and impacts.

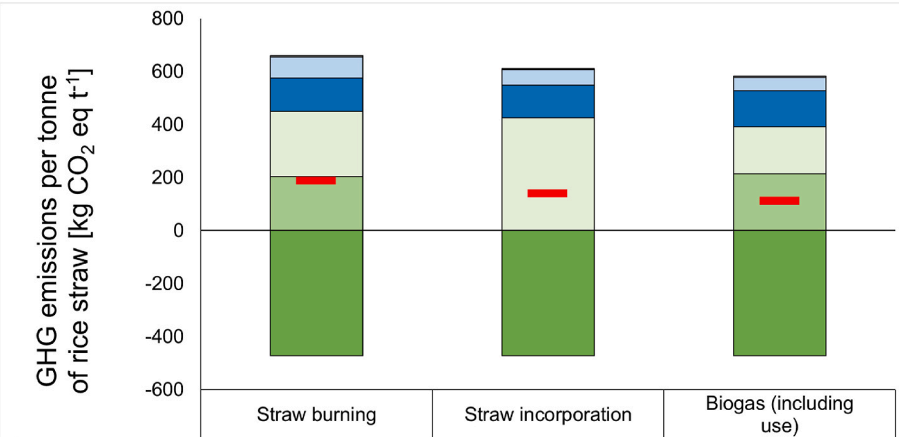
3.6. GHG flux and temporal climate change impact

The biogenic carbon sequestered during rice production is released as CO_2 and CH_4. Considering climate change impacts beyond GWP100 is important as the impact of long-term forcers like CO_2 and short-term forcers like CH_4 will have different timing and impact on climate change.

Fig. 10 presents the GHG profile by GHG type for the three rice straw management options: straw burning, straw incorporation, and biogas with electricity generation. Only one biogas option was selected as the emission profiles for the different biogas uses are similar.

All rice straw management options show the CO_2 sequestration as negative value, with straw burning releasing biogenic CO_2 and CH_4, straw incorporation releasing biogenetic CH_4 and biogas releasing biogenic CO_2 and CH_4. In all three cases, fossil CO_2 is released from supply chain activities, and N_2O is released from direct soil emissions related to fertiliser use. There are also very low fossil-based CH_4 emissions. Biogenic CO_2 release refers to the burning of straw or biogas, and biogenic CH_4 emissions relate to the decay of straw and stubbles in the field. A small amount of biogenic CH_4 is also released from fugitive and composting emissions for the biogas option.

Fig. 11 illustrates the temporal climate change effects of the three rice straw management options: burning, incorporation and biogas



	Straw burning	Straw incorporation	Biogas (including use)
Fossil CH4	5	4	4
N2O	80	57	50
Fossil CO2	125	124	135
Biogenic CH4	248	425	178
Biogenic CO2	203	0	215
CO2 sequestration	-472	-472	-472
Net GHG balance	188	139	110

Fig. 10. GHG emissions by type of gas for rice straw burning, rice straw incorporation and biogas with energy generation.

(electricity). Rice straw burning and incorporation include the emissions of energy use reference, in this case, grid electricity. Additionally, electricity, based on the current grid mix, was included to allow a comparison between bioenergy and fossil energy.

The different metrics of mass in the atmosphere, radiative forcing and temperature change effect allow the evaluation of the presence and impact of the different GHG changes after initial release. It is important to remember that this is a single point and not a cumulative assessment. Still, a cumulative assessment would result in the same trends of impact.

The CO_2 release to the atmosphere (mass in the atmosphere) is negative for all three management options as the amount of CO_2 sequestered during plant growth is larger than the amount of biogenic and fossil CO_2 released back to the atmosphere from straw management and supply chain activities. Regarding the CO_2 balances, all 3 options sequester more carbon as CO_2 from the atmosphere than they release. The mass of CO_2 in the atmosphere is lowest for the straw incorporation option as hardly any biogenic carbon is released in the form of CO_2 after harvest. The mass of CO_2 impact is highest for straw burning as biogenic CO_2 is released during biomass burning. Both straw burning and incorporation include fossil CO_2 emissions from using grid electricity. The mass of CO_2 in the atmosphere from incorporation is still lower than for biogas, as hardly any biogenic CO_2 is released from straw decay in flooded rice fields.

This does not mean that any of the 3 options is CO_2 negative as a significant amount of the biogenic carbon is released as CH_4 to the atmosphere, relating to straw decay or biogas production. The mass of CH_4 in the atmosphere is highest for straw incorporation and lowest for biogas.

This is also reflected in the radiative forcing of the three straw management options. Straw incorporation has the highest radiative forcing driven by the high CH_4 release. After 88 years, the radiative forcing starts to fall below that of the straw-burning option, as CH_4 has a shorter lifetime than CO_2. The biogas option with the lowest CH_4 and a low CO_2 release has the lowest radiative force in the short and long term.

While CH_4 has a stronger temperature response than CO_2, it also has a shorter lifetime. This is reflected in the temperature response to the radiative forcing. The high share of CH_4 means a peak temperature response is reached after about 10 years, followed by a steep decrease. While the temperature response of the straw incorporation option is 50 % and 136 % higher than for the burning of straw or biogas before and after the peak, this changes with the temperature response decrease and the straw incorporation option reaching similar temperature response levels as the straw burning option after 34 years and the biogas option after 57 years resulting in a lower response than the other 2 options in the medium and long term. The N_2O emissions are at similar magnitude and impact across the three rice straw management options with little influence on the overall dynamics of climate change effects.

Compared to biogas, the climate change impact of grid electricity is significantly different. While the radiative forcing is lower in the short term, it increases in the medium and long term, while the one of biogas decreases. Similarly, the temperature response increases and plateaus at the continuous warming level.

4. Discussion

4.1. GHG impacts from rice production and straw management

The results of this study demonstrate that rice straw biogas can lead to significant GHG emission reductions compared to rice straw burning or incorporation. The lifecycle assessment shows that rice straw biogas of the investigated pilot plant can lead to 18 % and 39 % GHG emission reductions compared to rice straw burning or incorporation, respectively. Various studies on emissions from straw burning and incorporation and rice straw biogas exist [2,11,15,37,39,45–54]. Most studies' values vary widely due to different research questions, data input, environmental and topographic characteristics, and experimental setups. While comparing these with the presented results makes it difficult, there is agreement that rice straw biogas approaches reduce supply chain emissions compared to traditional rice straw management practices like straw burning or incorporation.

Until the point of harvest, the GHG emissions of the three investigated straw management options, straw burning, incorporation, and biogas production, are very similar, if not identical (Fig. 3). The main emissions are from irrigating the crop for which diesel pumps are considered. The other main emission source is related to fertiliser use, including producing fertiliser and direct soil emissions once the fertiliser is applied. Other crop management activities like tillage and harvesting (including threshing) make up about 10 % of the rice production emissions of the investigated case study.

The most significant difference in emission impacts occurs during the

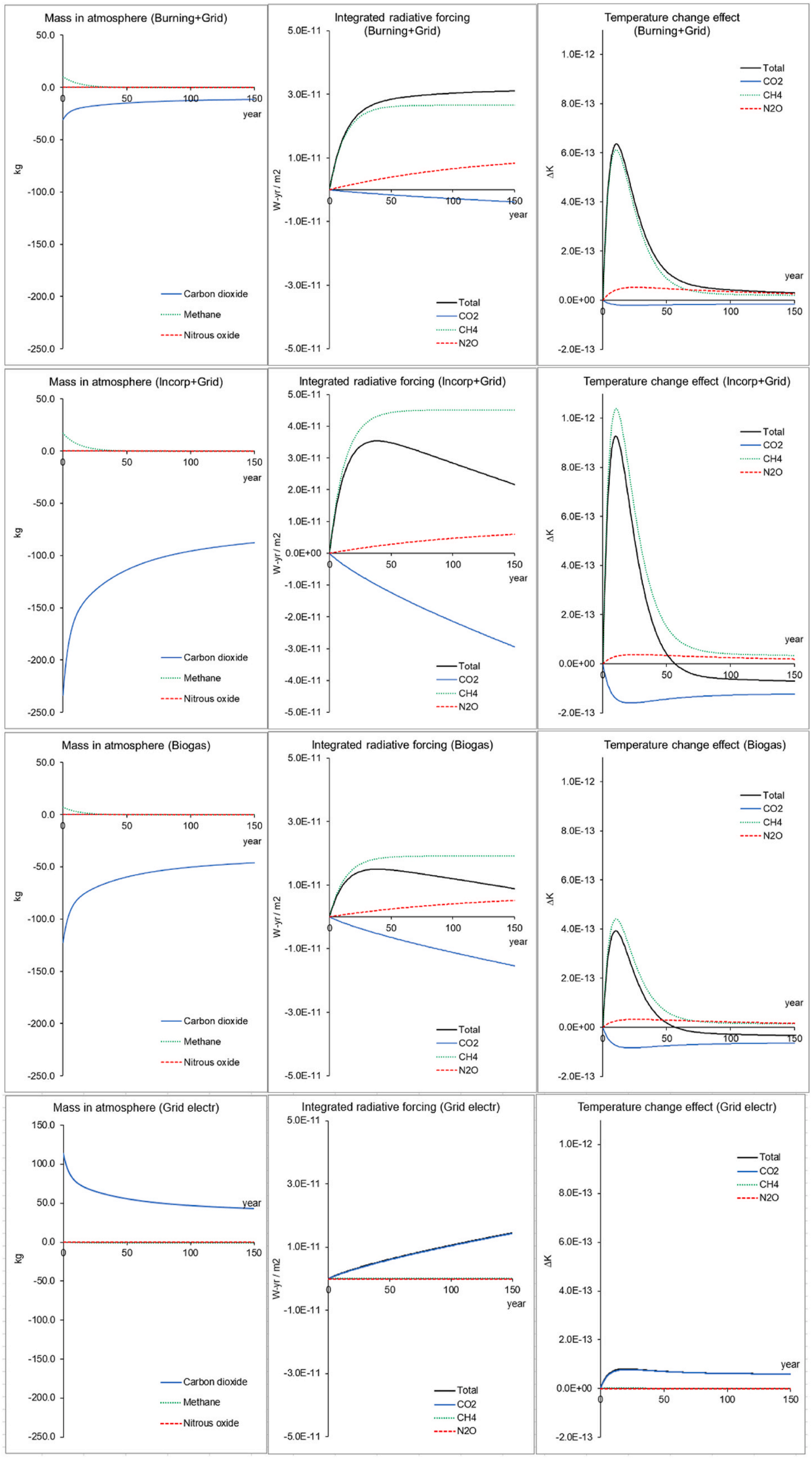


Fig. 11. Climate change effects of pulse emissions of CO_2, CH_4 and N_2O for rice straw burning, rice straw incorporation, biogas and grid electricity (single point emissions).

post-harvest activities. It may be argued that biogas production results in additional emissions from handling and processing activities associated with additional energy and fuel use. However, the biogas option's post-harvest emissions are 53 % and 46 % lower overall than those from straw burning or incorporation, respectively. The results indicate that the emissions related to rice straw management are significantly higher than those during crop production (Fig. 4), making sustainable approaches for rice straw management an important measure to mitigate climate change impacts from rice supply chains.

4.2. Biogenic GHG flux

The majority of the rice straw management emissions are biogenic and often labelled as carbon neutral. However, this research shows the importance of including the biogenic GHG fluxes in the assessment to capture the GHG, particularly carbon fluxes. This way, the transformation of biogenetic carbon from sequestered atmospheric CO_2 to emitted biogenic CO_2 and CH_4 and the climate change impact of the different gases can be evaluated. While the biogenic carbon flux is commonly included in incorporation scenarios, it is often neglected for straw burning and bioenergy options [37,45,47], and the release of biogenic CO_2 is considered carbon neutral. While the 4–6 months between carbon sequestration and release are very short, it is still important to understand the carbon flux in the biogas option to allow a comprehensive comparison with the other straw management approaches and evaluate the real climate-forcing impact of different rice straw management practices.

Including the biogenic carbon flux and all biogenic and fossil-based supply chain emissions allows the capture of the real GHG emission dynamics using the same system boundaries for each straw management option's carbon flux and emissions (burning, incorporation, biogas). Classifying straw burning and biogas use as carbon neutral misrepresents the climate effect of these management options. Considering all emissions, biogenic and fossil-based, as demonstrated in Fig. 10, allows a rigorous and accurate assessment of the GHG impact of the biogenic and fossil-based emissions for each of the three investigated options.

4.3. Emission reductions

Given that biogas displaces an existing use of fossil fuels, expanding the system boundaries has to go beyond including the biogenic carbon flux. To support a comprehensive assessment of the biogas use, the system boundaries were extended to include the displacement of fossil fuels. Investigating different biogas uses and existing fossil fuel use demonstrated that rice straw biogas can avoid 63 %–68 % of GHG emissions compared to straw burning and displacement of fossil fuels and 55 %–63 % of GHG emissions compared to straw incorporation and replacement of fossil fuels.

The displacement of diesel for pumping irrigation water delivers the largest emission benefit in absolute and relative terms, followed by cooking and electricity use when comparing the emissions per tonne of rice straw of different biogas uses and displacement of fossil fuels. However, emission savings for pumping and cooking are very similar (Fig. 6).

This changes when evaluating the emission impact per unit of energy (Fig. 7). The absolute emission reductions for electricity generation and cooking are half compared to pumping, which translates more clearly to the low operational efficiency of the irrigation pump compared to the assessed CHP unit and domestic cook stoves.

Evaluating different units of assessment can be important for policy decisions. For example, if a farmer receives an incentive for delivering rice straw for biogas, supporting biogas production for cooking and pumping could be similarly beneficial. For an energy user, the biggest GHG emission reductions are delivered with pumping and the lowest with cooking. If emission reductions were the main driver for biogas production and use, this could raise the question of the most feasible way to use biogas and how different actors and their decisions are incentivised to deliver the desired benefit. However, this can be misleading, and before switching to a low-carbon fuel, efficiency should be improved to ensure the renewable primary energy source is used best. Others have shown that looking at different metrics beyond emissions can inform decision-making and provide more detailed insight into how trade-offs can change with different operational and policy decisions [14,55–57].

4.4. Temporal climate change effects

Comparing emissions from biogas and fossil fuels at the point of energy generation, for example, electricity, indicate that the emissions from both energy carriers are similar (Table 7). However, the biogas combustion emissions are biogenic from CO_2 recently sequestered from the atmosphere. While some argue bioenergy emissions are worse than fossil fuels, this is not the case, looking at the atmospheric carbon flux. Biogenic CO_2 emissions from biogas combustion do not add to the atmospheric carbon budget or global warming like fossil fuels. This is particularly relevant where biogas replaces fossil fuels as no additional carbon is released to the atmosphere while existing atmospheric carbon is circulating between the atmosphere and biomass (see Fig. 10).

Investigating additional metrics beyond GWP100 allows for evaluating the GHG flux and time-dependent effects of the different rice straw management options and demonstrating the limitations of carbon neutrality and bioenergy being worse than fossil fuels. Fig. 11 demonstrates that all rice straw management options have a short-term peak in the atmospheric carbon (CO_2 and CH_4), but the temporal impact decreases over time.

Straw incorporation has the highest CH_4 and lowest CO_2 release into the atmosphere. This is reflected in high radiative forcing during the first 30–40 years and a high-temperature increase effect during the first 10 years. The more CO_2 is emitted, these pules reduce and prolong.

Due to the displacement of alternative straw management and fossil fuel use, the radiative forcing and temperature impact from biogas are the lowest. Additionally, after 56 years, the biogas and incorporation option's warming effect turns into a cooling effect. It is larger for incorporation than biogas in the longer term. In contrast, the radiative forcing of biogas is lowest in the long term. This differs greatly from the fossil alternative (grid electricity), which has an increasing negative climate and a plateauing temperature change effect over time.

4.5. Limitations and sensitivity of natural variation and operational uncertainty

Expanding the system boundaries, including counterfactual impacts, biogenic GHG flux and temporal climate change impact, demonstrated that biogas offers lower emissions and, therefore, emission savings compared to current rice straw management options and fossil fuel use.

However, there are limitations to the assessment. While some impacts from natural and operational sensitivities (composting and fugitive emissions) have been included, the significant variations and uncertainties make the assessment challenging. It could be argued that the return or use of digestate was not included, possibly overemphasising the GHG benefits of the biogas option. Still, some emission impacts are captured as the digestate is composted and used in horticultural activities. Moreover, work by others showed that a return of digestate of an integrated manure-straw system with a high proportion of manure can be beneficial [54].

The temporal climate change impacts do not consider the decay of organic volatile matter over time in the incorporation option. While rice straw burning leads to a singular emission point, the CH_4 release from the decay of incorporated straw will take place over time. It will likely take longer than the literature data considered in this study.

Additionally, the biogas option was calculated based on data collected from the operation of the pilot facility. At the point of data collection, the operation and performance of the facility were not optimised. The theoretical potential of the facility is estimated to be almost twice as high as the current performance, which would significantly improve the GHG benefits of the biogas option compared to the other straw management options and fossil fuel use.

Over time, the fuel and energy supply will likely change and decarbonise. This would affect the calculation of the reduced emissions, particularly for electricity. Decarbonising the energy system or a possible change in the narrative where biogas increases the overall energy supply would also change the results. Such a narrative would then need to include potential direct and indirect emission consequences from an increased energy supply from biogas.

5. Conclusion

Rice, as one of the main food crops, is also one of the main GHG emission sources globally. Integrating biogas into rice supply chains can significantly contribute to decarbonising the agricultural and energy sectors, making rice production more sustainable. This research demonstrates that integrating biogas production from rice straw can help reduce GHG emissions of paddy rice production systems in the Philippines. Burning, incorporating, and replacing fossil fuel use with biogas can lead to up to 68 % emission reductions compared to straw management. While there are GHG emission uncertainties related to different steps in the process, e.g. seasonal variations, digestate management and fugitive flux, which can decrease the GHG emission benefits of the system, the biogas pathways support emission reductions, reduction of air pollution and replacement of fossil fuels.

Most studies on the environmental impacts of rice production consider the release of biogenic CO_2 as carbon neutral. This work demonstrates the relevance of understanding the carbon flux of the whole system from plant growth to carbon release at straw disposal or energy utilisation, as CO_2 and CH_4 have different climate change impacts and timeframes. While single GHG emission figures on a GWP100 basis are a useful approach to inform decision-making, this single metric approach limits the understanding of short- and long-term impacts of rice production where carbon flux includes CO_2 and CH_4 as forcer with different time dependencies and pulses. Our research demonstrated that rice production and straw management result in higher radiative forcing and temperature change effects in the short term. However, these reduce significantly over time, with biogas bearing the lowest impact after 10 years for radiative forcing and 43 years for the temperature change impact. It may be argued that focusing on longer-life climate forcers, e.g. CO_2 from fossil fuel use, over short-lived ones, e.g. biogenic CH_4 from biogas, is more closely aligned with potential future temperature increases. While it is worth considering the impact of longer-life climate forcers, as they may have a closer relationship to future temperature increases, it is important also to consider the effects of short-life climate forcers. Therefore, providing more than one metric and timeframe supports more informed decision-making on climate change mitigation and adaptation strategies.

Additionally, our assessment shows that governance frameworks are needed to support sustainable practices that enable meaningful and wider benefits for climate change mitigation and rice-growing communities. Prohibiting unsustainable practices like rice straw burning may reduce air pollution but lead to rice straw incorporation, which has limited climate change and no socio-economic benefits. On the contrary, the integration of biogas supports a win-win approach for rice-growing communities and globally, as it increases renewable energy generation and reduces GHG emissions, supporting SDG 3, 7 and 13.

CRediT authorship contribution statement

Mirjam Röder: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Patricia Thornley:** Conceptualization, Validation, Writing – original draft, Writing – review & editing. **Craig Jamieson:** Funding acquisition, Project administration, Validation, Writing – original draft, Writing – review & editing.

Data availability

All relevant data is included in the manuscript

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