Renewed perspective on the role of biogas as local and or regional source of bio-hydrogen and bio-carbon dioxide within the future renewable hydrogen energy system

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Abstract

A radical change of the energy system is required in light of the dramatic effects of human-induced climate change. In this perspective, a future renewable hydrogen energy system was proposed, where biogenic resources are ascribed relevant potential as source of biogenic hydrogen and biogenic carbon dioxide. In this light, the research brings forward the concept of third-generation upgrading as the highest valorisation potential of biogas. This alters the perspective on biogas as source of renewable electricity, heat or fuel to biogas as platform molecule able to couple the renewable hydrogen and bio-economy domain. The research shows that concept of third-generation upgrading relies on a technologically feasible, environmentally benign and economically sound production process. In this respect, the adoption of the concept of third-generation upgrading is supported via the valuation of the bio-carbon dioxide as scarce renewable carbon-containing molecule and valuable carbon sink. Therefore, the concept of third-generation upgrading should be supported via regulatory commitment, market creation, policy mechanisms and infrastructural changes. In this way, biogas can act as an invaluable source of bio-hydrogen and bio-carbon dioxide, spark system integration and stimulate energy security. Ultimately, this research proposes to change the way biogas is seen.

Keywords: Biogas, Hydrogen, Carbon, Carbon Dioxide, Renewable Energy System
2022 MSC: TBD, TBD

1. Introduction

There is an immediate urge for climate action in order to respond to the dramatic effects of human-induced climate change. The time frame for interference is shortening, while the unprecedented changes to the climate are accelerating. These changes to the climate are already affecting extremes in weather and climate, are expected to become larger and many changes are irreversible [1] [2]. Therefore, decisive action is required to establish deep reductions in carbon dioxide and other greenhouse gases as the costs of inaction are immense and the risks and stakes are high: "It is a code red for humanity" [3] [4].

This calls for a far-reaching transformation of the economic system including the power, industrial, transportation and agricultural sectors [2]. The European Green Deal, in line with the Paris Agreement, aims for a climate-neutral energy system by 2050. This will fundamentally transform the economy and society towards a fair, green and prosperous future [5]. This radical change will require a mentality shift towards embracing the need for radical transformations as incremental changes alone will not be sufficient [6].

The urgent need to transform the energy system sparked renewed momentum for the utilisation of renewable hydrogen as carbon neutral and zero pollution energy vector [7] [8]. Renewable hydrogen will be, next to large scale electrification and circular usage of materials, vital to achieve a climate neutral energy system by 2050 [9]. Renewable hydrogen will allow for the cost-effective transport and storage of cheap renewable electricity over time and space [10]. Moreover, hydrogen will allow for the integration of the power, industrial, transportation and industrial sectors. In this respect, hydrogen can act as energy vector to decarbonise hard-to-abate sectors, balance the power sector or could be used to decarbonise processes, products and materials [11]. In this way, renewable hydrogen will be central in a climate-neutral energy system [12].

The proposed future renewable hydrogen energy system shows important similarities to the present natural gas system. Hydrogen will fulfill the role of zero pollution energy commodity that facilitates connection over time and space dimensions [13]. In this way, hydrogen will replace fossil fuel utilisation and contribute to an affordable, accessible, secure, reliable and fair transition [14]. Moreover, the proposed renewable hydrogen system will support the reduction of greenhouse gas emissions, the diversification and security of the energy supply, the integration of renewables and will spark economic growth and technology development. The proposed future renewable hydrogen energy system can be observed in figure 1 [13].

In the proposed renewable hydrogen energy system, biogenic resources constitute a vital role as local and or regional source of biogenic hydrogen and biogenic carbon dioxide. In this role, the biogenic hydrogen can be fed into the hydrogen infrastruc-

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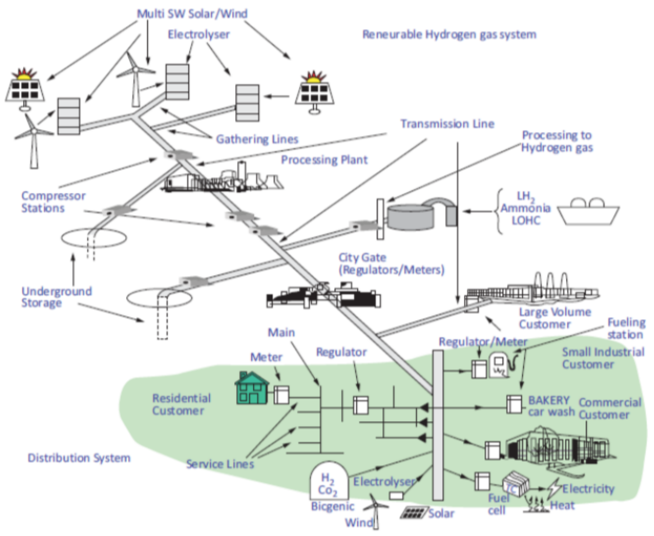

Figure 1: Schematic lay-out of the proposed future renewable hydrogen system

ture to be used as energy carrier or feedstock while the biogenic carbon dioxide can be utilised, for example, as building block in the industrial sector or as product in the horticulture sector. The intermediate synthetic gas could also directly be used as circular chemical feedstock [13]. In this perspective, biogenic resources are seen as a vital source of climate neutral carbon dioxide in the renewable hydrogen energy system.

Biogas, as wet biogenic resource, has been ascribed as an attractive source of bio-hydrogen from a technological [15], ecological [16] and economical perspective [17]. Nevertheless, the focus on biogas has been primarily on the direct energetic utilisation for power and or heat production or on the indirect energetic utilisation as green gas in the industrial, transportation and or build environment sector [18]. However, next to the contribution to the renewable energy domain, biogas has also been ascribed potential within the bio-economy domain as input for various bio-based products to replace fossil counterparts. Based on the cascading principle, biogas is ascribed a dual and time-dependent role in both transitions [19]. In this respect, biogas is seen as platform molecule of both green gas and bio-carbon dioxide. In the concept of second-generation upgrading of biogas, the separated bio-carbon dioxide is not disregarded but assigned a potential for the production of hydrocarbon-based high energy-density fuels that enables the closure of carbon cycles. This offers a flexible storage option important within an interconnected energy infrastructure [20]. However, this perspective lacks the potential of biogas to operate as source of zero pollution bio-hydrogen and the complete, circular, utilisation of the inherent bio-carbon dioxide.

Thus, the current vision on biogas has been limited to the direct or indirect energetic utilisation of biogas. This ignores the potential of biogas as valuable source of bio-hydrogen and bio-carbon dioxide in a fossil free energy system. Therefore, in light of the renewable hydrogen energy system the concept of third-generation upgrading is proposed as highest valorisation potential of biogas. This changes the way biogas is seen.

2. Research Scope

The concept of third-generation upgrading renews the vision on the utilisation of biogas within the proposed renewable hydrogen energy system. In this respect, the concept of third-generation upgrading can be seen as an extension of the historical development of the perspective on biogas utilisation. Biogas was traditionally seen as a renewable electricity, heat or fuel source due to the short-cycled nature of the emitted carbon dioxide. The concept of second-generation upgrading opened the perspective on the potential circular or climate negative utilisation of part of the captured atmospheric carbon dioxide. Now, the concept of third-generation upgrading envisions biogas as source of climate neutral bio-hydrogen and fully exploits the carbon content for circular or climate negative bio-carbon dioxide utilisation as can be seen in figure 2. In this way, biogas not only acts as an important carbon sink but also as a valuable source of bio-carbon within a fossil free energy system.

Therefore, biogas should be seen as a platform molecule able to connect the renewable hydrogen and bio-economy domain. This is based on four perspectives: the bio-hydrogen, bio-carbon, system integration and energy security perspective.

2.1. *Bio-hydrogen perspective*

In the renewable hydrogen energy system, the direct utilisation of biogas and green gas is devalued against the utilisation of renewable hydrogen. This is a result of reshaped boundary conditions, like infrastructural changes, policy support mechanisms and technological development. In this way, the upgrading of biogas to bio-hydrogen results in direct economic benefits. Therefore, the concept of third-generation upgrading could better the biogas plant economics [21] [22]. Additionally, the conversion of biogas to bio-hydrogen facilitates the repurposing of the current natural gas infrastructure. This stimulates a fast transition, avoids stranded assets and reduces a potential natural gas infrastructure lock-in [9]. Moreover, hydrogen could be valued as a more versatile renewable molecule with usage in high-value industrial applications. Next to that, the utilisation of hydrogen could see efficiency gains, for example, in fuel cell technology as compared to combustion engines [23]. Lastly, the conversion of biogas unlocks additional renewable hydrogen production capacity, where biogas or green gas can act as a replacement of natural gas in the production of hydrogen [24].

As a result, the concept of third-generation upgrading assigns high economic value to bio-hydrogen production in the short to medium term. This results from insufficient renewable hydrogen production capacity and is supported by infrastructural and regulatory boundary conditions. However, in light of the continued increase in the availability of renewable hydrogen, especially from locations with cheap renewable electricity resources, the relative value of bio-hydrogen is expected to decrease. The commodity value of renewable hydrogen supports the bio-carbon perspective over the longer term.

2.2. *Bio-carbon perspective*

The concept of third-generation upgrading assigns value to the inherent presence of bio-carbon in biogas. This is a result

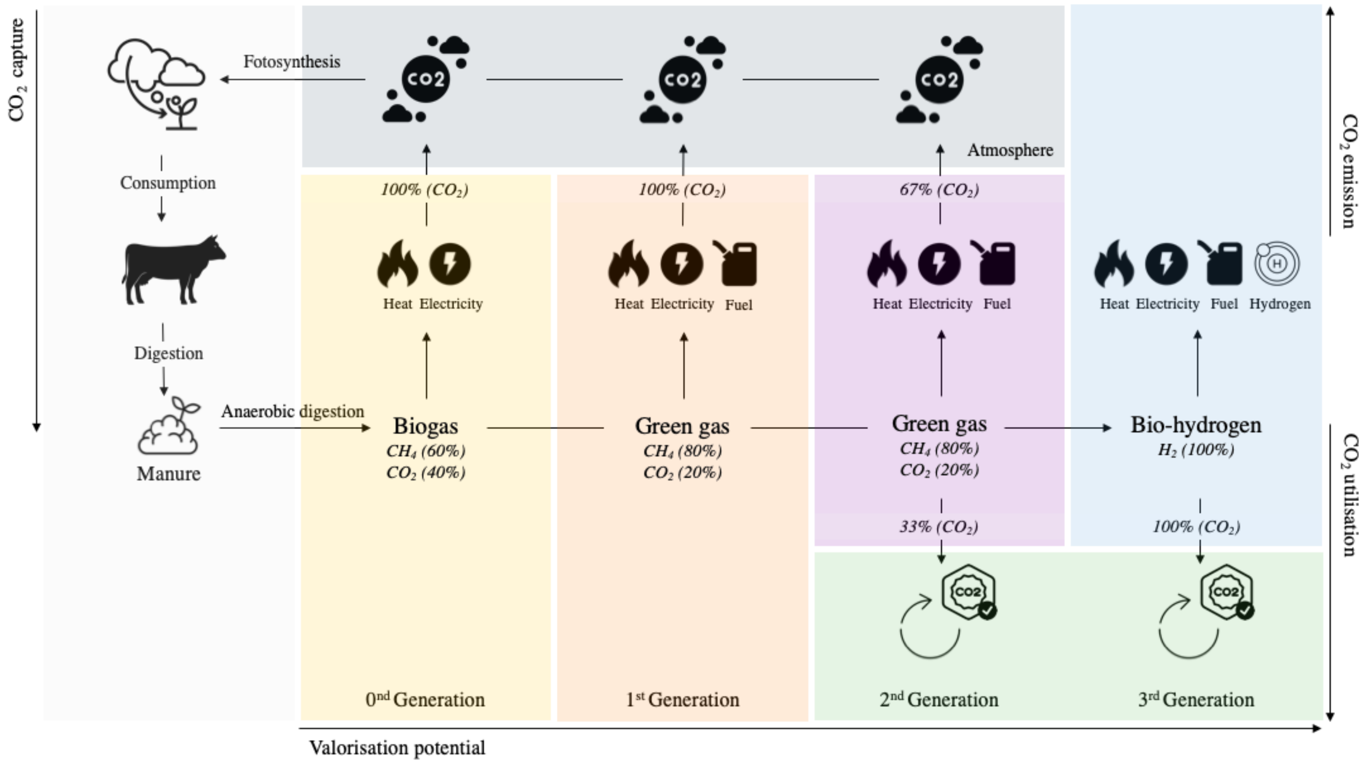

Figure 2: Visualisation of the concept of third-generation upgrading based on CO_2 utilisation and emission as opposed to previous generations of biogas upgrading

of the need for negative emissions and scarce renewable carbon containing molecules. In the future renewable energy system, sources of carbon are limited as a result of the absence of fossil resources. Here, carbon dioxide is no longer a waste product of the energy system [25]. Instead, the renewable energy system is based on electrons, where renewable hydrogen is utilised to transport cheap electrons over the time and space [13]. As a result, scarce renewable carbon containing molecules should primarily be utilised as feedstock and only be used for energetic ends if no other option exists. Bio-carbon will become vital for the production of products and materials within the future renewable hydrogen energy system [25]. Therefore, the complete utilisation of the inherent bio-carbon in biogas supports the cascading principle of the concept of third-generation upgrading.

The concept of third-generation upgrading also assigns value to negative carbon dioxide emissions. The negative carbon dioxide emissions result from the storage and or, circular, utilisation of bio-carbon dioxide [26]. In this way, biogas is not seen as a carbon neutral energetic resource but as a necessary carbon sink able to close the carbon cycle. This is based on the condition that the carbon is captured within products or materials, not released within its lifetime and or is used circularly [27]. This is in contrast to, for example, the energetic utilisation of the captured bio-carbon dioxide in hydrocarbon-based high energy-density fuels [20]. Therefore, the concept of third-generation upgrading allows biogas to operate as a cost-effective carbon capture technology [28].

Thus, the concept of third-generation upgrading values assigns value to bio-carbon dioxide in terms of the physical delivery of bio-carbon dioxide and the closure of captured atmospheric carbon dioxide. In this respect, the value of bio-carbon dioxide is presumed to continue to increase in reaction to the shift from a molecular-based energy system towards an electron-dominated energy system. On top of that, the value of negative carbon emissions are assumed to remain relevant due to the absolute atmospheric carbon balance and lack of feasible alternatives. In this perspective, the relative value of bio-carbon dioxide supports the valorisation potential of the concept of third-generation upgrading.

2.3. *System integration perspective*

In the proposed renewable hydrogen energy system, biogenic resources are discussed to be a relevant local and or regional source of biogenic hydrogen and biogenic carbon dioxide [13]. This is supported by potential delivery cost reductions as result of lower infrastructural requirements. This reduces the relative cost position of bio-hydrogen. In this respect, the system integration potential is dependent on factors like biogas potential, production capacity, industrial demand centers and the current infrastructural network [29]. Next to the relative cost position, the system integration potential could impact the product mix of the concept of third-generation upgrading. For example, production locations in close proximity to industrial demand centers could benefit from the direct utilisation of the produced syngas. In this way, the concept of third-generation upgrading supports local and or regional system optimisation.

For that reason, the concept of third-generation upgrading focuses, besides repurposing of the natural gas infrastructure, on system integration optimalisation to reduce the infrastructural requirements. This could be supported through the use of local and or regional production and demand hubs [30]. In this way, the agricultural sector could be coupled with the industrial, power and or transportation sector. This reduces the burden on infrastructural development, supports an affordable transition and stimulates the adoption of the concept of third-generation upgrading of biogas.

2.4. Energy security perspective

The concept of third-generation upgrading focuses on short supply chains to boost energy security and enable a secure, reliable and accessible energy transition. This becomes increasingly relevant in light of the vulnerabilities associated with globalised and concentrated energy supply chains [31]. Moreover, the focus on local optimisation and short supply chains could also stimulate energy security within small scale and or standalone systems. In this respect, small scale systems could become energy independent through the use of bio-hydrogen for heat, fuel and or feedstock requirements. This is supported via the utilisation of a widely available problematic waste input stream for biogas production. This could also be used to enable social development of rural communities [22].

Therefore, the concept of third-generation upgrading supports local and or regional energy security and could spark social development. This fits within the wider renewable hydrogen energy system and allows for a secure, reliable and accessible transition.

3. Results

The concept of third-generation upgrading changes the way biogas is seen. The conversion of biogas to bio-hydrogen and bio-carbon dioxide is ascribed the highest valorisation potential due to production of zero pollution bio-hydrogen and the complete, circular, utilisation of the inherent bio-carbon dioxide. Thereby, the concept of third-generation upgrading is supported by a technologically feasible, environmentally benign and economically supportive production process. The concept of third-generation upgrading is placed in the context of the different generations of biogas upgrading.

3.1. Technological

Table 1 shows the production steps required for the different generations of biogas upgrading. Moreover, table 2 shows the key process related parameters for the different generations of biogas upgrading.

3.1.1. Conversion

In table 1 it can be observed that all generations of biogas upgrading require the anaerobic digestion of manure to produce biogas. Anaerobic digestion (AD) is a biochemical process that converts organic matter under depleted oxygen conditions to a gaseous mixture consisting mainly of methane (CH_4) and carbon dioxide (CO_2) [24]. The resulting biogas consists, depending on the organic waste composition and reactor conditions, of CH_4 (50-70 v%), CO_2 (30-50 v%) and trace species like nitrogen, hydrogen sulphide, ammonia, oxygen and hydrogen. Biogas has, based on the methane content, a lower calorific value of 20-25 MJ/Nm^3 biogas as compared to around 36 MJ/Nm^3 natural gas [32]. Moreover, next to biogas, a digestate by-product is produced, in the AD process, which is rich in nutrients and could be used as bio-fertiliser, animal bedding and or other horticulture products [22].

Production	Zero	First	Second	Third
Anaerobic digestion	Yes	Yes	Yes	Yes
Biogas upgrading	No	Yes	Yes	Yes/No
Reforming technology	No	No	No	Yes

Table 1: Technological production steps required for different generations of biogas upgrading

Moreover, table 1 indicates that a biogas upgrading production step is required to convert biogas to green gas. The biogas upgrading production step is preceded by a contaminants removal product step to remove contaminants, like hydrogen sulfide, water, ammonia and siloxanes, that have a detrimental effect on the downstream production process, including catalyst poisoning, conversion efficiencies, depositions and corrosion [33]. A wide range of contaminants removal technologies are possible, including absorption, adsorption, membrane separation and biological systems [34]. The exact, combination of, removal technology is in general site dependent due to factors like contaminants present, flow rates and process adaptability. However, in basis activated carbon is mainly used to remove hydrogen sulfide, and siloxanes, while water, and ammonia, is adsorbed on silica gel [35] [36]. Hereafter, the biogas upgrading production step is deployed to separate CO_2 and CH_4 in order to arrive at a natural gas quality green gas. The separation occurs based on the different chemical and or physical behaviours of CH_4 and CO_2 via either membrane technology, pressure swing adsorption, cryogenic technology or scrubbing technology [35]. In case of membrane technology, a multi-stage membrane process is used to separate the CH_4 and CO_2 based on the difference in permeability of both constituents driven by a concentration differences. Here, effective separation occurs as CO_2 permeates through the membrane while the CH_4 retains on the inlet side, resulting in high methane purity and recovery [35]. At the moment, membrane separation is the dominant upgrading technology due to the simplicity of operations, low costs, low energy usage and environmental friendliness [37].

Finally, table 1 shows that the production of bio-hydrogen and bio-carbon dioxide require the reforming of green gas or biogas. In this respect, green gas serves as chemical identical replacement of natural gas in the traditional reforming process [38]. In the commercial steam methane reforming (SMR) process, hydrogen (H_2) is obtained via subsequent oxidation of methane with steam in the SMR reaction to obtain a syngas, the oxidation of carbon monoxide (CO) with steam in the water gas shift reaction (WGSR) to increase the hydrogen content, and the separation of H_2 and CO_2 via pressure swing adsorption (PSA) to adhere to the hydrogen purity requirements [39] [40]. The SMR process is the dominant industrial hydrogen production technology due to the high hydrogen yield, the process reliability and low cost perspective [41] However, also alternative process are possible that focus on the utilisation of alternative oxidation agents [17] [37]. In this respect, alternative reforming reactions are partial oxidation reforming (POX) and dry reforming (DR) that utilise oxygen and carbon dioxide as oxidant respectively. Moreover, autothermal reforming (ATR) combines the exothermic POX and the endothermic SMR reactions [42]. ATR has been ascribed additional benefits in relation to the lower process energy requirement, controllable hydrogen over carbon ratio, ease of operations, high efficiency and high hydrogen yield, despite a more complex reactor design, oxygen input requirement and higher operating pressure and temperature [39]. The ultimate reaction mechanisms in the ATR, where POX and SMR occur consecutively in the same reactor, can be summarised as follows: [39]:

$$CH_4 + \frac{1}{2}O_2 \longrightarrow CO + H_2O \qquad (-519\ kJ/mol) \qquad (1)$$

$$CH_4 + H_2O \longrightarrow CO + 3H_2 \qquad (+206\ kJ/mol) \qquad (2)$$

The subsequent WGSR can be summarised as follows [39]:

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \qquad (-41\ kJ/mol) \qquad (3)$$

For the final H_2 purification step several hydrogen separation methods exist that can be characterised as either physical methods, including PSA, cryogenic distillation, and membrane separation and chemical methods like metal hydride separation [40] [43] [44]. Nevertheless, PSA, a semi-continuous process that relies on the static capacity difference of hydrogen in relation to other majority gas molecules, is the industrial dominant separation technology due to the high H_2 purity requirement, low operational costs and long service life [40].

Next to the traditional reforming layout, several alternatives surface that focus on the intensification of the conversion process through elimination of the biogas upgrading step and or hydrogen purification step [45]. In this respect, biogas reforming could be characterised as DR due to the CO_2 levels naturally present in the biogas and could be stated as [42] [46]:

$$CH_4 + CO_2 \longrightarrow 2CO + 2H_2 \qquad (+247.2\ kJ/mol) \qquad (4)$$

In typical DR reactions, a more useful syngas could be obtained due to the lower concentration levels of H_2 and higher levels of CO present [33]. However, due the unfavourable carbon deposition and low hydrogen yield is DR not applied [47] [48]. In response, a combination of oxidants is utilised to lower the carbon deposition and enhance the hydrogen yield. These include biogas dry reforming [49] [50], as combination of steam and carbon dioxide, biogas dry reforming [51], as combination of oxygen and carbon dioxide, and biogas autothermal reforming [52] [53] [54], as combination of steam, oxygen and carbon dioxide. This showed the potential to prevent carbon decomposition, regulate the hydrogen over carbon ratio, increase the hydrogen yield and obtain almost complete methane and carbon monoxide conversion. Nevertheless, a higher CO_2 content and a lower H_2 yield could be obtained due to unfavourable WGSR equilibrium conditions [46]. Other process intensification methods aim to simplify the reaction process through the integration of the hydrogen production and separation step. These process intensification methods offer the potential to lower the process complexity at high hydrogen yield. The dominant process methods are steam-iron reforming [55] [56], membrane reforming [57] [58] [59] [60], sorption enhanced reforming [61] [62] and methane cracking [63].

Overall, ATR related conversion methods are presumed to have the highest potential for the conversion of biogas within the proposed renewable hydrogen energy system. This is related to the high level of system flexibility, production scalability and process output. This is further supported by the high level of technological feasibility, high carbon capture rate potential and the low cost perspective. Biogas ATR might prove to be most useful while membrane reforming might be more specific for instances with high hydrogen output requirements. In contrast, SMR and methane cracking might be less relevant for the concept of third-generation upgrading due to the high production scale and low system flexibility. Lastly, the process intensification options of sorption enhanced reforming and steam-iron reforming could prove to become important over the medium to long term as a result of the low technological readiness level. In this respect, the research focuses on the traditional reforming process and the innovative biogas ATR process.

Therefore, it can be seen that the concept of third-generation upgrading requires an additional, commercially available, green gas reforming step. Nonetheless, process intensification via biogas ATR has the potential to exclude the biogas upgrading step and lower the system complexity and cost.

Variable	Zero	First	Second	Third
Energy vector	Biogas	Green gas	Green gas	Hydrogen
Volume (Nm^3)	0.84	0.6	0.6	1.1
Energy LHV (MJ)	18.1	21.6	21.6	12.1
Carbon yield (kg)	0	0	0.44	1.36

Table 2: Key process related variables for different generation of biogas upgrading per Nm^3 biogas input

3.1.2. Process

In table 2 it can be seen that the energy content decreases over biogas upgrading generations while the carbon yield per Nm^3 biogas increases. This can be explained by non-energetic benefits over upgrading generations via, for example, increased energy flexibility, technological applications and political support [26]. Moreover, the higher carbon yield supports an adequate valuation of the inherent bio-carbon dioxide via, for example, negative CO_2 emissions and or bio-carbon dioxide applications.

The conventional bio-hydrogen production process could be described as biogas production (0nd generation upgrading), biogas upgrading (1st and 2nd generation upgrading) and green gas reforming (3rd generation upgrading). First, the biogas pro-

Production	Zero	First	Second	Third
Waste management	Yes	Yes	Yes	Yes
Methane emissions	Yes	Yes	Yes	Yes
Water, soil, air pollution	Yes	Yes	Yes	Yes
Bio-digestate production	Yes	Yes	Yes	Yes
Energy system flexibility	Limited	Yes	Yes	Yes
Carbon dioxide capture	Ne	No	Limited	Yes

Table 3: Overview of the environmental benefits for different generations of biogas upgrading

duction yield is around 25 Nm^3 biogas/tonne cow manure in case of mono-digestion [64] [65]. However, based on a presumed internal heat demand of the digester of 16%, approximately 0.84 Nm^3 biogas could be obtained per Nm^3 biogas [64]. The subsequent upgrading of biogas, of approximately 60% CH_4 and 40% CO_2, to green gas, of approximately 80% CH_4 and 20% CO_2, lowers the output product volume by an approximate factor of 70%. The resulting loss in production volume is recovered in the form of a bio-carbon dioxide stream of around 0.44 kg CO_2/Nm^3 biogas. This is based on a CH_4 loss of *conf.*, a CO_2 loss of *conf.* and the assumption that external renewable electricity is provided [26] [35]. Hereafter, based on an approximate 30% internal heat demand, 90% CH_4 conversion, 95% CO conversion and 85% H_2 recovery rate, a high-purity bio-hydrogen stream of 1.1 Nm^3/Nm^3 biogas is obtained [17] [40] [50] [65]. Moreover, based on a process capture rate of 90% [66], an additional 0.93 kg CO_2/Nm^3 biogas stream can be recovered in the reforming process. Here, around 0.29 kg CO_2/Nm^3 biogas could be obtained from the fuel gas and 0.64 kg CO_2/Nm^3 biogas from the process gas respectively. However, in the case of the biogas ATR layout a 5-10% decrease in hydrogen yield to 0.085 kg H_2 or 1.01 Nm^3 H_2/Nm^3 biogas could be observed as a result of the lower stoichiometric hydrogen output. Nonetheless, an increase of over 10% in bio-carbon dioxide to 1.54 kg carbon dioxide/Nm^3 biogas could be seen. This ultimately yields an approximate decrease in energy content of 45% but a factor 3 increase in carbon yield in case of third-generation upgrading as opposed to the concept of second-generation upgrading.

Therefore, the concept of third-generation upgrading shows longer energetic value as compared to previous generations of biogas upgrading. Nevertheless, the concept of third-generation upgrading shows a significant increase in bio-carbon dioxide output that reinforces the cascading principle.

3.2. Environmental

Table 3 shows the environmental benefits for different generations of biogas upgrading.

In table 3 it can be observed that most environmental benefits are related to the production of biogas. The production of biogas is considered an established sustainable process for the simultaneous generation of renewable energy and treatment of, problematic, organic waste [24] [26]. It is identified that AD is the preferred waste to energy route [22]. Thereby, mono-digestion of manure offers additional benefits related to lower methane leakage, other water, soil and air pollutants and odour pollution [21] [67]. Moreover, the by-product digestate could lower nutrient runoff, avoid methane emissions, conserve soil quality and ultimately adhere to the circularity principle [68]. In this respect, the sequestration of the process digestate could result in net negative process life cycle CO_2 emissions [44]. On top of that, AD could offer a solution to the nitrogen crisis [69]. Lastly, in case of AD problems associated with land use change, land availability and food competition are circumvented and overall the usage of manure shows the strongest positive climate impact [70] [71].

Moreover, in table 3 it can be seen that positive effects of increased energy flexibility are associated with the upgrading of biogas. This relates to less renewable electricity curtailment, as a result of the better storage potential of green gas [26]. Additionally, in table 3 it can be observed that second-generation upgrading and, especially, third-generation upgrading offers direct benefits related to the potential to capture, and utilise, the inherent bio-carbon dioxide. In this respect, biogas could be considered a carbon capture technology of both atmospheric CO_2 and CO_2-equivalent emissions that would otherwise have been released to the air [20]. On the other hand, the utilisation of green gas is characterised by similar CO_2 emissions as fossil counterparts, despite considered carbon neutral [35] [72]. This reduces the potential to obtain negative CO_2-equivalent emissions in case of second-generation upgrading. Moreover, the exact utilisation of the captured bio-carbon dioxide is important. In this respect, the utilised CO_2 is considered small-cycled in case of food applications as the CO_2 is presumed to be released within weeks. This is extended to months in case of application in chemicals or fuels. In case of CO_2 usage in plastics and or minerals the CO_2 is presumed to be captured over (tens of) years [27]. This in turn puts emphasis on the circular utilisation of bio-carbon dioxide with preferred use cases as bio-feedstock to obtain net negative process emissions. Therefore, through the capture and subsequent storage or circular utilisation of process and product CO_2, the concept of third-generation upgrading shows net negative process emissions [44]. In this way, the concept of third-generation upgrading could contribute to the carbon economy by closing the carbon loop.

The concept of third-generation upgrading is ascribed environmental benefits as source of zero pollution renewable hydrogen and as, potential, negative carbon source. In the short term, the role of biogas as carbon sink is seen vital to not overshoot the global carbon balance [28]. In the longer term, the potential circular utilisation of bio-carbon dioxide is seen vital within a fossil free and electron dominated energy system [25]. As a result, a carbon mass analysis is deployed to quantify the environmental benefits of the concept of third-generation upgrading in relation to previous generations of biogas upgrading.

Figure 3 portrays the carbon balance over the different steps in the traditional bio-hydrogen production process, based on similar process assumptions as mentioned in section 3.1.2. Figure 3 excludes other relevant environmental benefits and drawbacks associated with biogas production. It also excludes potential carbon sequestration via bio-fertiliser utilisation. In this respect, around 40-60% of the input organic matter ends up in the bio-fertiliser out of which around 30% ends up in the soil [44]. On the other hand, negative effects, like transportation and storage related CO_2-equivalent emissions, are also excluded. In this respect, the integration with renewables could lower the downstream impact. On top of that, figure 3 presumes renewable energy integration throughout the production process, which includes electrical energy consumption in case of membrane separation [73] and the deployment of renewable electricity and heat in the reforming, bio-hydrogen separation and carbon capture steps [65] [74].

In Figure 3 it can be observed that an initial 46.7 kg CO_2 equivalent is locked in 25 Nm^3 biogas produced or 1.9 kg CO_2/Nm^3 biogas. This is based on the theoretical complete combustion of CH_4 to obtain CO_2, or around 2.7 kg CO_2/kg CH_4. Ultimately, 10.9 kg CO_2 could be recovered in the concept of second generation upgrading. In case of third-generation upgrading an additional 23.2 kg CO_2 could be obtained to increase the total carbon capture potential to 34.1 kg or 1.4 kg CO_2/Nm^3 biogas. A total of 7.4 kg CO_2-equivalent is lost due to internal heat demand in the biogas production step, 0.2 kg CO_2 due to losses in the biogas upgrading step and 5.0 kg CO_2 as a result of the imperfect capture rate in the reforming step. In case of the biogas ATR process the approximate theoretical carbon capture yield would be 1.53 kg CO_2/Nm^3 biogas or a total of 38.4 kg CO_2/t manure. As a result, the biogas ATR reaction shows an approximate 15% increase in bio-carbon dioxide capture potential as compared to the reference installations, despite the potential lower hydrogen yield.

Therefore, the concept of third-generation upgrading shows additional environmental benefits in relation to the carbon capture potential of biogas both in absolute terms and in reference to the concept of second-generation upgrading. In this respect, the concept of third-generation upgrading has the potential to increase the bio-carbon dioxide capture potential with a factor 3. In this way, the concept of third-generation upgrading has the potential to unlock the value of bio-carbon dioxide and contribute to a circular carbon economy.

3.3. Economical

Table 4 shows the relevant economic parameters for the different generations of biogas upgrading. Table 5 shows the levelised cost figures for the different generations of biogas upgrading. Finally, table 6 indicates the relevant process, production and costs assumptions underlying the calculations.

In table 4 it can be observed that the production costs of the different generations of biogas upgrading is mainly determined by the biogas input price. In the case of green gas production, the biogas input price accounts for over *conf.* of the total unit cost price, while for the traditional third-generation upgrading layout the biogas input price accounts for over *conf.* of the total unit cost price. This highlights the importance of feedstock costs in case of reforming technologies [66] and implies

Variable	Zero	First	Second	Third
Output product	Biogas	Green gas	Green gas	Hydrogen
Output unit	Nm^3	Nm^3	Nm^3	kg
Input Costs (EUR)	0	0.36	0.36	2.34
CAPEX annualised (EUR)	N/A	*conf.*	*conf.*	1.22
OPEX annualised (EUR)	N/A	*conf.*	*conf.*	0.54
Total Unit Cost (EUR)	0.25	*conf.*	*conf.*	4.11
Unit cost (€/Nm^3 biogas)	0.25	*conf.*	*conf.*	0.44

Table 4: Key process related variables per output unit for different generation of biogas upgrading per Nm^3 biogas input based on 5.5 MW biogas installation

the lower economic performance of bio-hydrogen production in relation to traditional lower cost natural gas reforming [37]. The higher cost position as compared to traditional natural gas reforming can also be explained by lower economies of scale in case of bio-hydrogen production. This relates to the strong CAPEX contribution of more than double the OPEX contribution [66] [75]. In contrast, the 5.5 MW biogas production reference installations shows important economies of scale in the biogas upgrading plant due to the relatively large-scale capacity [64]. Overall, the production cost in case of second-generation upgrading is *conf.* €/Nm^3 green gas and for third-generation upgrading is 4.11 €/kg H_2, or 3.61 €/kg hydrogen excluding carbon capture and storage technology. However, in case of biogas ATR, the unit cost of bio-hydrogen production could be reduced to 3.81 €/kg H_2 and 3.31 €/kg H_2 respectively as a result of process integration and similar cost structure, despite the lower hydrogen yield and higher feedstock contribution.

Moreover, in table 4 it can be seen that the unit cost per biogas input increases over the generations of biogas upgrading. In this respect, the biogas upgrading adds approximately *conf.* to the unit cost price, while the green gas reforming adds around an additional *conf.* As a result, the concept of third-generation upgrading adds around *conf.* €/kg H_2 to the second-generation upgrading to produce bio-hydrogen and bio-carbon dioxide. The bio-hydrogen yield of the concept of third-generation upgrading is around 1.2-1.3 Nm^3 H_2/Nm^3 biogas and 1.5-1.6 kg CO_2/Nm^3 biogas in contrast to a green gas yield of 0.7 Nm^3 green gas/Nm^3 biogas and 0.5 kg CO_2/Nm^3 biogas. As a result, an approximately double normal volume amount of bio-hydrogen per normal volume amount of green gas and three times the amount of bio-carbon dioxide should recover the *conf.* €/kg H_2 increase in production costs for the concept of third-generation upgrading. However, the energy content of hydrogen per normal volume as compared to natural gas equivalent is around 25-30% [76], which results in an energetic value decrease of around 45-55% of the bio-hydrogen output in comparison to the green gas output. On the other hand, higher downstream application efficiencies, of 20-50% [23], would effectively reduce the energy disparity to 25-40% in disfavour of bio-

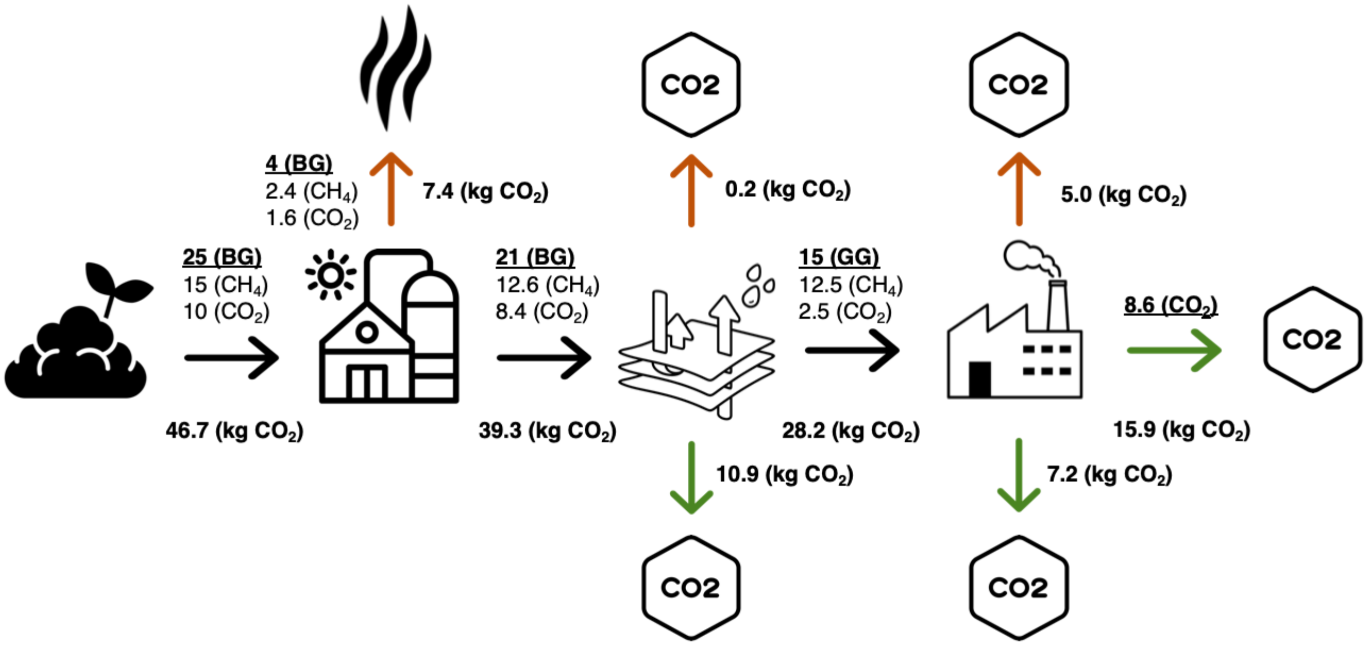

Figure 3: Carbon mass (equivalent) balance analysis over the different traditional bio-hydrogen production steps in Nm^3 (Green arrows indicate carbon capture potential and red arrows indicate potential carbon losses. BG is biogas and GG is green gas.)

Production	Zero	First	Second	Third
LCOE (€/MWh)	50	*conf.*	*conf.*	130-145
LCOH (€/kg H_2)				4.4-4.9

Table 5: Dominant levelised cost figures for the different generations of biogas upgrading

hydrogen. Therefore, the additional captured bio-carbon dioxide in the concept of third-generation upgrading should be able to recoup an additional *conf.* €/kg hydrogen production costs and an energetic value loss of around *conf.* €/kg. Therefore, based on a bio-carbon dioxide yield of around 15 kg CO_2/kg H_2 as opposed to 5 kg CO_2 in the concept of second-generation upgrading, a theoretical bio-carbon dioxide value of 200-275 EUR/t CO_2 would support a positive cost position of the concept of third-generation upgrading.

Table 5 indicates that the levelised cost of hydrogen (LCOH) of the biogas ATR and traditional steam green gas reforming is 4.4-4.9 €/kg H_2 or equal to a levelised cost of energy (LCOE) of 130-135 €/MWh. The higher LCOH as compared to the unit cost could be explained by the different assumptions with respect to the total plant costs (TPC). Additionally, in table 5 it can be observed that the LCOE for the third-generation upgrading *conf.* as compared to the concept of second-generation upgrading. The relative lower difference in energetic value between the second and third-generation upgrading relates to assumptions with respect to the energetic content of the output products and the TPC. Nevertheless, the LCOE results show agreement with previous results with respect to second-generation upgrading [37] [77] [78] and third-generation upgrading of biogas [15] [16] [41] [46].

The LCOH is derived from equation 5 [17] [79].

$$LCOH = \frac{(TPC * CCF) + C_{O\&M_{fix}} + C_{O\&M_{var}}}{kg_{H_2}} \quad (5)$$

The TPC can be determined by equation 6 [17].

$$TPC = [(\Sigma C_{i,2022} * (1 + \%_{TIC})) * (1 + \%_{IC})] * (1 + \%_{C\&OC}) \quad (6)$$

In equation 5, the capital charge factor (CCF) is equal to 0.08 [79]. Moreover, in equation 6 the total installation costs (TIC), indirect costs (IC) and owner's and contingencies costs (C&OC) are presumed to be 0.65, 0.14 and 0.15 respectively [17] [41]. The O&M fixed, O&M variable and equipment costs are calculated based on the assumptions in table 6. Ultimately, the LCOE is derived from the levelised cost of production and altered based on the energetic content per volumetric unit.

The assumptions in table 6 are derived from producer data, literature sources, quotas and reports. In this respect, the biogas upgrading occurs in a containerised solution that includes the biogas pretreatment step. Moreover, the bio-hydrogen production containerised solution contains the bio-hydrogen purification step by design. On top of that, the CCUS integration unit is presumed to have a fixed price per hydrogen output unit [80]. Moreover, the process data are obtained from the respective producers. Other data was presumed similar to literature sources and reports. Finally, the relevant data points are scaled based on a 5.5 MW biogas installation, which mimics large-scale average biogas production in the Netherlands [64].

Nonetheless, the bio-hydrogen unit cost price and LCOH are based on static model assumptions. Figure 4 shows the sensitivity of the LCOH over the key parameters of the economic

Component	Unit	Value
Feedstock		
Biogas price	€/Nm^3	0.25
Pretreatment plant cost	€	0
Biogas upgrading		
Plant cost	€/(Nm^3/h biogas)	*conf.*
Scaling factor	Green gas flow	*conf.*
Electricity consumption	kWh/Nm^3 biogas	*conf.*
Reforming plant		
Plant cost	€/(Nm^3/h hydrogen)	*conf.*
Scaling factor	Green gas flow	0.6
Electricity consumption	kW_e	29.5
Water consumption	L/h	300
Cooling water	m^3/h	30
Compressed air	Nm^3/h	4.5
CCUS integration		
CAPEX addition	€/kg H_2	0.33
OPEX addition	€/kg H_2	0.17
Production		
Plant availability	% h/year	95
Extra total plant costs	% TPC	5
Other CAPEX	% IC	1
Lifetime	year	20
Interest percentage	% IC	5
Leverage percentage	% IC	50
Maintenance costs	% IC	2.5
Labour cost	€/FTE/year	46,800
Labour	FTE/year	0.5
R&D cost	% labour	20
Overhead cost	% labour	50
Electricity cost	€/kWh	0.10
Process		
CH_4 conversion	%	0.9
CO conversion	%	0.95
H_2 capture rate	%	0.85
CH_4 combustion	%	100
Capture rate reforming	% CO_2	90
Capture rate fuel gas	% CO_2	90
Capture rate upgrading	% CO_2	100
Slip biogas upgrading	% CH_4	*conf.*
Slip biogas upgrading	% CO_2	*conf.*
Biogas composition	v% CH_4	*conf.*
Biogas composition	v% CO_2	*conf.*
Green gas composition	v% CH_4	*conf.*
Green gas composition	v% CO_2	*conf.*

Table 6: Overview of relevant production, process and cost components for a 5.5 MW biogas installation used to determine the economical perspective of the different generation of biogas upgrading.

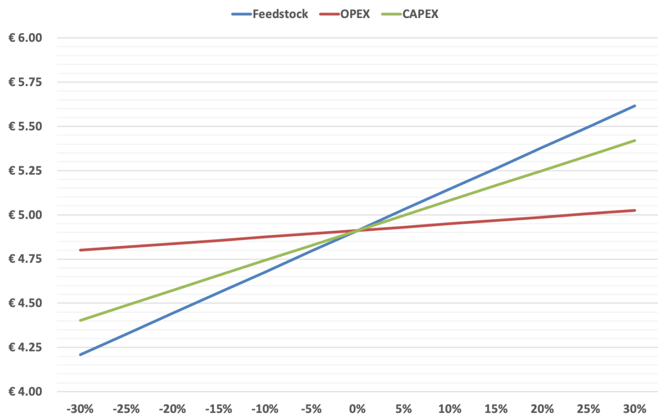

Figure 4: Sensitivity analysis of the LCOH for traditional steam green gas reforming for different levels of feedstock costs, CAPEX and OPEX

model. In figure 4 it can be seen that alterations in the feedstock price and or yield has the strongest effect on the LCOH. This can be explained by the strong contribution of the biogas feedstock costs to the total bio-hydrogen costs. This relates to the biogas input of 9 Nm^3 biogas/kg H_2, or around 2.25 €/kg H_2. In similar terms, an alteration in CAPEX, via the investment costs (IC) and labour costs, has more impact than changes in OPEX. This can be explained by the relative contribution of the different factors to the LCOH. Overall, the average LCOH can be stated to be in the range of 4.47-5.35 €/kg H_2. In similar terms, the average bio-hydrogen unit price is presumed in the range of 3.75-4.47 €/kg H_2. In case of biogas ATR, this reduces to 4.02-4.80 €/kg H_2 and 3.48-4.14 €/kg H_2 respectively.

Firstly, the variation in feedstock costs could be explained as a result of a reduction in biogas production costs and or biogas input. The biogas production costs are presumed to decrease due to an increase in production scale, commercialisation, technological efficiency, system optimisation and or favourable regulatory economic support [30] [81]. The biogas production costs could be reduced by 35%-45% in 2030-2050 by as compared to the 2018 cost levels [25] [78]. Moreover, improvements in the production process, like conversion, yield and capture rates could lower the feedstock demand [7] [66]. Secondly, with respect to CAPEX variations, the presumed production cost of biogas upgrading is assumed to lower with 10-20% as a result of economies of scale and technological improvements [37]. Additionally, the bio-hydrogen production CAPEX are presumed to decrease due to economies of scale, economies of scope, technological improvements and or process intensification options [37]. Lastly, In case of OPEX variations, improvements in industrial symbiosis, renewables integration, process and operations alterations and or efficiency improvements could support an overall reduction in OPEX [37]. Overall, these improvements could lower the apparent LCOH and bio-hydrogen unit cost to 3-5 €/kg H_2.

The bio-hydrogen cost structure also needs to be considered in relation to competitive hydrogen production methods to facilitate adoption of the concept of third-generation upgrading. In this respect, electrolysis technology is expected to see a significant decrease in production costs over time and space [6] [7]. However, a reduction in the wider value chain costs could improve the relative retail cost position of bio-hydrogen. This relates to the significant contribution of the delivery costs in the overall cost perspective of hydrogen [66]. In this perspective, an additional 0.5-1.5 €/kg H_2 is presumed to be added to the bio-hydrogen production costs for on-site, local and or regional conversion, transportation and storage of bio-hydrogen. This is in contrast to an additional 1-6 €/kg H_2 in case of international transport or 1-3 €/kg H_2 in case of regional transport of hydrogen [7] [13] [38] [66]. In case of bio-carbon dioxide transport the additional cost could add around 30-65 €/t CO_2 for liquefaction or compression and transportation [82]. Therefore, the wider value chain costs restate the importance of local system optimisation and integration to improve the relative cost perspective of bio-hydrogen and facilitate the adoption of the concept of third-generation upgrading.

Moreover, the additional benefits associated with bio-hydrogen production support the relative cost position as compared to competitive hydrogen production methods. In case of biogas production, these benefits relate to, for example, the sales of the by-product digestate that could stimulate an additional price benefit [26] [83]. On top of that, favourable regulatory support schemes and infrastructural developments could boost the relative price perspective [37] [64] [83]. Most importantly, the additional value of CO_2 savings and or sales could improve the economic model [84]. This relates to the bio-carbon dioxide yield of around 15 kg CO_2/kg H_2 or 1.6 kg CO_2/Nm^3 biogas. As a result, an increase in the bio-carbon dioxide value of 10 €/t CO_2 would effectively reduce the bio-hydrogen production cost price with 0.15 €/kg H_2. However, based on a fixed carbon capture technology cost of 0.5 €/kg H_2, and the observation that around 10 kg CO_2/kg H_2 could be captured in the reforming step, an inherent bio-carbon dioxide value of 50 €/t CO_2 is required to recover the costs of the CCUS unit. As a result, the effective bio-hydrogen production costs price, as a result of the inclusion of a bio-carbon dioxide value of 80 €/t CO_2 [85], would reduce the bio-hydrogen production price point with 1.2 €/kg H_2, or 0.7 €/kg after the CCUS costs, to 3.2-3.7 €/kg H_2.

Therefore, the concept of third-generation upgrading shows a higher cost perspective and lower energetic value, as compared to previous generations of biogas upgrading. This indicates the importance of the appropriate valuation of the additional bio-carbon dioxide stream. Moreover, additional benefits and lower relative value chain costs could further improve the price point of bio-hydrogen production. In this respect, system integration optimisation could stimulate the relevant cost position of bio-hydrogen and bio-carbon dioxide. Overall, adequate valuation of bio-carbon dioxide shows strong potential to enhance the relative cost perspective. As a result, the concept of third-generation upgrading is supported over alternative biogas utilisation and competitive hydrogen production through appropriate valuation of the bio-carbon dioxide.

H_2 value (€/kg H_2)	CO_2 value (€/t CO_2)	NPV (€/kg H_2)	ROI (%)	Payback (years)
3.6	*80*	*-0.37*	*9*	*12*
1.2		-25.79	-22	N/A
2.4	80	-13.08	-7	N/A
4.8		12.34	25	5
	40	-6.69	1	N/A
3.6	120	5.95	17	6
	160	12.28	25	5

Table 7: Investment parameters for traditional steam green gas reforming layout based on similar cost structure for 5.5MW biogas installation capacity and cost of capital of 7%

4. Discussion

The results indicate that the concept of third-generation upgrading is supported via a technologically feasible, environmentally benign and economically sound production process. Nonetheless, adequate valuation of the bio-carbon dioxide stream was indicated to be crucial for the adoption of the concept of third-generation upgrading.

Table 7 shows the net present value (NPV) investment parameter for the traditional steam green gas reforming layout based on the bio-hydrogen and bio-carbon dioxide value and a cost of capital of 7% [6] [86]. In table 7 it can be seen that the investment decision for the concept of third-generation upgrading is not supported at a bio-hydrogen value of 3.6 €/kg H_2 [76] and a bio-carbon dioxide value of 80 €/t CO_2 [85]. Nonetheless, a small increase in the respective output value results in a positive investment decision. In this respect, the concept of third-generation upgrading is supported at a bio-hydrogen price of 3.6 €/kg H_2 and a bio-carbon dioxide price of 80-90 €/t CO_2 or a bio-hydrogen price of 3.65 €/kg H_2 and a bio-carbon dioxide price of 80 €/t CO_2. This could be reduced to a bio-hydrogen price of 3.6 €/kg H_2 and a bio-carbon dioxide price of 40-50 €/t CO_2 or a bio-hydrogen price of 3.1-3.2 €/kg H_2 and a bio-carbon dioxide price of 80 €/t CO_2 for the biogas ATR layout. This reduces the required bio-hydrogen value by around 20% and the bio-carbon dioxide value by approximately 50%. Overall, the concept of third-generation upgrading is supported at a bio-carbon dioxide contribution of 25-30%.

Nonetheless, the concept of third-generation upgrading has to be considered within the context of competitive hydrogen production and alternative biogas upgrading generations. In this respect, the bio-hydrogen value is determined based on the available competitive production capacity. Moreover, the bio-carbon dioxide value is determined in the context of negative carbon emissions and physical bio-carbon dioxide delivery. Table 8 shows the relevant price assumptions to determine the economic feasibility of the concept of third-generation over time. Here, the presumed total bio-hydrogen income in 2022 overlaps with the current hydrogen market income of 4-6 €/kg H_2 [7]. Moreover, in table 8 it can be observed that the bio-hydrogen income reduces to 3.71 €/kg H_2 by 2050. On the other hand, the total bio-carbon dioxide value, through physical sales of bio-carbon dioxide and inherent carbon savings, increases from 115 €/t CO_2 in 2022 to 400 €/t CO_2 by 2050.

Income	2022	2030	2050
Sales value (€/kg H_2)	2.20 [87]	3.60 [76]	2.00 [13]
Subsidy value (€/kg H_2)	2.46[a] [72]	0.21[b]	0[c]
Sales value (€/t CO_2)	35 [82]	60 [82]	200[d]
ETS price (€/t CO_2)	80 [85]	135 [88]	200 [89]
Sales value (€/Nm^3 GG)	1.5 [90]	1.1 [91]	0.30 [e]

Table 8: Price assumptions of main output products over time period 2022-2050. [a] subsidy scheme similar to current green gas SDE+ subsidy. [b] Reflect difference in production cost and sales value. [c] Reflect no subsidy need by 2030-2050. [d] Reflect ETS trading price by assumption. [e] Reflect bio-hydrogen sales value by assumption.

	2022	2030	2040	2050
NPV 3rd generation (€/kg H_2)	20.76	26.94	33.41	38.86
NPV 2nd generation (€/kg H_2)	60.13	35.02	15.62	11.06
Δ NPV (3rd - 2nd)	-39.37	-8.08	17.79	27.80

Table 9: NPV calculation for the 3rd and 2nd generation biogas upgrading over time period 2022-2050 in €/kg H_2

Table 9 indicates that the concept of third-generation upgrading is supported over second-generation upgrading after 2030 and shows significant better economics by 2050. More specifically, the concept of third-generation upgrading is supported as of 2032 at a net bio-carbon dioxide value of around 200 €/t CO_2 and a bio-hydrogen net value of around 3.5 €/kg H_2.

Figure 5 shows that the bio-carbon dioxide value will contribute around 75% to the total income of the concept of third-generation upgrading over time. It is expected that the bio-carbon dioxide value will contribute over 50% to the total value around 2035. This results from a decreasing value of bio-hydrogen, as a result of the commodity value of cheap renewable hydrogen, and following an increase in the value of bio-carbon dioxide, due to the need for emission reductions and demand for scarce bio-carbon dioxide in a climate neutral energy system. As a result, it can be observed that the concept of third-generation upgrading is dependent on the value of bio-carbon dioxide over time. This result from the value of negative emissions or circular usage of bio-carbon dioxide and the demand for scarce renewable carbon-containing molecules in an electron dominated energy system. Therefore, the concept of third-generation upgrading portrays the highest valorisation potential of biogas through increased utilisation and valuation of the inherent bio-carbon dioxide over time.

Therefore, to support the renewed perspective on the upgrading of biogas, within the regulatory vision on a fossil free energy system, adequate boundary conditions should be in place. This relates to the cascading principle of biogas, where the highest societal value is achieved in applications with limited practical and or economic feasible alternatives. In this respect, the decoupling of the energetic bio-hydrogen and molecular bio-carbon dioxide supports the interpretation of the valorisation potential of the concept of third-generation upgrading from bio-hydrogen to bio-hydrogen and bio-carbon dioxide to ultimately bio-carbon utilisation. This could be achieved via market creation, infrastructural development and financial support mechanisms to address the relevance of biogas within the future renewable hydrogen energy system from a bio-hydrogen, bio-carbon, system integration and or energy security perspective.

4.1. Bio-hydrogen perspective

The societal benefits of bio-hydrogen production relate to the zero pollution hydrogen product, the system infrastructure optimisation and the value chain cost benefits. Moreover, bio-hydrogen production directly adds relevant renewable hydrogen production capacity and lowers the environmental impact of fossil based production methods. As a result, the production of bio-hydrogen requires adequate governmental support to facilitate supply-side and demand-side adoption.

In this respect, the dominant policy options to stimulate the development of renewable molecules in the Netherlands, the 'Stimuleringsmaatregeling Duurzame Energie' (SDE) and the 'Hernieuwbare Brandstof Eenheid' (HBE), should be altered to support the concept of third-generation upgrading. In case of the SDE subsidy, this relates to a limited long-term perspective on the future renewable hydrogen energy system. This translates into uneven support for short-term and large-scale projects, a narrowly defined concept of CO_2 emissions savings per cost unit and the inability to value negative carbon emissions. In case of the HBE support scheme, the inherent bio-carbon in biogas is insufficiently valued. As a result, the HBE requirement limits the potential for zero pollution fuels, the valuation of negative carbon savings and the efficient allocation of scarce carbon-containing molecules. Therefore, alternative support schemes should be prescribed to support the concept of third-generation upgrading within the envisioned renewable hydrogen energy system.

4.2. Bio-carbon perspective

The societal benefits of the bio-carbon perspective relate to the potential to facilitate negative CO_2 emissions through circular utilisation of bio-carbon dioxide and the contribution of biogas as scarce carbon-containing molecule within a fossil free energy system. This highlights the valorisation potential of renewable carbon-containing molecules to operate as feedstock in the bio-economy and unlock the feedstock transition [25] [67].

In this respect, the boundary conditions should resolve the current market failures, as result of the presence of negative externalities in the current energy system, which limit the adoption of the concept of third-generation upgrading [77]. The market failures relate to shortcomings like the inadequate valuation of bio-carbon dioxide and or negative CO_2 emissions. Moreover, this is also associated with the environmental valuation of zero pollution hydrogen. Additionally, this relates to the limited perspective on the efficient allocation of renewable

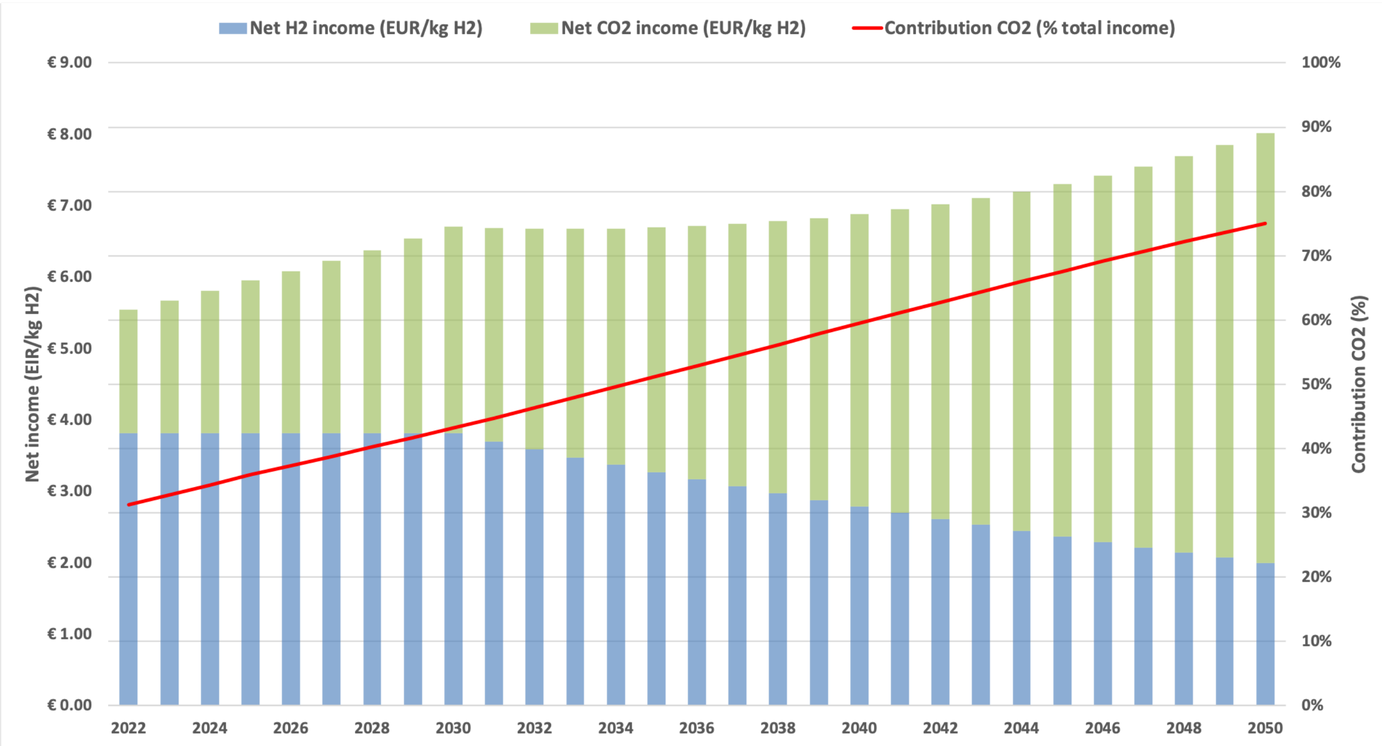

Figure 5: Income streams of the concept of third-generation upgrading over time from 2022 to 2050 and the relative contribution of the bio-carbon dioxide value to the total income value

molecules. Therefore, the concept of third-generation upgrading should be supported via market creation and supportive policy mechanisms that correctly value bio-carbon dioxide over time within the proposed renewable hydrogen energy system.

4.3. System integration perspective

The societal benefits of the system integration perspective relate to the cost benefits associated with limited infrastructure needs. This supports the relative price point of bio-hydrogen and bio-carbon dioxide in relation to competitive hydrogen production methods and alternative biogas applications. As a result, adequate infrastructural planning and development is required to stimulate the concept of third-generation upgrading.

In this respect, a infrastructural development plan could be developed that focuses on the professionalisation and commercialisation of the biogas industry. The design would support the integration of processes, incorporation of renewables and the coupling of sectors [30]. In the infrastructure design, the production of bio-hydrogen is central to support the demand from the decentralised industrial, agricultural, transportation and or build environment sector. Moreover, the production locations should account for end demand of bio-carbon dioxide and focus on the increasing relevance of bio-carbon dioxide within the future renewable hydrogen system. On top of that, local optimisation should ensure limited value chain related costs and or requirements. As a result, the design should link the current infrastructural network with the biogas potential, the green gas production locations and the presumed end demand. The objective is to optimise from a system cost perspective, within the boundary conditions related to the transport requirements of the biogas feedstock. Therefore, the infrastructure design could facilitate the adoption of the concept of third-generation upgrading through the cost-effective connection of bio-hydrogen and bio-carbon dioxide production with end demand locations.

4.4. Energy security perspective

The societal benefits of the energy security perspective relate to the problematic waste streams, the short supply chains and the geopolitical vulnerabilities. This underwrites the support for the concept of third-generation upgrading as local and or regional bio-hydrogen production method.

In this respect, the technical potential of AD biogas production is around 5.1 bcm natural gas equivalent in the Netherlands [29]. However, the economic potential is limited to 1.1 bcm by 2030. This could be lowered as a result of a decrease in livestock [29]. In perspective, the approximate total current natural gas usage in the Netherlands is around 40 bcm, where the power sector is responsible for around 30%, the industrial sector for 25% and the build environment for 20% [92]. As a result, the technical AD biogas potential represent around 3% of the natural gas demand in the Netherlands. This translates into 10%, 12% and 14% for the power, industrial, build environment sector demand respectively. On the other hand, based on a theoretical stoichiometric conversion potential, the technical AD biogas potential could fulfill around 45% of the current hydrogen production, or around 55% of the SMR produced hydrogen, in the Netherlands [93]. Therefore, the concept of third-generation upgrading shows could facilitate energy security.

5. Conclusion

Radical alterations in the current energy system are required in light of the dramatic effects of human-induced climate change. The envisioned renewable hydrogen energy system supports the need for a climate neutral energy system in the European Union by 2050. In this perspective, biogas is of vital importance for the local and or regional production of bio-hydrogen and bio-carbon dioxide. This renews the perspective on the cascading principle of biogas from source of renewable electricity, heat or fuel to biogas as platform molecule able to couple the renewable hydrogen and bio-economy domain. In this way, biogas is a relevant source of zero pollution hydrogen and an indispensable source of bio-carbon dioxide, which is presumed to become increasingly relevant in light of scarce renewable carbon-containing molecules in an electron dominated energy system. Therefore, the concept of third-generation upgrading renews the perspective on the valorisation potential of biogas and values the bio-carbon dioxide content in light of required negative carbon dioxide emissions and the need for, the circular utilisation of, renewable carbon-containing molecules in a fossil free energy system.

The concept of third-generation upgrading relies on a technologically feasible, environmentally benign and economically sound production process. In this respect, the adequate valuation and utilisation of the additional bio-carbon dioxide ensures a positive economic valuation of the concept of third-generation upgrading, despite a decrease in energetic value and increase in the relative price point. This is supported by the increased valuation and contribution of the bio-carbon dioxide value as compared to the bio-hydrogen value over time. As a result, biogas is initially valued as source of bio-hydrogen, later as source of both bio-hydrogen and bio-carbon dioxide and ultimately as source of bio-carbon.

Therefore, the concept of third-generation upgrading should be supported via regulatory commitment, market creation, policy mechanisms and infrastructural changes. In this way, biogas could act as an invaluable source of bio-hydrogen and bio-carbon dioxide, spark system integration and stimulate energy security in light of the renewable hydrogen energy system.

Ultimately, the way biogas is seen should be changed.

References

[1] Intergovernmental Panel For Climate Change, Ar6 climate change 2021: The physical science basis, accessed on 17-04-22 (August 2021). URL https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM_final.pdf

[2] Intergovernmental Panel For Climate Change, Climate change 2022: Impacts, adaptation and vulnerability, accessed on 17-04-22 (March 2022). URL https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_SummaryForPolicymakers.pdf

[3] International Energy Agency, World energy outlook 2021 (October 2021).

[4] United Nations, Ipcc report: 'code red' for human driven global heating, warns un chief, accessed on 17-04-22 (August 2021). URL https://news.un.org/en/story/2021/08/1097362

[5] European Commission, European green deal: Commission proposes transformation of eu economy and society to meet climate ambitions, accessed on 06-10-21 (July 2021). URL https://ec.europa.eu/commission/presscorner/detail/en/IP_21_3541

[6] A. van Wijk, The green hydrogen economy in the northern netherlands (April 2017).

[7] McKinsey & Company, Hydrogen insights: A perspective on hydrogen investment, market development and cost competitiveness (February 2021).

[8] DNV GL, Rising to the challenge of a hydrogen economy (July 2021).

[9] European Commission, A hydrogen strategy for a climate-neutral europe, accessed on 17-04-22 (July 2020). URL https://op.europa.eu/en/publication-detail/-/publication/5602f358-c136-11ea-b3a4-01aa75ed71a1/language-en

[10] A. van Wijk, J. Chatzimarkakis, Green hydrogen for a european green deal a 2x40 gw initiative (April 2020).

[11] International Energy Agency, Global hydrogen review 2021 (October 2021).

[12] Hydrogen Europe, Hydrogen europe position paper on the "fit for 55 package", accessed on 17-04-21 (June 2021). URL https://www.world-hydrogen-summit.com/wp-content/uploads/2022/02/Hydrogen-Europe-Position-paper-Fit-for-55-Package.pdf

[13] A. van Wijk, Hydrogen - a carbon-free energy carrier and commodity (November 2021).

[14] A. van Wijk, F. Wouters, Hydrogen, the bridge between africa and europe (October 2019).

[15] Y. S. M. Camacho, S. Bensaid1, G. Piras, M. Antonini, D. Fino, Techno-economic analysis of green hydrogen production from biogas autothermal reforming, Clean Technologies and Environmental Policy 19 (2017) 1437–1447. doi:https://doi.org/10.1007/s10098-017-1341-1.

[16] Y. Yao, M. Kraussler, F. Benedikt, H. Hofbauer, Techno-economic assessment of hydrogen production based on dual fluidized bed biomass steam gasification, biogas steam reforming, and alkaline water electrolysis processes, Energy Conversion and Management 145 (2017) 278–292. doi:https://doi.org/10.1016/j.enconman.2017.04.084.

[17] G. D. Marcoberardino, D. Vitali, F. Spinelli, M. Binotti, G. Manzolini, Green hydrogen production from raw biogas:a techno-economic investigation of conventional processes using pressure swing adsorption unit, Processes 6 (19) (2018). doi:https://doi.org/10.3390/pr6030019.

[18] J. P. Sheets, A. Shah, Techno-economic comparison of biogas cleaning for grid injection, compressed natural gas, and biogas-to-methanol conversion technologies, Biofuels Bioproducts and Biorefining 12 (2018) 412–425. doi:10.1002/bbb.1848.

[19] S. F. Pfau, J. E. Hagens, B. Dankbaar, Biogas between renewable energy and bio-economy policies—opportunities and constraints resulting from a dual role, Energy, Sustainability and Society 17 (7) (2017). doi:https://doi.org/10.1186/s13705-017-0120-5.

[20] S. N. B. Villadsen, P. L. Fosbøl, I. Angelidaki, J. M. Woodley, L. P. Nielsen, P. Møller, The potential of biogas: the solution to energy storage, Chemistry-Sustainability-Energy-Materials 12 (2019) 2147–2153. doi:https://doi.org/10.1002/cssc.201900100.

[21] N. Scarlat, J.-F. Dallemand, F. Fahl, Biogas: Developments and perspectives in europe, Renewable Energy 129 (2018) 457–472. doi:https://doi.org/10.1016/j.renene.2018.03.006.

[22] S. Sharma, S. Basu, N. P. Shetti, M. Kamali, P. Walvekar, T. M. Aminabhavi, Waste-to-energy nexus: A sustainable development, Environmental Pollution 267 (2020). doi:https://doi.org/10.1016/j.envpol.2020.115501.

[23] U.S. Department of Energy, Fuel cells technology office, accessed on 24-04-22 (November 2015). URL https://www.energy.gov/sites/prod/files/2015/11/f27/fcto_fuel_cells_fact_sheet.pdf

[24] I. Khan, Waste to biogas through anaerobic digestion: Hydrogen production potential in the developing world - a case of bangladesh, International journey of hydrogen energy 45 (2020) 15951–15962. doi:https://doi.org/10.1016/j.ijhydene.2020.04.038.

[25] J. P. van Soest, H. Warmenhoven, Green liaisons: hernieuwbare moleculen naast duurzamen elektronen (April 2018).

[26] I. Angelidaki, L. Treu, P. Tsapekos, G. Luo, S. Campanaro, H. Wenzel, P. G. Kougias, Biogas upgrading and utilization: Current status and perspectives, Biotechnology Advances 36 (2018) 452–466. doi:Biogasupgradingandutilization:Currentstatusandperspectives.

[27] B. Kampman, D. Jaspers, J. Vendrik, Kosteneffectieve alternatieven voor ccs (November 2020).

[28] R. J. Detz, B. van der Zwaan, Transitioning towards negative co2 emissions, Energy Policy (133) (2019). doi:https://doi.org/10.1016/j.enpol.2019.110938.

[29] R. van der Veen, N. Naber, C. Leguijt, Potentieel van lokale biomassa en invloedlocaties van groengas (February 2020).

[30] R. Bianchi, Strategische hubs voor de opschaling van groen gas in nederland (May 2018).

[31] C. Clifford, Russia-ukraine war: Lessons for global energy markets, accessed on 12-06-22 (March 2022). URL https://www.cnbc.com/2022/03/02/russia-ukraine-war-lessons-for-global-energy-markets.html

[32] A. Calbry-Muzyka, H. Madi, F. Rusch-Pfund, M. Gandiglio, S. Biollaz, Biogas composition from agricultural sources and organic fraction of municipal solid waste, Renewable Energy 181 (2022). doi:https://doi.org/10.1016/j.renene.2021.09.100.

[33] S. A. Chattanathan, S. Adhikari, M. McVey, O. Fasin, Hydrogen production from biogas reforming and the effect of h2s on ch4 conversion, Hydrogen Energy 39 (2014) 19905–19911. doi:https://doi.org/10.1016/j.ijhydene.2014.09.162.

[34] O. W. Awe, Y. Zhao, A. Nzihou, D. P. Minh, N. Lyczko, A review of biogas utilisation, purification and upgrading technologies, Waste and biomass valorization 8 (2) (2017) 267–283. doi:https://doi.org/10.1007/s12649-016-9826-4.

[35] I. U. Khan, M. H. D. Othmanb, H. Hashima, T. Matsuurad, A. Ismailb, M. Rezaei-DashtArzhandib, I. W. Azeleeb, Biogas as a renewable energy fuel – a review of biogas upgrading, utilisation and storage, Energy Conversion and Management 150 (2017) 277–294. doi:https://doi.org/10.1016/j.enconman.2017.08.035.

[36] P. S. Domingues, H. Pala, N. S. Oliveira, Main biogas upgrading technologies, Journal of Environmental Science and Nature 27 (4) (2021). doi:10.19080/IJESNR.2021.27.556219.

[37] C. Wouters, M. Buseman, J. van Tilburg, T. Berg, J. Cihlar, A. V. Lejarreta, J. Jens, A. Wang, D. Peters, K. van der Leun, Guidehouse: Market state and trends in renewable and low-carbon gases in europe (January 2021).

[38] M. Alvera, J. M. Kang, J. Moore, Bloombergnef: Global gas report 2020 (August 2020).

[39] R. Carapellucci, L. Giordano, Steam, dry and autothermal methane reforming for hydrogen production: A thermodynamic equilibrium analysis, Journal of Power Sources 469 (2020). doi:https://doi.org/10.1016/j.jpowsour.2020.228391.

[40] Z. Du, C. Liu, J. Zhai, X. Guo, Y. Xiong, W. Su, G. He, A review of hydrogen purification technologies for fuel cell vehicles, Catalyst 11 (393) (2021). doi:https://doi.org/10.3390/catal11030393.

[41] G. D. Marcoberardino, S. Foresti, M. Binotti, G. Manzolini, Potentiality of a biogas membrane reformer for decentralized hydrogen production, Chemical Engineering and Processing: Process Intensification 129 (2018) 131–141. doi:https://doi.org/10.1016/j.cep.2018.04.023.

[42] S. Araki, N. Hino, T. More, S. Hikazudani, Autothermal reforming of biogas over a monolithic catalyst, Journal of natural gas chemistry 19 (2010) 477–481. doi:http://dx.doi.org/10.1016/S1003-9953(09)60102-X.

[43] M. Succi, G. Macchi, S. R. Vogt, High purity hydrogen: guidelines to select the most suitable purification technology, Journal of Electrical Engineering 5 (2017) 262–269. doi:10.17265/2328-2223/2017.05.005.

[44] C. Antonini, K. Treyer, A. Streb, M. van der Spek, C. Bauer, M. Mazzotti, Hydrogen production from natural gas and biomethane with carbon capture and storage – a techno-environmental analysis, Sustainable Energy and Fuels 4 (2020) 2967–2986. doi:https://doi.org/10.1039/D0SE00222D.

[45] Y. Nalbant, C. Colpan, An Overview of Hydrogen Production from Biogas, 2020, pp. 355–373. doi:10.1007/978-3-030-40738-4_16.

[46] Fuel Cells and Hydrogen Joint Undertaking, Study on hydrogen from renewable resources in the eu (July 2015).

[47] E. Kennedy, J. M. Botero, J. Zonneveld, Hydrohub hychain 3: Analysis of the current state and outlook of technologies for the production hydrogen supply chain - technology assessment (April 2019).

[48] A. Galvagno, V. Chiodo, F. Urbani, F. Freni, Steam methane reforming system for hydrogen production: Advanced exergetic analysis, International journal of hydrogen energy 38 (2013) 3913–3920. doi:10.5541/ijot.331.

[49] L. B. Braga, J. L. Silveira, M. E. da Silva, C. E. Tuna, E. B. Machin, D. T. Pedroso, Hydrogen production by biogas steam reforming: A technical, economic and ecological analysis, Renewable and Sustainable Energy Reviews 28 (2013) 166–173. doi:https://doi.org/10.1016/j.rser.2013.07.060.

[50] N. Hajjaji, S. Martinez, E. Trably, J.-P. Steyer, A. Helias, Life cycle assessment of hydrogen production from biogas reforming, International journal of hydrogen energy 41 (2016) 6064–6075. doi:https://doi.org/10.1016/j.ijhydene.2016.03.006.

[51] H. J. Alves, C. B. Junior, R. R. Nickelvicz, E. P. Frigo, M. S. Frigo, C. H. Coimbra-Araujo, Overview of hydrogen production technologies from biogas and the applications in fuel cells, International journal of hydrogen energy 38 (2013) 5215–5225. doi:https://doi.org/10.1016/j.ijhydene.2013.02.057.

[52] L. Pino, A. Vita, M. Lagana, V. Recupero, Hydrogen from biogas: Catalytic tri-reforming process with ni/la-ce-o mixed oxides, Applied Catalysis B: Environmental 148 (2014) 91–105. doi:https://doi.org/10.1016/j.apcatb.2013.10.043.

[53] G. Nahar, D. More, V. Dupont, Hydrogen production from reforming of biogas: Review of technological advances and an indian perspective, Renewable and Sustainable Energy reviews 76 (2017) 1032–1052. doi:https://doi.org/10.1016/j.rser.2017.02.031.

[54] F. Battista, Y. M. Camacho, S. Hernandez, S. Bensaid, A. Herrmannm, H. Krause, D. Trimis, D. Fino, Lca evaluation for the hydrogen production from biogas through the innovative biorobur project concept, International Journal of Hydrogen Energy 42 (2017) 14030–14043. doi:https://doi.org/10.1016/j.ijhydene.2016.12.065.

[55] J. Lachen, J. Herguido, J. A. Pena, Production and purification of hydrogen by biogas combined reforming and steam-iron process, International Journal of Hydrogen Energy 44 (2019) 19244–19254. doi:10.1016/j.ijhydene.2018.04.151.

[56] S. Bock, R. Zacharias, V. Hacker, Experimental study on high-purity hydrogen generation from synthetic biogas in a 10 kw fixed-bed chemical looping system, RSC advances 9 (2019). doi:https://doi.org/10.1039/C9RA03123E.

[57] G. D. Marcoberardino, X. Liao, A. Dauriat, M. Binotti, G. Manzolini, Life cycle assessment and economic analysis of an innovative biogas membrane reformer for hydrogen production, Processes 86 (7) (2019). doi:https://doi.org/10.3390/pr7020086.

[58] A. Lulianelli, S. Liguori, Y. Huan, A. Basile, Model biogas steam reforming in a thin pd-supported membrane reactor to generate clean hydrogen for fuel cells, Journal of Power Sources (273) (2015) 25–32. doi:https://doi.org/10.1016/j.jpowsour.2014.09.058.

[59] J. M. V. Castillo, T. Sato, N. Itoh, Effect of temperature and pressure on hydrogen production from steam reforming of biogas with pdeag membrane reactor, International Journey of Hydrogen Energy (40) (2015) 3582–3591. doi:https://doi.org/10.1016/j.ijhydene.2014.11.053.

[60] P. Ugarte, P. Duran, J. Lasobras, J. Soler, M. Menendez, J. Herguido, Dry reforming of biogas in fluidized bed: Process intensification, International journal of hydrogen energy 42 (2017) 13589–13597. doi:https://doi.org/10.1016/j.ijhydene.2016.12.124.

[61] S. M. Soltani, A. Lahiri, H. Bahzadb, P. Cloughd, M. Gorbounova, Y. Yan, Sorption-enhanced steam methane reforming for combined co2 capture and hydrogen production: A state-of-the-art review, Carbon capture science and technology (1) (2021). doi:https://doi.org/10.1016/j.ccst.2021.100003.

[62] A. D. Giuliano, K. Gallucci, Sorption enhanced steam methane reforming based on nickel and calcium looping: a review, Chemical Engineering and Processing: Process Intensification (130) (2018) 2440–252. doi:https://doi.org/10.1016/j.cep.2018.06.021.

[63] S. Schneider, S. Bajohr, F. Graf, T. Kolb, State of the art of hydrogen production via pyrolysis of natural gas, Chemical and biochemical en-

gineering reviews 7 (5) (2020) 150–158. doi:https://doi.org/10.1002/cite.202000021.

[64] P. Wolbers, F. Lenzmann, S. Lensink, Pbl: Conceptadvies sde++ 2022 vergisting (April 2021).

[65] T. Ohkubo, Y. Hideshima, Y. Shudo, Estimation of hydrogen output from a full-scale plant for production of hydrogen from biomass, International journal of hydrogen energy 35 (2010) 13021–13027. doi:10.1016/j.ijhydene.2010.04.063.

[66] IEA, The future of hydrogen, seizing today's opportunities (June 2019).

[67] ECN, GroengasNL, DeGemeynt, RVO, Routekaart hernieuwbaar gas (July 2014).

[68] D. Corbey, B. van Asselt, Routekaart nationale biogrondstoffen. naar een groter aanbod en betere benutting (June 2020).

[69] DuurzaamNieuws, Stikstofcrisis oplossen met kleinschalig groengas is goedkoper, accessed on 13-06-22 (April 2022).
URL https://www.duurzaamnieuws.nl/stikstofcrisis-oplossen-met-kleinschalig-groengas-is-goedkoper/

[70] B. Strengers, H. Elzenga, Pbl: Beschikbaarheid en toepassingsmogelijkheden van duurzame biomassa (May 2020).

[71] H. Croezen, I. Odegard, G. Bergsma, Hoe duurzaam is biogas? (October 2013).

[72] A. Uslu, O. M. dos Santos, S. Lensink, Pbl: Conceptadvies sde++ 2022 geavanceerde hernieuwbare brandstoffen (April 2021).

[73] M. Struk, I. Kushkevych, M. Vitezova, Biogas upgrading methods: recent advancements and emerging technologies, Review Environmental Science and Biotechnology (19) (2020) 651–671. doi:https://doi.org/10.1007/s11157-020-09539-9.

[74] G. Collodi, G. Azzaro, N. Ferrari, Techno - economic evaluation of smr based standalone (merchant) hydrogen plant with ccs (February 2017).

[75] J. Holstein, R. van Gerwen, J. Douma, Y. van Delft, M. Saric, Technologiebeoordeling van groene waterstofproductie (November 2018).

[76] A. van Wijk, C. Hellinga, Waterstof voor gebouwverwarming, naar 500.000 woningen op waterstof in 2030 (May 2021).

[77] J. L. Moraga, M. Mulder, P. Perey, Future markets for renewable gases & hydrogen (May 2019).

[78] IEA, Average cost of biogas production technologies per unit of energy produced, accessed on 24-04-22 (March 2020).
URL https://www.iea.org/data-and-statistics/charts/average-costs-of-biogas-production-technologies-per-unit-of-energy-produced-excluding-feedstock-2018

[79] E. Rubin, G. Booras, J. Davison, C. Ekstrom, M. Matuszewski, S. McCoy, C. Short, Toward a common method of cost estimation for co2 capture and storage at fossil fuel power plants (January 2013).

[80] L. van Cappellen, H. Croezen, F. Rooijers, Feasibility study into blue hydrogen (July 2018).

[81] M. Banja, R. Sikkema, M. Jegard, V. Motol, J.-F. Dallemand, Biomass for energy in the eu – the support framework, Energy Policy 131 (2019) 215–228. doi:https://doi.org/10.1016/j.enpol.2019.04.038.

[82] S. Lamboo, K. Smekens, M. Muller, Pbl: Conceptadvies basisbedragem sde++ 2022 categorie ccu (April 2021).

[83] M. Schimmel, D. Peters, K. van der Leun, Setting a binding target for 11 % renewable gas (January 2021).

[84] H-vision, Blue hydrogen as accelerator and pioneer for energy transition in the industry (July 2019).

[85] Ember Carbon Pricing, Eua (eu ets) futures prices, accessed on 24-04-22 (April 2022).
URL https://ember-climate.org/data/data-tools/carbon-price-viewer/

[86] KPMG, Cost of capital study 2020, accessed on 10-06-22 (January 2020).
URL https://home.kpmg/de/en/home/insights/2020/10/cost-of-capital-study-2020.html#:~:text=The%20weighted%20average%20cost%20of,in%20the%20current%20reporting%20year.

[87] International Energy Agency, Hydrogen production costs by production source, 2018, accessed on 26-04-22 (March 2020).
URL https://www.iea.org/data-and-statistics/charts/hydrogen-production-costs-by-production-source-2018

[88] Nederlandse Vereniging Duurzame Energie, Ontwikkeling nederlandse etsinkomsten 2021-2030 (November 2021).

[89] Centraal Plan Bureau, Wlo-klimaatscenario's en de waardering van co2-uitstoot in mkba's (November 2016).

[90] S. Lensink, Pbl: Voorlopige correctiebedragen 2021 en basisprijzen voor categorieËn in de sde++ 2021 (May 2021).

[91] Rijksoverheid, Besluit tot wijziging van het besluit energie vervoer in verband met de implementatie van richtlijn(eu) 2018/2001 van het europees parlement en de raad van 11 december 2018, accessed on 26-04-22 (October 2021).
URL https://www.rijksoverheid.nl/documenten/besluiten/2021/10/08/bijlage-1-wijziging-besluit-energie-vervoer

[92] S. Chong, K. van Leeuwen, R. van den Oever, M. Rensman, L. Siebeling, Cbs: De ontwikkeling van vraag en aanbod van aardgas sinds 2013, accessed on 19-04-22 (November 2020).
URL https://www.cbs.nl/nl-nl/longread/de-nederlandse-economie/2020/de-economische-rol-van-aardgas-na-de-productiebeperkingen/4-de-ontwikkeling-van-vraag-en-aanbod-van-aardgas-sinds-2013

[93] Milieu Centraal, Klimaat en aarde - energiebronnen - waterstof, accessed on 19-04-22 (2022).
URL https://www.milieucentraal.nl/klimaat-en-aarde/energiebronnen/waterstof/