Hydrogen from organic waste with an integrated biological-thermal-electrochemical process

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Abstract

In this project we have investigated the feasibility of an innovative process to produce hydrogen from biodegradable organic waste. The process uses a combination of biological (dark fermentation and anaerobic digestion), thermochemical (steam gasification and water gas shift) and electrochemical (plasma reforming) stages. This report includes: mass and energy balances (WP1), carbon life cycle assessment (WP2), lab scale prototype (WP3), engineering design of the pilot plant (WP4), plan for the operation of the pilot plant (WP5), costed plan for Phase 2 (WP6), commercialisation plan (WP7), stakeholder engagement events (WP8).

The hydrogen yield and energy consumption of the process were calculated in a range of assumptions about the yield and energy consumption of the individual stages. For carbohydrate-based organic matter and the most favourable yield assumptions (base case), the total hydrogen yield was 0.13 kg_{H2}/kg_{OM} (OM=organic matter). Under these conditions, the energy consumption was estimated to be 0.33 kWh/kWh_{H2} and the consumption of water for chemical reactions 3.3 kg_{H2O}/kg_{H2}. For fat-based organic matter, the hydrogen yield was 0.35 kg_{H2}/kg_{OM}. The hydrogen yield, energy and water consumption are affected by the assumptions on the efficiency of the individual stages. If each stage has an efficiency of 50% compared to the base case, the total hydrogen yield reduces to 0.05 kg_{H2}/kg_{OM}, the energy consumption increases to 1.40 kWh/kWh_{H2} and the water consumption increases to 18.7 kg_{H2O}/kg_{H2}. The chemical stages (PR, SG and WGS) are those with the most important effect on the total hydrogen yield, while the biological stages (DF and AD) have a strong effect on the energy and water consumption. It is therefore important to optimise all stages of the process to achieve the most sustainable process. For a hypothetical commercial plant treating 100 t/d of carbohydrate-based food waste, the assumptions of the base case translate into a daily production of 2.4 t of H_2.

The carbon emissions were estimated to be, for the base case, 0.10 kg_{CO2eq}/kWh_{H2} for the current mix of electricity generation used in the UK and 0.036 kg_{CO2eq}/kWh_{H2} assuming the required electricity is entirely obtained from renewable resources. The carbon emissions can be reduced even further if hydrogen from this process rather than natural gas is used to supply the required process heat. Inefficiencies and yield losses will lead to an increase in the carbon emissions, for example if each stage has an efficiency of 50 % compared to the base case the carbon emissions become 0.43 kg_{CO2eq}/kWh_{H2} which confirms the importance of optimising all stages.

A lab-scale prototype has been assembled and preliminary tests are currently going on. The lab-prototype include biological reactors in batch and sequencing batch reactor mode, plasma and steam gasification reactors. The set up is capable of simulating the process at lab scale. The plan is to use the lab set up to optimise all stages of the process in Phase 2, in parallel with the runs of the pilot plant.

The design of the pilot plant which we plan to build in Phase 2 is in progress. The plant is expected to include all the required reaction (DF, AD, PR, SG and WGS) and purification stages (membranes) processing 20 kg/d of food waste, with an estimated production of 0.52 kg_{H2}/d at >99% hydrogen purity. The DF and AD stages will be operated in SBR mode with volumes of 100 and 300 L respectively. The volume of the chemical stages will be lower, in the order of 2-20 L.

The operation of the pilot plant will aim to collect data on the actual hydrogen yield and on the energy and water consumption under process conditions. The plant will use two types of feedstocks: food waste and municipal wastewater. The flow rate,

temperature and pressure of all the main streams will be monitored regularly, together with the electricity and water consumption.

The total budget of Phase 2 is expected to be close to £5M, with the following split: staff time and overheads £1.4 M; capital equipment £2.5M; consumables £800,000; travel £100,000. Staff time will include the contribution of 15 members of academic staff at University of Aberdeen, who will supervise the various process stages and the build of the pilot plant, and of five research assistants responsible for the running of the lab-prototype and of the pilot plant. Capital equipment will include all the pilot plant equipment: two biological reactors (DF and AD), three mixing vessels (storage of intermediate products), storage vessels for the waste and water, chemical reactors for SG, PR and WGS, membrane unit, gas storage vessels, pumps and compressors. Consumables will include for the lab set up and for the pilot plant, e.g. filters, gas bags, kits for chemical measurements (e.g. COD), consumables for chromatography analyses.

The commercialisation report (by the company Optimat) investigated the nature and amounts of organic waste generated in the UK, including food waste, farm waste, sewage sludge and other waste. In the UK, organic waste is generated at rates of over 100 million tonnes per year, which indicates a large potential for hydrogen production with this process, however waste collection is a main issue that needs to be addressed soon. Possible commercialisation routes via a spin-off company or licensing of the technology have been explored, however data from the pilot plant study are needed for a full understanding of the commercial potential of the process.

Stakeholder engagement events have been held, involving representatives from academia and industry. These events have allowed a discussion about our process and the wider topics of hydrogen from waste and anaerobic digestion.

Contents

List of frequent abbreviations

DF	Dark Fermentation
AD	Anaerobic Digestion
PR	Plasma Reforming
SG	Steam Gasification
WGS	Water Gas Shift
COD	Chemical Oxygen Demand
DM	Dry matter
OM	Organic matter
GC	Gas Chromatography
HPLC	High Performance Liquid Chromatography
SBR	Sequencing Batch Reactor

Introduction and aims

Introduction

This project aims to investigate the feasibility of an innovative process to produce hydrogen from biodegradable organic waste. The process (Figure 1) uses a combination of biological, thermal and electrochemical stages to maximise hydrogen yield while minimising energy consumption. We estimated that the production of biodegradable organic waste is in the region of $8\text{-}9\cdot10^9$ t_{DM} globally [1] and that the biodegradable organic waste produced yearly in the UK, if collected and converted into hydrogen using optimised biological and chemical processes, could potentially produce ~6 Mt of hydrogen per year, which would account for ~26 % of the UK's energy demand for domestic heating and road transport in renewable energy scenarios [2].

The process feedstock can be biodegradable organic matter of any type, from concentrated waste in solid form such as food waste to diluted water streams like municipal sewage. The first two stages are biological and use anaerobic open mixed cultures similar to the ones used in commercial-scale anaerobic digestion processes: the first stage is dark fermentation (DF), where microorganisms convert the biodegradable organic matter into hydrogen and carbon dioxide (gas phase) and into organic acids (liquid phase); the liquid phase, containing the organic acids, water, microorganisms and any organic matter undigested in DF, goes to the second stage, an anaerobic digester (AD) which produces biogas, mainly composed of methane and carbon dioxide. The biogas from AD is sent to the third stage, plasma reforming (PR), where methane and carbon dioxide react to form hydrogen and carbon monoxide, under conditions of non-thermal plasma with high electricity voltage and solid catalysts. The digestate from AD, containing microorganisms and any undigested organic matter, is sent to the fourth stage, a steam gasification reactor (SG) where the organic matter is converted into gases, mainly composed of hydrogen and carbon monoxide, by reaction with steam at high temperature. Finally, the carbon monoxide produced by the PR and SG stages is converted into hydrogen and carbon dioxide in the fifth reaction stage, the water gas shift (WGS) which uses steam and a solid catalyst. The hydrogen can be purified to the desired purity using existing gas purification technologies, e.g. membranes.

The biological stages DF and AD are expected to produce hydrogen with the least energy consumption. These stages can be operated at ambient or near ambient temperature with no or minimum heating requirements, requiring energy only for low-speed mixing. The SG stage can be energy intensive due to the high required temperature (expected to be approximately 800 ^{O}C), however this stage will only process the residual organic matter after the AD stage, which is expected to be low. Therefore, the total energy consumption of the SG stage is expected to be low. Furthermore, the energy requirements for SG could be entirely provided by electricity, with advanced design of the gasification equipment. Electricity is more easily obtainable from renewable resources (e.g. sun and wind) than heat, contributing to the sustainability of our process. The PR stage is also expected to be energy intensive, however it only uses electricity and only processes the biogas from the AD stage, while the biogas from the DF stage already contains hydrogen and doesn't need further chemical conversion. The WGS stage is operated at a temperature of approximately 350 ^{O}C with solid catalyst and, similar as other stages, could be powered entirely by electricity. The use of electricity for energy supply makes it possible to use excess electricity from curtailment. Excess electricity is generated when the generation of electricity from renewable resources, especially solar panels and wind turbines, exceeds electricity usage and is available in principle at zero cost. At commercial scale, our process can be designed with appropriate storage vessels so that the stages that have high electricity requirements, mainly PR, SG and WGS, are operated only when excess electricity is available, minimising electricity costs and not competing with other demands on the power grid.

Objectives

This project had the following objectives:
- WP1. To use mass and energy balances to calculate the hydrogen yield estimate the energy consumption, using a range of assumptions;
- WP2. To calculate the carbon emission from the process, using the results of WP1 and a range of assumptions on the resources used;
- WP3. To set-up a lab prototype obtaining preliminary experimental data;
- WP4. To produce an engineering design the pilot plant to be built in Phase 2;
- WP5. To produce a plan for the operation of the pilot plant, with lists of parameters to be monitored to measure the hydrogen yield and the energy consumption;
- WP6. To produce a costed plan for Phase 2;
- WP7. To produce a commercialisation plan, reviewing potential markets for waste and for hydrogen and strategies for commercialisation;
- WP8. To organise events with academic and industrial stakeholders.

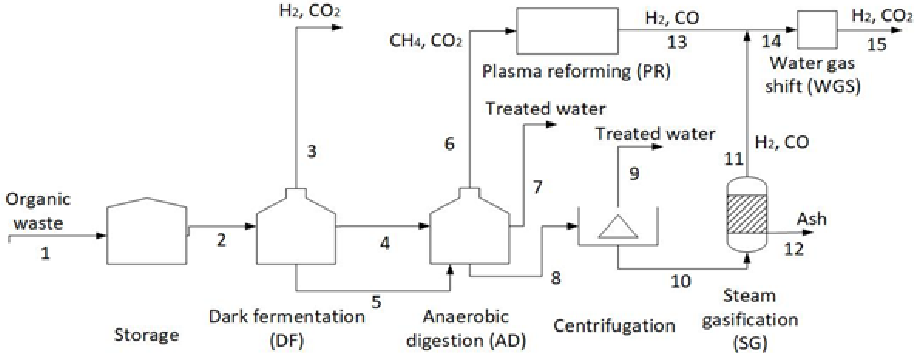

Figure 1. Scheme of the proposed process for hydrogen production from biodegradable organic waste. Stream numbers: 1. Organic waste to the storage vessel; 2. Organic waste to the DF stage; 3. Biogas (mainly hydrogen and carbon dioxide) from the DF stage; 4. Clarified liquid (mainly organic acids in water) from the DF stage; 5. Concentrated suspended solids from the DF stage; 6. Biogas (mainly methane and carbon dioxide) from the AD stage; 7. Treated water from the AD stage; 8. Concentrated suspended solids from the DF stage; 9. Treated water from the centrifuge; 10. Concentrated suspended solids to the SG stage; 11. Gases (mainly hydrogen and carbon monoxide) from the SG stage; 12. Ash (mineral elements, e.g. N, P, K, Mg) to reuse (e.g. in agriculture); 13. Gas products (mainly hydrogen and carbon monoxide) from the PR stage; 14. Gas stream combination of streams 11 and 13; 15. Gas stream (mainly hydrogen and carbon dioxide) from the WGS stage.

References

[1] Dionisi, D., Bolaji, I., Nabbanda, D., & Silva, I. M. (2018). Calculation of the potential production of methane and chemicals using anaerobic digestion. Biofuels, Bioproducts and Biorefining, 12(5), 788-801.
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1. WP1. Mass and energy balances

Introduction

This chapter covers calculations of the hydrogen yield and of the energy and water consumption for each stage and for the process as a whole. The calculations were based on assumptions about the composition of the organic waste, the stoichiometry of the chemical reactions and the efficiency of conversion in each stage. The effect of the assumptions on the efficiency and energy consumption of each stage was investigated. Detailed methodology and results are reported in Appendix A.

1.1 Summary of methodology

The conversions and the hydrogen yields from each of the five stages of our process have been reported to vary significantly, depending on the process conditions and on the nature of the feedstock. For DF, the experimental data in the literature have been recently reviewed by our group [1.1]. For AD, a recent review reports the methane yields in various process configurations [1.2]. Experimental studies on the gasification of digestate and on the PR and WGS reactions have also been recently reviewed [1.3, 1.4, 1.5]. Under optimal conditions, conversions and hydrogen yields close to the theoretical maximum have been reported for all stages.

Considering the experimental evidence from literature, our approach in this section was to calculate the hydrogen yield for our process assuming the highest conversions in each stage (base case) and then to calculate the effect of lower efficiencies in each stage. The same approach was followed to calculate the energy and water consumption. Appendix A reports the details of the methodology and of the assumptions used for the calculations in this section.

1.2 Results

1.2.1 Hydrogen yield, energy and water consumption

Table 1.1 summarizes the total H_2 yield, energy consumption and water consumption for the base case, which assumes 100% efficiency for all stages. The total hydrogen yield per unit of organic matter obtainable with this process (0.13 and 0.35 kg_{H2}/kg_{OM} assuming organic matter composed of carbohydrates and lipids, respectively) is higher than for other proposed processes that use biomass as feedstock, due to the combination of different stages and different technologies which maximise the hydrogen yield. Note that the assumption of organic matter composed of carbohydrates or lipids was made to simulate two extremes for the possible chemical composition of the organic matter in biodegradable waste, i.e. low (carbohydrates) or high (lipids) COD and energy content. The real composition of the organic matter will include a mixture of carbohydrates, proteins, lipids and other components (as reported, e.g., in our recent study [1.6]). Therefore, the organic matter fed to our process will have COD and energy content intermediate to the one of carbohydrates and lipids and the actual hydrogen yield obtainable from our process will likely fall between these calculated values.

The total energy consumption per unit of hydrogen produced is lower than for other processes, e.g. water electrolysis or gasification. Again, this is due to the fact that our process combines different technologies, optimising the energy consumption. Indeed, the biological stages DF and AD can run at ambient or close to ambient temperature with low energy consumption. The thermal and electrochemical stages

PR, SG and WGS complete the biomass conversion maximising the hydrogen yield and, while they have a higher energy consumption than the biological stages, they only process a fraction of the total organic matter fed to the process, therefore their contribution to the total energy consumption is limited.

Table 1.1. Total hydrogen yield, energy and water consumption calculated for the base case (assumption of high conversion efficiency for all stages).

Case	**Total H_2 yield (kg_{H2}/kg_{OM})**	**Total energy consumption (kWh/kWh_{H2})**	**Total water consumption (kg_{H2O}/kg_{H2})**
Food waste (carbohydrates)	0.13	0.335	3.33
Food waste (lipids)	0.35	0.317	3.51
Wastewater (carbohydrates)	0.13	0.335	3.33

Clearly, if the process stages are less efficient than what was assumed for the base case, the hydrogen yield will be lower while the total energy and water consumption will be higher than what was calculated for the base case. The effect of the assumptions used for the efficiency and energy consumption is shown in detail Appendix A. As an example of the effect of these assumptions, Figure 1.1 compares the total hydrogen yield, total energy and water consumption for the base case (high efficiency) and for the case where the conversion efficiency of each stage is 50 % of the base case (low efficiency). The hydrogen yield reduces from 0.13 to 0.054 kg_{H2}/kg_{OM}, while the energy consumption increases from 0.335 to 1.40 kWh/kWh_{H2} and the water consumption increases from 3.33 to 18.68 kg_{H2O}/kg_{H2}.

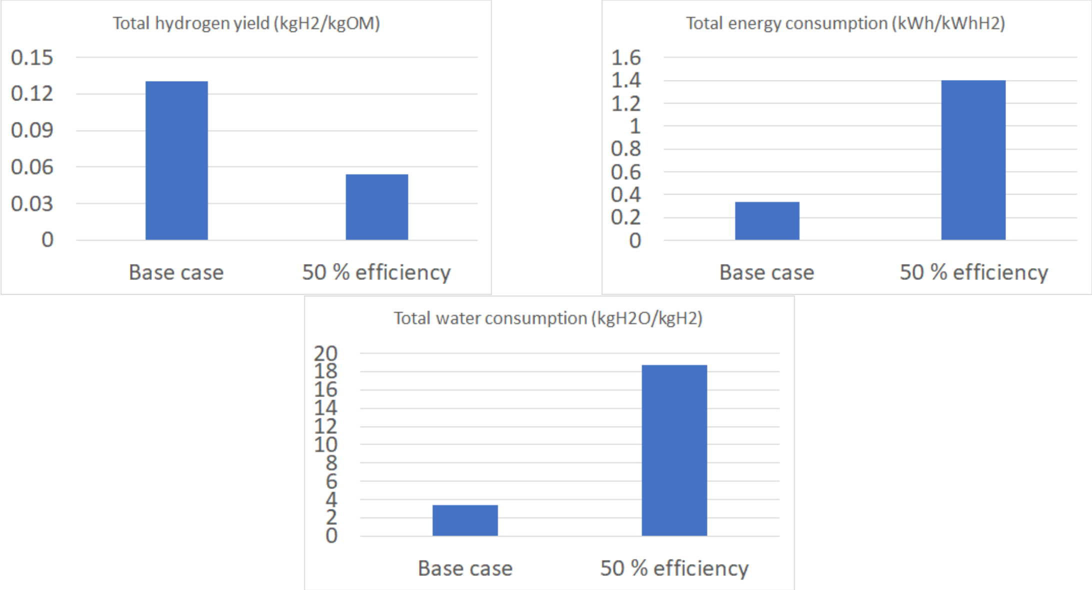

Figure 1.1. Comparison of the calculated total hydrogen yield, energy consumption and water consumption for the base case and for the assumptions of 50 % conversion efficiency in each stage.

The high increase in the energy and water consumption is mainly due to the fact that, if the biological stages have a lower efficiency, then the SG stage will process more organic matter with a higher energy and water consumption. However, all stages contribute to the hydrogen yield and energy consumption so it is important to optimise each stage to maximise the performance and sustainability of the process.

1.2.2 Stream table for full-scale process

Table 1.2 shows the stream table for the process with the assumptions of the base case. The stream table refers to a hypothetical commercial plant treating 100 t/d of food waste, which is, according to our estimations, the approximate amount of food waste generated by a urban community the size of Aberdeen. The plant is estimated to produce a total of 2.4 t_{H_2}/d, the only other gas product being carbon dioxide (approx. 27 t_{CO_2}/d). The CO_2 produced by the plant is biogenic because the carbon derives from the carbon in the food waste, which was absorbed from atmospheric CO_2 when the biomass was growing. As such, the CO_2 directly emitted by the plant does not count towards net carbon emissions, however this carbon can be captured and stored using existing technologies obtaining a carbon negative process.
In the practical realisation of the commercial plant, it is expected that all required energy will be obtained from solar panels placed on the roof of the plant itself, without drawing energy from the grid and using batteries for energy storage. Furthermore, any combustible by-products produced by the plant, e.g. any carbon monoxide and methane from incomplete conversions in the PR and WGS stages, will be combusted on site in a CHP (combined heart and power) unit to generate electricity for the plant. These technologies will be implemented in the pilot plant in Phase 2 and are also described in Chapter 4 on pilot plant design.

Table 1.2. Stream table for commercial scale. Stream numbers according to Figure 1 in the Introduction and aims

	Streams with main component mass flows in kg/d														
Component	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Water	80,000	80,000													
Organic matter	20,000	20,000		13,157	200			502		502					
H_2			877								25		743	768	1,520
CH_4						2,973									
CO											112		10,406	10,518	
CO_2			9,648			8,176					155		972	972	17,346

References

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2. WP2. Carbon life cycle assessment

Introduction

This section investigated the carbon emissions for the proposed process. The carbon emissions are due to the energy consumption by the process. Since the organic waste feedstock of the process derives from biomass, direct carbon dioxide emissions due to the chemical reactions were not considered, as, in analogy with other energy from biomass processes, this carbon is absorbed from the atmosphere when biomass grows. The methodology and the detailed results are reported in Appendix B.

2.1 Results

Figure 2.1 shows comparative analysis of carbon emissions per kg of H_2 produced using 2 different electricity sources (UK grid and Renewables) for both the feedstock cases. Figure 2.2 does a similar comparison for carbon emissions per kWh of H_2 produced. Figures 2.1 and 2.2 refer to a hypothetical commercial plant treating 100 m^3/d of waste, which, for the case of food waste as feedstock, is represented by the stream table in Table 1.2. As detailed in Appendix B, the carbon emissions in Figures 2.1 and 2.2 include all the main contributions: transportation of the feedstock, energy used by the process (electricity and heating) and use of water. Transportation of the feedstock is only considered for food waste, while for wastewater it is assumed that the process will use the existing sewage network, effectively replacing an existing biological wastewater treatment plant, with no additional transport emissions beyond those of current processes. The absence of emissions due to the transportation of the feedstock is the reason for the slightly lower emissions calculated for wastewater rather than for food waste processing.
As explained in Appendix B, all our calculations of carbon emissions assume that heating is provided by natural gas, as this is the most common resource for heating in the UK. However, it is expected that commercial plants will use electricity from solar panels coupled with battery storage for all energy requirements, including heating, with further reduction in the carbon emissions.
Figures 2.1 and 2.2 show that considerable reduction in carbon emissions can be obtained by using electricity entirely from renewable resources, compared to using electricity from the UK grid which for the majority derives from fossil fuels (mainly natural gas). This considerable reduction is due to the fact that electricity is the main energy consumption in the process, mainly due to the PR stage (Chapter 1 and Appendix A), and any reduction in the carbon emissions associated to electricity generation will give an important benefit to the carbon emissions of the process.
Overall, the carbon emissions of the process correspond, for food waste, to 0.10 kg_{CO2eq}/kWh_{H2} with electricity from the UK grid and 0.036 kg_{CO2eq}/kWh_{H2} with electricity from entirely renewable resources, assuming the HHV of hydrogen (these figures correspond to, respectively, 33 g_{CO2eq}/MJ_{LHVH2} and 12 g_{CO2eq}/MJ_{LHVH2}). These emissions can be further reduced by using, for process heating, low-carbon renewable electricity (as discussed above) and/or some of the low-carbon hydrogen produced by this process.
As shown in the detailed calculations in Appendix B, the carbon emissions from the process will be higher in case of inefficiencies in the conversion from the various stages or in case the energy consumption of the stages is higher than in our

assumptions. This indicates the importance of optimising the conversion and energy efficiency of all stages, which will be one of the objectives of Phase 2.

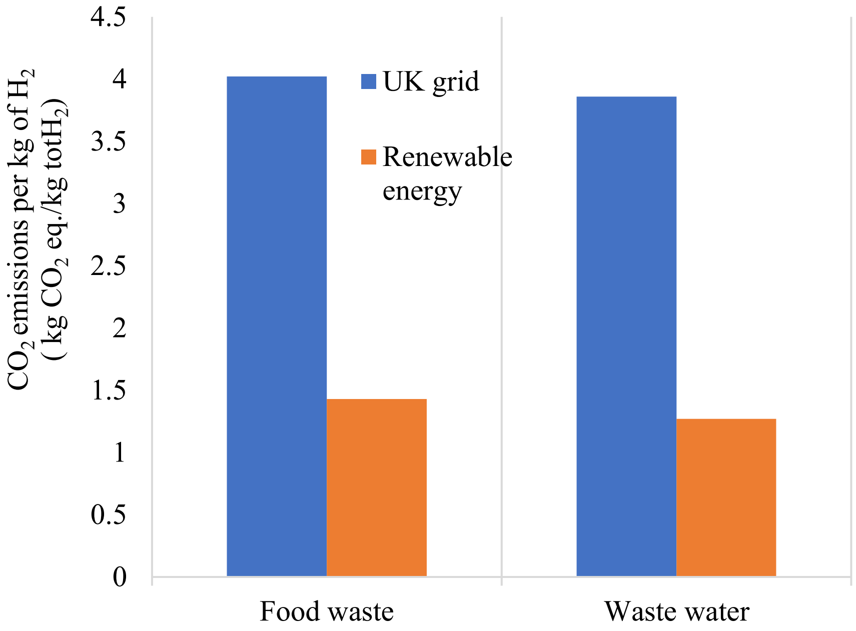


Figure 2.1 Carbon emissions per kg of H_2 produced using 2 different electricity sources (UK grid and Renewables).

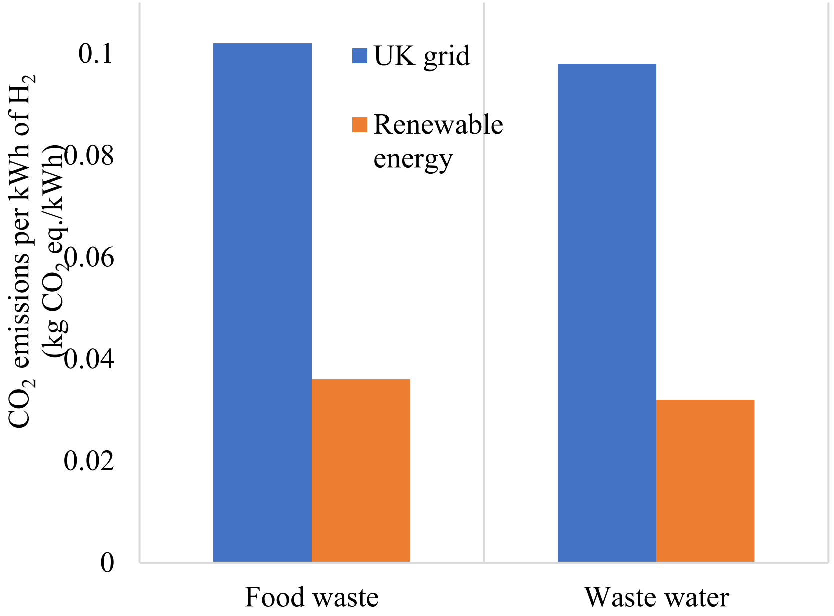


Figure 2.2 Carbon emissions per kWh of H_2 produced using 2 different electricity sources (UK grid and Renewables).

WP3. Lab-scale prototype

Introduction

The aim of this WP was to purchase and assemble a lab-scale prototype of the proposed process and to run some preliminary experiments of the main process stages. It is planned to use extensively the lab prototype in Phase 2 of the project to investigate the effect of the main process parameters on process performance, to optimise process design and to maximise the hydrogen yield. The results of the Phase 2 runs of the lab-scale prototype will be fed into the operation of the pilot plant, allowing to adjust and optimise its operating conditions.

The lab-prototype consists of the four main process stages: DF, AD, PR and SG. Detailed information on the experimental set-up and on the results is reported in Appendix C.

3.1 Results

3.1.1 Biological stages

The detailed results of the experiments on biological stages are reported in Appendix C. As described in Appendix C, the batch experiments (summarised in Figure 3.1) were mostly done using glucose at 2 g/L as feed, while the SBR experiments (Figure 3.3) were done with a feed composed of glucose only (2 g/L) for the first week and of a mixture of glucose, yeast extract and oleic acid (total concentration 10 g/L) from day 7 onwards. Hydrogen production was quantified from the COD balance and from analysis of the composition of the produced gas. According to the COD balance [3.1], under anaerobic conditions any decrease in the total (soluble plus insoluble) COD in the liquid/solid phase is due to the production of either hydrogen or methane, which were measured independently using GC. In addition, the production of organic acids in the liquid phase was also measured by HPLC, obtaining further information on the biological metabolism and products.

Figure 3.1 compares the removal of total COD from the liquid phase in the three experiments where dark fermentation conditions were established (Experiment 1, Experiment 3, Experiment 4 under unbuffered conditions, Experiment 5 and Experiment 6, details of these experiments are in Appendix C). In these experiments, the removal of total COD indicates hydrogen production as the liquid phase pH was acidic and, when measured, no methane was detected (Figure 3.2). The absence of methane production was due to the acidic conditions (final pH was approximately 4 in these experiments). In all these experiments, acidogenic conditions were established, with production of short chain organic acids of variable composition, but in general rich in butyric and acetic acid.

The results indicate some variability in COD removal and therefore in hydrogen production in the dark fermentation stage. Experiments 1, 3 and 6 reported a COD removal which was quite close to the one assumed for base case calculations in WP1, which was 33 % for carbohydrate feedstock (Equation A.5). Phase 2 will be dedicated to the optimisation and control of the dark fermentation conditions. However, it is important to observe that in the proposed process, any lower yield in the DF stage can be compensated by the following stages, although it is important to maximise the efficiency of all stages to achieve the most sustainable process.

The results of the SBR processes (DF and AD stages in series) are shown in Figure 3.3. Overall, the SBR process works as expected, with lower effluent total COD in the AD than in the DF, complete conversion of the glucose in the AD stage and lower concentration of acids in the effluent of AD than in the effluent of DF.

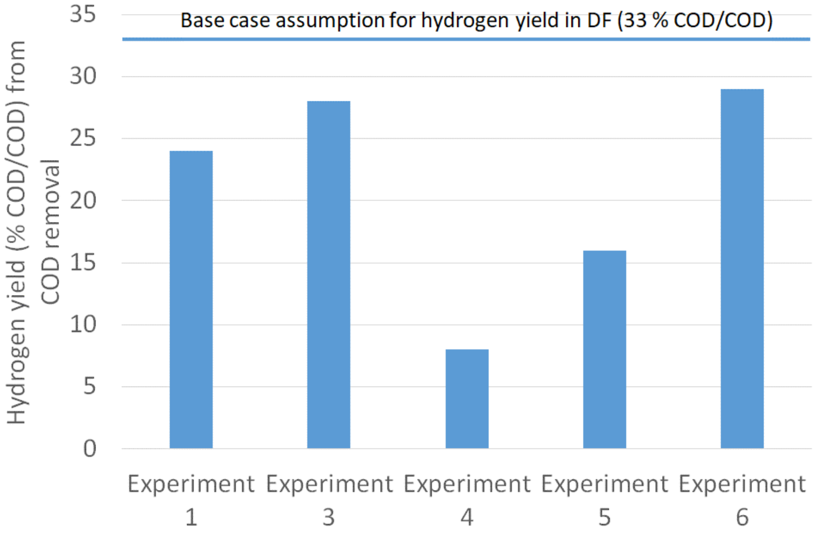


Figure 3.1. Comparison of COD removal in experiments with DF conditions

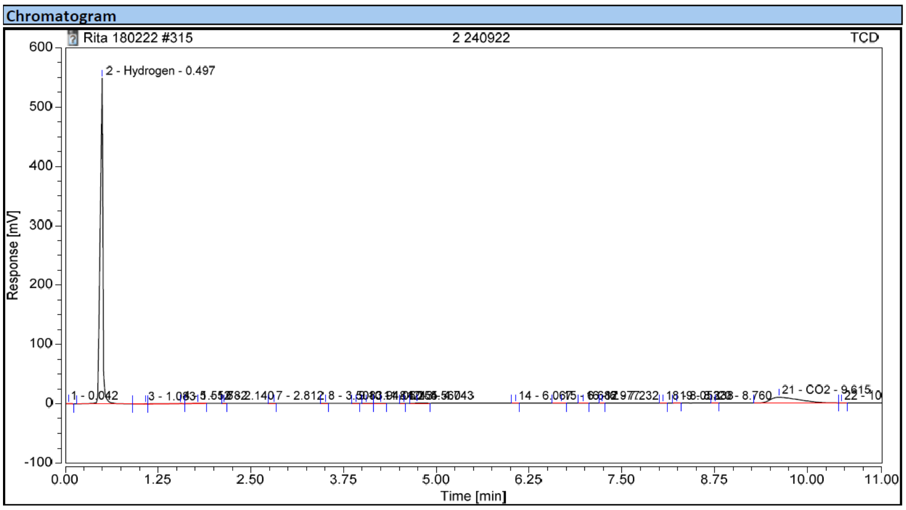


Figure 3.2. Chromatogram showing hydrogen production and no methane in Experiment 3.

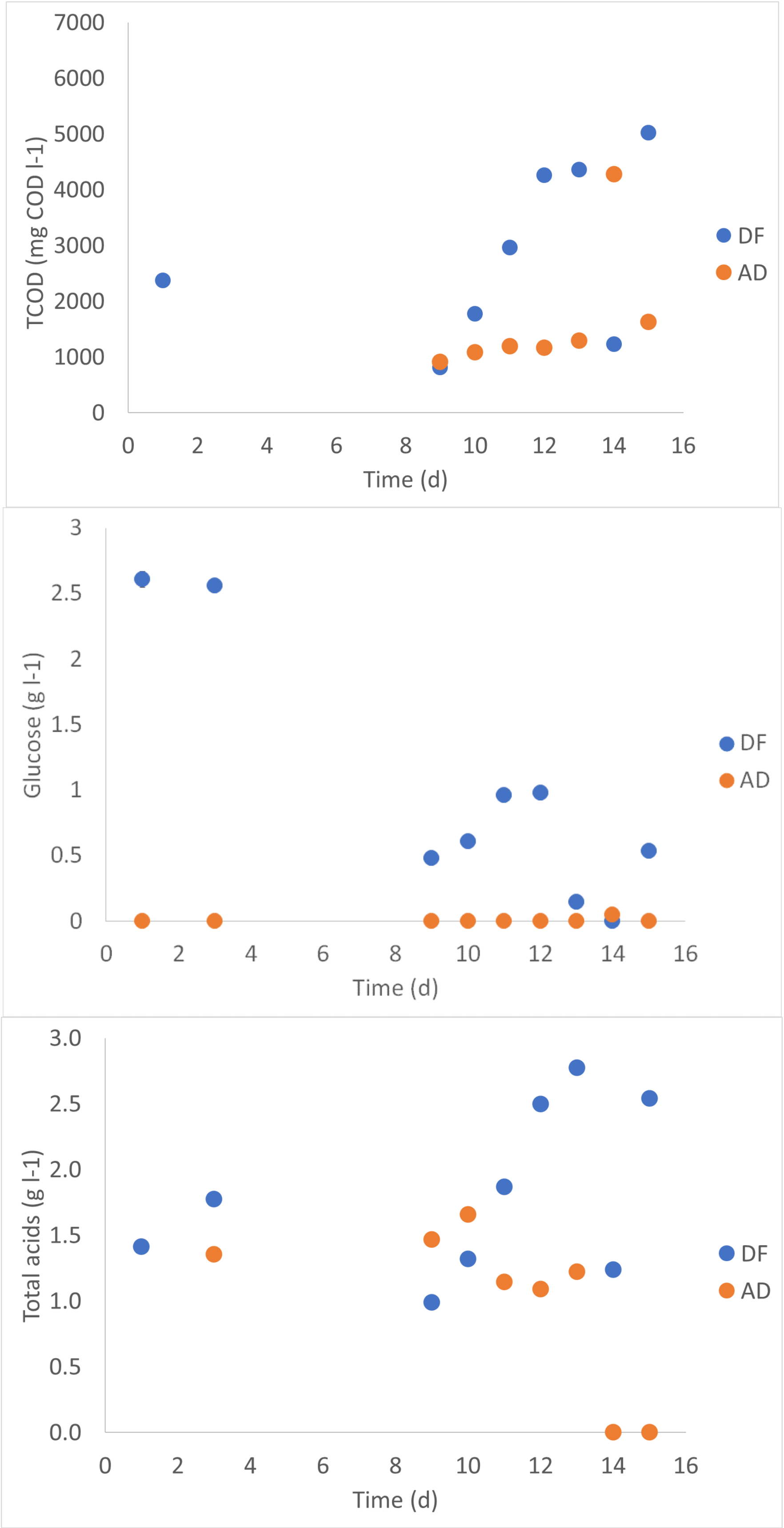
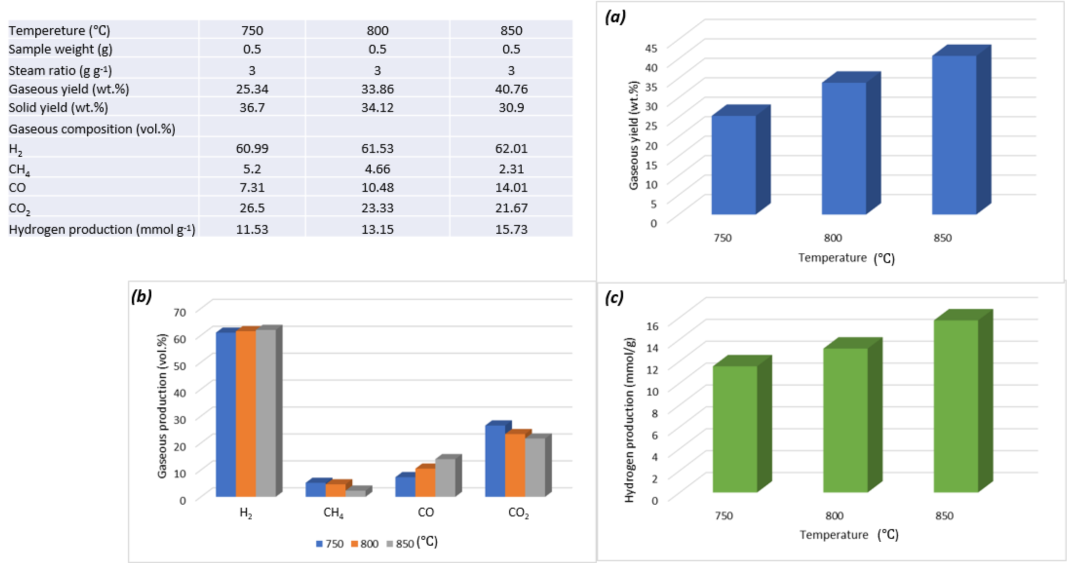


Figure 3.3 Performance of the lab-scale SBR process. Top: total COD in the effluent of DF and AD stages; middle: glucose in the effluent; bottom: total acids in the effluent

3.1.2 Steam Gasification (SG) stage

The results of the SG experiments are shown in Figure 3.4. The gas yield increased as the gasification temperature increased from 750 to 850 ^{O}C. Combined to a slight increase in the hydrogen concentration in the gases, the increase in the gas yield indicated a strong increase in the hydrogen production yield, which reached 15.7 mmol/g=0.03 gH_2/g_{OM}. This is comparable with the highest hydrogen yield used in the mass balances in WP1 (Chapter 1), i.e. 0.05 gH_2/g_{OM}, and indicates that this higher yield is likely to be obtainable with further optimisation of the reaction conditions in Phase 2.



Tempereture (°C)	750	800	850
Sample weight (g)	0.5	0.5	0.5
Steam ratio (g g^{-1})	3	3	3
Gaseous yield (wt.%)	25.34	33.86	40.76
Solid yield (wt.%)	36.7	34.12	30.9
Gaseous composition (vol.%)			
H_2	60.99	61.53	62.01
CH_4	5.2	4.66	2.31
CO	7.31	10.48	14.01
CO_2	26.5	23.33	21.67
Hydrogen production (mmol g^{-1})	11.53	13.15	15.73

Figure 3.4. Summary of results of SG experiments. a) gas yield; b) gas composition; c) hydrogen yield

3.1.3 Plasma reforming (PR) stage

The set of experiments presented in Figure 3.5 shows the effect of increasing power on the non-catalytic plasma chemistry of biogas. The flowrate was set to a total of 50 ml min^{-1} using biogas concentration of 60% CH_4, 40% CO_2. The reactor used a configuration with a 6 cm stainless steel outer electrode as the HV (high voltage) electrode. As seen in Figure 3.5 there is a clear increase in the conversion of both CH_4 and CO_2 with increasing power. The conversion of methane was up to 15 %, lower than the assumptions of the base case, however higher conversions have been obtained in follow-up experiments (Appendix C) and optimization of the conversion will be targeted in Phase 2. An increase in power leads to a stronger electric field, which results in higher radical generation, enhanced ionization and promotion of reactants conversion. The electron energy provided by the plasma is in the range of 1-10 eV well within the range of energy required to dissociate CH_4 and CO_2. The CH_4 conversion is consistently higher to that of CO_2 at all powers tested, due to the higher dissociation energy of CO_2 compared to CH_4. Noteworthy, are the carbon-based selectivities, with a range of high hydrocarbons being produced, besides CO which is the dominant product. The production of H2 is associated to the production of CO in equimolar ratio according to the reaction $CH_4 + CO_2 \rightarrow 2H_2 + 2CO$. Hydrocarbons are produced from coupling reactions of CH_x radicals, while CO is produced from the direct dissociation of CO_2. Results are indicative of the highly reactive nature of plasmas, and the need to use a catalyst to drive the selectivity towards syngas production. Results with catalyst are reported in Appendix C.

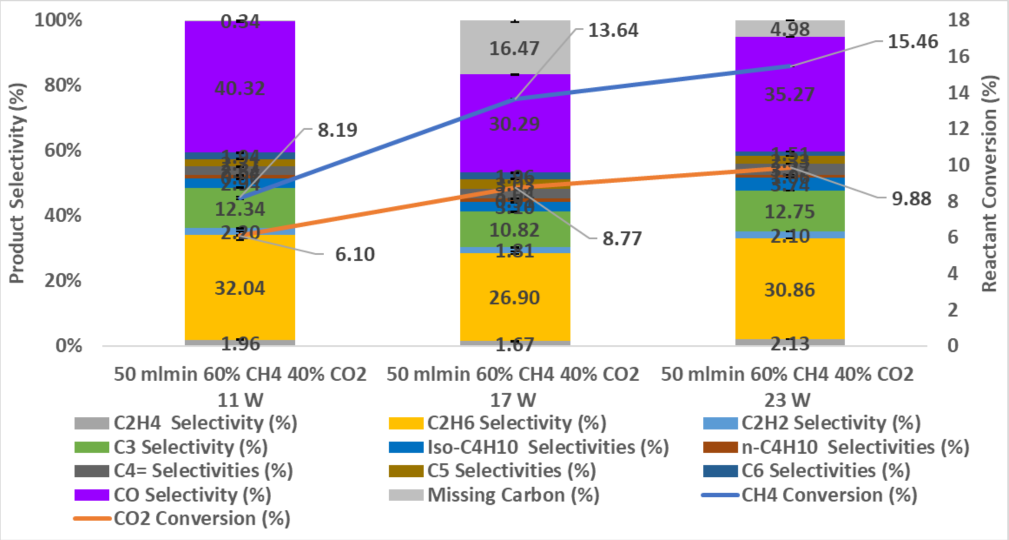


Figure 3.5. Effect of power on the non-catalytic conversion of biogas at a constant flowrate of 50 ml min^{-1} with a gas composition of 60% CH_4/40% CO_2.

References

[3.1] D. Dionisi. Biological wastewater treatment processes: mass and heat balances. CRC Press, Boca Raton, FL, USA, 2017.

4. WP4. Engineering design of the pilot plant

Introduction

This section presents the design of the pilot plant with stream tables and specification of the main process equipment. The plant will be located in Aberdeen (UK), on the premises of University of Aberdeen, in an outdoor location. The pilot plant will only use electricity for all its energy requirements, without any external supply of natural gas or other fuels. To demonstrate its energy self-sufficiency, the plant will not be connected to the electricity grid or to the gas grid but will generate all its electricity requirements from solar panels on its roof. In addition, any combustible by-product gases (e.g. any residual methane and carbon monoxide) will be sent to a CHP (combined heat and power) unit which will be installed within the pilot plant and will generate additional electricity. If needed, some of the hydrogen produced by the plant will be used in a fuel cell unit to produce additional electricity. The solar panels, CHP and fuel cell units will be combined with a battery pack, which will allow electricity storage and 24/7 plant operation.

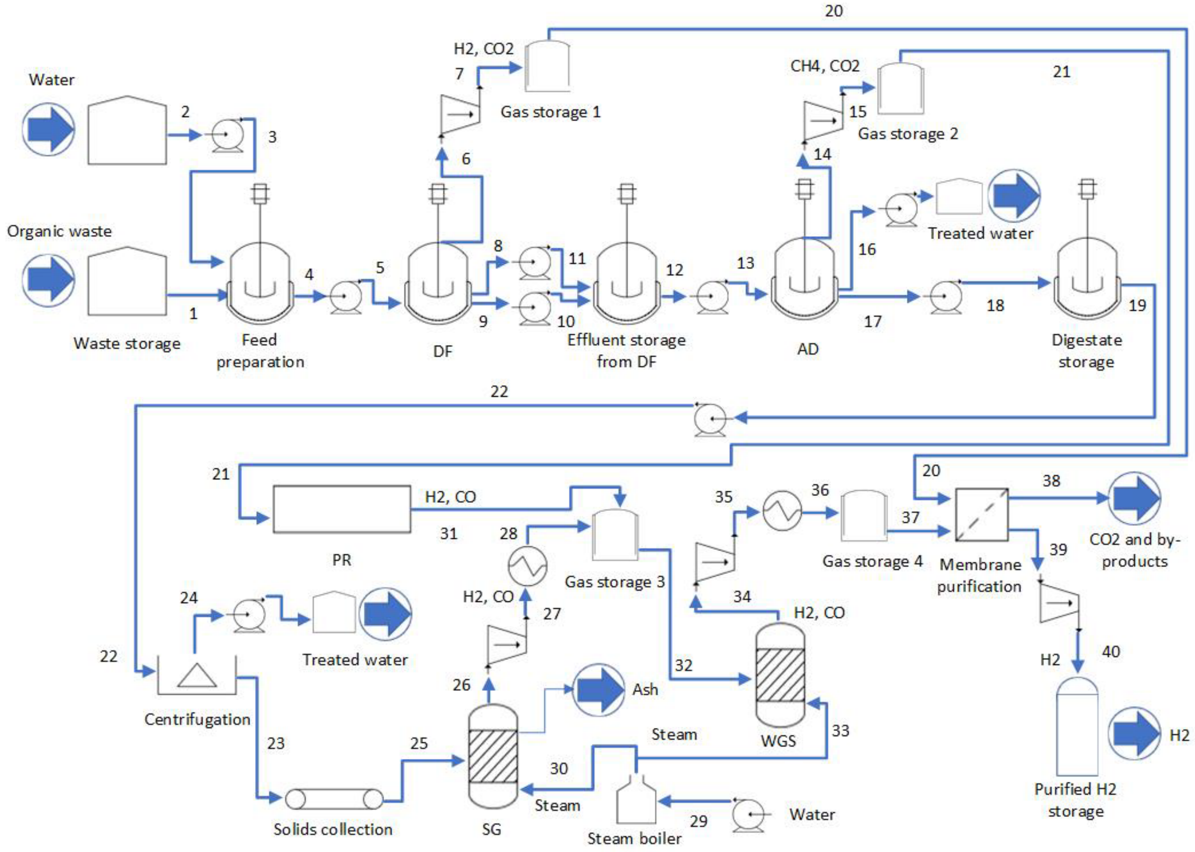
The pilot plant will use locally sourced food waste (e.g. kitchen waste from University of Aberdeen's canteen) and will produce hydrogen at the required purity (e.g. >99.99 %) for use by our labs and by other activities at University of Aberdeen, e.g. the ProtoTau Team who use hydrogen cars for the Tau racing competition.

More information on the design of the pilot plant is available in Appendix D.

4.1 Pilot plant description and stream table

The conceptual scheme and stream table for the pilot plant is shown in Figure 4.1. This scheme has been converted in a process flow diagram (PFD) in Appendix D, Figure D.1, with the appropriate adaptations. The conversions and yields used in the stream table are based on the mass balances done in WP1 for the base case with food waste of carbohydrate composition. The stream table reports mass and volume flow rates of all the streams as daily average flow rates.

Organic waste (20 kg/d) is fed to the feed preparation vessel, where it is mixed with water to ensure the appropriate concentration of solids. Food waste is expected to have a concentration of organic matter of 20 % w/w. Based on our experience, it is desirable to have a concentration of organic matter of 4 % as feed to the DF stage, therefore, the food waste will be diluted with tap water in the feed preparation vessel. From the feed preparation vessel, the feed mixture will be fed to the DF reactor. The DF reactor will be operated in sequencing batch mode (Sequencing Batch Reactor, SBR) with periodic feeding (stream 5) and periodic withdrawal of the clarified effluent (stream 8) and of the concentrated sludge (stream 9). The biogas, composed mainly of hydrogen and carbon dioxide, will be produced continuously in the DF vessel (stream 6). The effluents from the DF vessel will be collected in the effluent storage from DF before being fed to the AD stage, which is also operated in SBR mode. The clarified effluent from AD (stream 16) is a treated water that is disposed of. The settled solids (stream 17), which are made of produced microorganisms and undegraded organic matter in a water stream, are sent to the digestate storage vessel from which they are sent to centrifugation (stream 19 and 22), while the produced biogas (stream 14), mainly composed of methane and carbon dioxide, is sent to the PR stage. Centrifugation produces cleaned water to be disposed of (stream 24) and concentrated organic solids (stream 23) to be processed in the SG stage. The biogas from AD enters the PR stage (stream 21) where it is converted into a mixture of hydrogen and carbon monoxide (stream 31). The product gases from the SG stage (stream 26) are expected to have similar composition as the effluents of the PR stage (stream 31). These two streams are therefore combined and sent to the WGS stage where the carbon monoxide reacts with steam to produce carbon dioxide and hydrogen (stream 34). The product gases are sent to a membrane purification unit where pure hydrogen is produced in the permeate and carbon dioxide (together with any impurities, e.g. methane and carbon monoxide from incomplete reactions in the previous stages) is produced in the retentate. The purified hydrogen is compressed and stored in cylinders.



	Streams with main component mass flows in kg/d																			
Component	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Water	16	80	80	96	96			75.27	20.73	20.73	75.27	96	96			90	6.22	6.22	6.22	
Total organic matter	4			4	4			1.52	2.28	2.28	1.52	3.80	3.80			0.08	0.68	0.68	0.684	
Soluble organic matter	1.60			1.60	2			1.52	0.42	0.42	1.52	1.94	1.94			0.08	0.0053	0.0053	0.005	
Insoluble organic matter	2.40			2.40	2				1.86	1.86		1.86	1.86				0.679	0.679	0.679	
H_2						0.031	0.031													0.031
CH_4														0.95	0.95					
CO																				
CO_2						0.69	0.69							2.61	2.61					0.69
Steam																				
Temperature (^{O}C)	20	20	20	20	20	20	20	20	20	20	20.00	20	20	20	20	20	20	20.00	20	20
Pressure (atm)	1	1	1	1	1	1	200	1	1	1	1	1	1	1	200	1	1	1.00	1	1
Stream volumetric flow rate (L/d or Nl/d for gases)	20	80	80	100	100	740	740	76.8	23.01	23.01	76.79	99.8	100	2843	2843	89.858	6.902	6.902	6.902	740

Component	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**40**
Water		6.22	3.11	3.11	3.11				3.39											
Total organic matter		0.684	0.684	0.0003	0.684															
Soluble organic matter		0.005	0.003	0.0026	0.003															
Insoluble organic matter		0.679	0.679		0.679															
H_2						0.03	0.03	0.03			0.214	0.25		0.45	0.45	0.45	0.449		0.449	0.45
CH_4	0.95																			
CO						0.153	0.153	0.153			2.993	3.15								
CO_2	2.61					0.21	0.21	0.21				0.21		5.15	5.15	5.15	5.15	5.15		
Steam										1.367			2.02							
Temperature (^{O}C)	20	20	20	20	20	800	800	100	20	200	100	20	200	250	250	100	20	20	20	20
Pressure (atm)	1	1	1	1	1	1	200	200	1	1	1	1	1	1	200	200	1	1	1	200
Stream volumetric flow rate (L/d or Nl/d for gases)	2843	6.902	3.793	3.1094	3.793	2409	2409	2409	3.39	2950	6546	5800	4363	14670	14670	14670	8219	2815	5404	5404

Figure 4.1 Flowsheet of the pilot plant for the proposed process with stream table indicating the mass flows with food waste.

5. WP5. Plan for operation and testing of the pilot plant

It is planned to operate the pilot plant described in Section 4. with two feedstocks: food waste and municipal wastewater. With each feedstock, the planned length of the pilot plant operation is of at least two months, however we expect to run the pilot plant for longer than this minimum length, allowing for investigation of the effect of the main process parameters. The operation of the pilot plant is expected to start in May 2024 and last until the end of the project in March 2025. The whole plan of activities for Phase 2 is shown in the Gantt chart in Appendix E.

During the operation of the pilot plant it is planned to collect the following data on a regular basis (continuously, daily or weekly as appropriate):

- feedstock: mass and volume fed, COD (Chemical Oxygen Demand), VS (Volatile Solids), elemental composition (N, P, K, Ca, Mg);
- gas streams: flow rate, composition (% in volume of hydrogen, methane, carbon dioxide);
- liquid and solid streams: flow rate, COD, VS;
- agitated vessels (DF and AD stages): temperature, agitation rate, COD, VS;
- hydrogen produced and used: total mass, volume and purity of the hydrogen produced and total mass of hydrogen converted into electricity in the hydrogen fuel cell system;
- other gases produced and used: total mass, volume and composition of the other gases (e.g. methane, carbon monoxide, carbon dioxide) produced by the plant and used in the CHP unit for electricity generation;
- final liquid streams: total mass and volumes produced, COD, VS;
- final solid stream: total mass produced, elemental composition (N, P, K, Ca, Mg)
- energy consumption: power and energy absorbed by each piece of equipment;
- energy generation and storage: power generated by the solar panels, stored energy in the battery packs, energy generation from the hydrogen fuel cell and from the CHP unit.

The data collected during the operation of the pilot plant will be analysed to calculate the following variables, which will allow for a full estimation of the technical and economical viability of the process:

- hydrogen yield: mass of hydrogen produced per unit of organic matter fed;
- other gases yield: mass of methane, carbon monoxide and other gases produced by the plant per unit of organic matter fed;
- energy use: energy consumption per unit mass of hydrogen produced and per unit energy content (measured as HHV and LHV) in the produced hydrogen;
- COD and VS removal: COD and VS of the influent streams minus the COD and VS of the effluent streams

6. WP6. Costed project plan for Phase 2

The Labour & overhead costs and the total costs for Phase 2 are shown in Appendix F.

Due to the nature of the project, which combines different types of chemical reactions and separation processes, a large academic team with a wide range of skills will work together in Phase 2.

The project team at University of Aberdeen will mainly include chemical engineering academics, with also contributions from academics in electrical, electronic and structural engineering. Professor Dionisi will co-ordinate the project and will be the scientific lead for the biological stages (DF and AD) for both the lab-prototype and the pilot plant. The researchers already involved in Phase 1, Dr Kechagiopoulos, Dr Majumder, Dr Zhang and Dr Afzal, will lead at lab and pilot scale the optimisation and operation of the PR stage (Kechagiopoulos) and of the SG stage (Zhang) and will lead the construction of the pilot plant (Afzal and Majumder). Dr McCue, also already involved in Phase 1, will support the SG/WGS/PR stages together with Dr Graca. Dr Claudia Fernandez Martin and Dr Euan Bain will work together on the analysis of the pilot plant safety, with considerations, respectively, of gas dispersions and HAZOP analysis. The electrical engineering academics, Dr Jamshidi Far and Dr Li, will support the design of the solar panels and battery pack for the pilot plant, with integration with the hydrogen fuel cell and CHP unit. Dr Verdicchio and Dr Secchi, academics in electronic engineering, will support the design and installation of the sensors and control systems. Dr Osofero, academic in civil engineering, will support the structural design of the pilot plant. Dr Martinez Felipe, academic in chemical engineering and the School of Engineering lead for the hydrogen theme, will contribute to dissemination activities and to links with companies.

The project partners, University of Cranfield and Verona, already involved in Phase 1, will continue supporting the project by sharing their experience with the biological stages and with the SG stage, for both the optimisation study with the lab-prototype and the pilot plant operation.

Consumables are required for the lab-prototype study and for the pilot plant. Capital equipment includes the purchase of all equipment required for the pilot plant. Travel and subsistence costs include meetings among the project partners, dissemination events and activities, conferences.

7. WP7. Commercialisation plan

Introduction

This section aims to:
- review data on generation and collection of organic waste in the UK;
- review the current and potential market for hydrogen in the UK;
- analyse options for commercialisation of the process;
- analyse how the process fits with the UK's 2050 Net Zero Target

This section is based on the report [7.1] done for this project by the company Optimat, who was hired as subcontractor for commercialisation. The full report by Optimat is in Appendix G.

7.1 Organic waste in the UK

The generation and collection of various types of organic waste in the UK has been analysed. Food waste is estimated to be generated at rates of approximately 10 Mt/year, of which a significant fraction is sent to landfill. Farm waste is generated at rates of up to 100 Mt/year. Sewage sludge is produced at rates of around 4 Mt/year, with a significant proportion being treated in anaerobic digestion plants. Other sources of organic feedstock are energy crops, distillery waste and fats and oils wastes. One issue in the availability of organic waste as feedstock for our process and more in general for valorisation is the collection of the waste. For example, the Optimat report [7.1] estimates that of the 90-100 Mt/year of farm waste only about 7 Mt/year are collected and used for energy recovery via anaerobic digestion. In an earlier study by this research group [7.2], it has been estimated that the global generation of organic waste is in the region of 8,000-9,000 Mt/year as dry matter, which, if collected, could give a significant contribution to the circular economy in the energy and chemicals sectors.

7.2 Hydrogen market

Currently about 90 Mt of hydrogen are produced on a global scale. Approximately 40 Mt/year of hydrogen are used in oil refining, while the chemical industry uses 45 Mt/year mainly for ammonia and methanol production. The steel making industry uses approximately 5 Mt/y of hydrogen. Currently the use of hydrogen for energy generation is very limited. For example, the use of hydrogen for transport accounts for 20,000 t/year globally.

In the near future the hydrogen use is expected to increase significantly, however any forecasts about future uses of hydrogen are subject to considerable uncertainty. New markets for hydrogen are expected to open in heavy duty road transport, shipping, heating in buildings (hydrogen blending with natural gas) and power generation.

In a recent study by this research group [7.3], the potential hydrogen production for organic waste in the UK using a combination of biological and chemical processes (in part different and with a slightly lower hydrogen yield than the process proposed here) was estimated to be in the order of 6 Mt/year, which would represent 26 % of the total UK's energy requirements for domestic heating and road transportation. Although our study was based on the total organic waste generated and improvements are needed in the collection of the waste, our study indicated the potential significant impact of hydrogen production from organic waste. It is likely that the production of hydrogen from organic waste will result in smaller scale plants than current large scale plants for hydrogen production from natural gas. According to our own estimates in this study (WP1), the collection of food waste from a city the size of Aberdeen (Scotland) would result in a plant producing 1,000 t of hydrogen per year, while current large-scale plants processing natural gas can produce up to 100,000 t of hydrogen per year.

For the stakeholders interviews in the Optimat report, it is not expected that selling hydrogen from our process would be an issue.

7.3. Commercialisation plan

It is expected that, after the pilot plant runs, the university partnership will exploit the research and seek to commercialise the process with appropriate commercial organisations. The Wood Group, one of the stakeholders interviewed by Optimat, expressed interest in commercialising this technology, subject to reaching an appropriate financial agreement. Many other companies in the UK have also the capabilities in process plant manufacturing required to commercialise this process. The Optimat report highlights the need for the project team to present this project to conferences and stakeholders events, as well to publish it in international journals, in order to make the project more visible and to highlight its benefits for the environment and for sustainability.

After Phase 2, the university partners are expected to decide their business model for the commercialisation of the process. In any cases, it is essential that the university partners retain the process design and operational know how that they will have gained through Phase 1 and Phase 2 of this project. Two main types of business models will be available for the university partners: to continue as a university partnership or to set up a spin out company. The spin out company would be focused on close to market process design and commercialisation. Various options are available for holding the shares of the spin out company, e.g. the shares could be held by the partner universities, relevant academic staff and other investors. The spin out company would focus on process engineering and design rather than research and would form strong links with commercial companies. It is expected that the spin out company will generate income through know how and licensing agreements with process manufacturing companies. The university partners will take a decision on the business model to follow in the latter stages of Phase 2, when the process capability will be more well defined.

7.4. Alignment with the UK's Government Net Zero Legal Commitment by 2050

The process is fully aligned with the UK Government's Legal Commitment to achieve net zero emissions by 2050. Indeed, the hydrogen from this process is produced from a renewable resource and the process can be entirely powered by renewable energy. Furthermore, the direct carbon dioxide emitted from the process can be captured using existing technologies, which can give a carbon negative process.

References

[7.1] Optimat. Commercialisation plan – Hydrogen Production Process. Final Report, University of Aberdeen, 19/10/2022. Reported in Appendix C.

[7.2] Dionisi, D., Bolaji, I., Nabbanda, D., & Silva, I. M. (2018). Calculation of the potential production of methane and chemicals using anaerobic digestion. Biofuels, Bioproducts and Biorefining, 12(5), 788-801.

[7.3] Pinto, Shawn, Aliakbar Jamshidi Far, and Davide Dionisi. "Land and water requirements for the supply of renewable heating and transport energy using anaerobic digestion and water electrolysis. A case study for the UK." Sustainable Energy Technologies and Assessments 48 (2021): 101636.

8. WP8. Stakeholder engagement events

Introduction

The aim of the stakeholder engagement activities was to share the scientific and technical details of the investigated process and to seek for feedback and support from key players in the sectors of wastewater treatment and waste management. These activities addressed the critical aspect of the feasibility study and identified the conditions supporting the technology development and implementation.

The engagement activities for the project have been organised over three events. Two online meetings were organised during the first part of the project to introduce the concepts of the process and share the preliminary results.

The third event was organised for in person attendance at Cranfield University in the form of a workshop to deepen the discussion with interested parties and stakeholder from industry and academia, gain the final feedback on the feasibility study and establish contacts with potential partners for the proposal for Phase 2.

8.1 Introductory meetings

The first two meetings were organised online on the 31st of August 2022 and the 4th of September 2022 with the attendance of representatives from UK water companies (Scottish Water, Severn Trent, Yorkshire Water), the UK waste management sector (Biffa), the industrial gas industry (BOC) and local authorities (Aberdeen City Council).

The attendees represented the key stakeholder for the implementation at full scale of the proposed process and were able to identify the benefit of the solution and advice for areas of concern for them. The UK water industry is currently aiming to become carbon neutral by 2030 and at the same time is also looking at reliable solutions for the management of biosolids from wastewater treatment plants. The waste management sector is also evaluating the impact of changes in waste collection strategies and at opportunities to maximise the recovery of value from solid waste and prevent final disposal in landfill. Local authorities are interested at solutions that can increase the availability of low cost and sustainable green hydrogen for example to run bus fleets and decarbonise public transport.

The positive feedback expressed by the stakeholders confirmed the potential impact of the project and highlighted the benefits of exploring innovative solutions that can enhance the value of the current anaerobic digestion asset and create opportunities for future energy market developments.

Another aspect that the stakeholder were particularly interested on is the perspectives of technology development for full scale application, the conditions to stimulate implementation and the timeline for process development from current TRL to full scale.

These aspects were considered in more details in the next engagement event.

8.2. Final engagement and dissemination event

The third event was organised as in person workshop at Cranfield University.

This event is described and discussed in Appendix H.

9. Conclusions

The work done is Phase 1 indicates that the proposed process is feasible and attractive to produce low carbon hydrogen from biodegradable organic waste. Due to the combination and integration of biological and chemical technologies, it is expected that the process will convert the organic matter in wet waste with high yield and with low energy consumption. The biological stages are expected to produce hydrogen and methane with low energy consumption, as it is expected that they will only require energy for mixing. The chemical stages will convert the methane and more of the organic matter into hydrogen, maximising the total hydrogen yield. Even though the chemical stages give higher energy consumption than the biological stages, the chemical stages will only process a fraction of the inlet organic matter, therefore their impact on the total energy consumption of the process will be reduced. Furthermore, the process can be energetically self-sufficient, as it can be powered entirely from renewable low-carbon electricity generated from solar panels on the plant roof, subject to the choice of an appropriate location for the plant, without the use of any electricity or natural gas from the grid.

Although the efficiency of waste conversion at pilot scale will be measured in Phase 2, the process can potentially convert most or all of the carbon in the organic waste into carbon dioxide. This carbon dioxide is biogenic in nature, as it derives from the carbon dioxide absorbed from the atmosphere when the biomass which originated the waste was growing. Therefore, the direct carbon dioxide emissions from the process do not contribute to net carbon emissions. However, any carbon dioxide emitted from the plant can be captured using existing technologies, which would give a carbon negative process.

In order to achieve the full-scale commercialisation of the process, it is essential to prove the technology at pilot scale, which will be the aim of Phase 2. In Phase 2, it is planned to build a pilot plant on the University of Aberdeen’s premises. The pilot plant will run all the reaction stages and the hydrogen purification stage, aiming to produce hydrogen at high purity (>99.99 %) suitable for any applications. The pilot plant will obtain all its energy required from solar panels placed on the plant’s roof, proving the concept of the energy self-sufficiency of the process.

The data collected in Phase 2 will allow to quantify the hydrogen yield and the energy consumption of the process under conditions comparable to full scale commercial plants, which will bring us closer to commercial development of the process.

Appendix A. WP1. Mass and energy balances

A.1 Methodology

The simulations were carried out for food waste and municipal wastewater as the feedstock. Food waste was assumed to be composed of 20 % organic matter and 80 % water. To represent different compositions of the organic matter, the organic matter was assumed to be composed either of carbohydrates or of lipids. The empirical formulas of glucose ($C_6H_{12}O_6$) and oleic acid ($C_{18}H_{34}O_2$) were assumed for carbohydrates and lipids respectively. In reality, the composition of organic matter in organic waste and biomass is much more complex, including a mixture of carbohydrates, lipids, proteins, lignin and other components. In this study, we used the empirical formulas of glucose and oleic acid to simulate the two extremes of organic matter composition, i.e. 100 % carbohydrates or lipids. The actual empirical formula of biomass/waste and the theoretical hydrogen yield will lie somewhere between these extremes. Our recent study reports some data on the chemical composition of biomass and waste, obtained from various literature sources. [A.1] Municipal wastewater was assumed to have an organic matter content of 500 mgCOD/L, assumed to be carbohydrates with the empirical formula of glucose.

The base case assumed the best performance at each stage, providing the maximum amount of H_2 possible. It relies on several assumptions: the complete biodegradability of the organic matter in the DF and AD stages, and 100% efficiency of PR, SG and WGS. A sensitivity analysis was investigated of the total H_2 yield, energy consumption and water consumption on the efficiency of the various stages. The efficiency of each of the stages were varied from 0% to 100%. Simulations were carried out by varying the efficiency for one stage while leaving the rest of the stages at the highest efficiency.

The calculations were based, unless specified otherwise, on the methods and numerical values used in our recent papers [A.1, A.2]. For the biological stages DF and AD, the mass balances were based on the stoichiometry and on the COD balance. The COD balance is an important tool in mass balances for biological processes under anaerobic conditions, as the total COD of the feed will be either present in the digestate or converted to hydrogen or methane, with no contribution of the carbon dioxide [A.3].

A.1.1 Food waste and municipal wastewater

The summary of the assumptions used for the waste composition and flow rate is reported in Table A.1. The total wet waste flow rate was assumed to be 100 m^3/d, which, for the case of food waste represents the approximate generation rate from a region of 200,000 people in the UK.

Table A.1: Assumptions for the waste composition.

Waste composition			
	Food waste (carbohydrates)	Food waste (lipids)	Municipal wastewater
Organic matter (kg/kg)	0.2	0.2	0.000469
COD factor (kg COD/kg)	1.067	2.894	1.067
COD composition (kg COD/kg)	0.2134	0.5788	0.000500
Waste density (kg/m^3)	1,000	1,000	1,000
Total wet waste flow rate (m^3/d)	100	100	100
Organic matter (dry) flow rate (kg/d)	20,000	20,000	20,000

The theoretical COD conversion factor for each component is determined using the stoichiometry of the balanced oxidation equation. For a general oxidation equation, the conversion factor is calculated the following way

$$C_nH_aO_bN_d + (\frac{a}{4} - \frac{3d}{4} + n - \frac{b}{2})O_2 \rightarrow nCO_2 + (\frac{a}{2} - \frac{3d}{2})H_2O + dNH_3 \qquad \text{(A.1)}$$

$$Conversion\ factor\ (g\ COD/g) = \frac{32(\frac{a}{4}-\frac{3d}{4}+n-\frac{b}{2})}{(12n+a+16b+14d)} \qquad \text{(A.2)}$$

The COD factor was calculated for glucose (1.067 kgCOD/kg) and oleic acid (2.894 kgCOD/kg) as shown in Table A.1. The COD composition can be obtained by the product of the COD factor and organic matter composition. The organic matter flow rate (dry) was obtained using the product of organic matter composition, waste density and total wet waste flow rate.

There are several assumptions considered for energy consumption for each of the stages. The assumptions are taken from the literature: the electricity consumption for DF and AD was the same assumed in our study [A.2]; the electricity consumption in PR was within the range reported in a recent study [A.4]; the energy consumption for the SG and WGS stages was calculated from the energy balance of these processes. Table A.2 summarizes the assumptions on the energy consumption for each of the stages. The energy consumption is further investigated by doubling the values at each stage to check its effect on H_2 production.

Table A.2: Energy consumption assumptions

Assumptions for energy consumption	
Electricity consumption DF	277.78 kWh/t organic matter
Electricity consumption AD	277.78 kWh/t organic matter
Electricity consumption PR	5.375 kWh/kgCH_4
Energy consumption SG	4.23 kWh/kg organic matter
Energy consumption WGS	0.40 kWh/kgCO

SG and WGS are the stages that require water. The water consumption of these stages was calculated from the reaction stoichiometry and is reported in Table A.3.

Table A.3: Water consumption assumptions

Assumptions for water consumption	
Steam gasification	2 kg water/kg organic matter
Water gas shift	0.64 kg water/kg CO

A.1.2 Conversion and efficiency in the process stages

The equations below are for food waste that assumes carbohydrates as the main constituent. The conversion to products is shown at each stage. The conversions assume best performance at all the stages (the base case) as shown in Table A.4.

Table A.4: Assumptions for conversions.

Stages	**Range investigated**	**Base case value**
Fraction non-biodegradable in DF (%COD/COD or kg/kg) (v)	0 - 100	0
Fraction non-biodegradable in AD (%COD/COD or kg/kg) (w)	0 – 100	0
Efficiency of PR (%) (x)	0 – 100	100
Efficiency of SG (%) (y)	0 – 100	100
Efficiency of WGS (%) (z)	0 – 100	100

A.1.2.1 Conversions in dark fermentation stage

The DF stage used the following equations and numerical values for the microorganism yield ($Y_{X/S}$) and for the conversions. The value of $Y_{X/S}$ was assumed at a low value, according to the literature, the remaining equations were calculated from the stoichiometry of DF of glucose assumed in [A.3].

$$Y_{X/S}\left(\frac{kg\ microoganisms}{kg\ organic\ matter\ into\ DF}\right) = 0.01 \quad \text{(A.3)}$$

$$H_2\left(\frac{kg\ H_2}{kg\ organic\ matter\ into\ DF}\right) = \frac{(4-5.3\times Y_{X/S})\times 2\times\left(1-\frac{v}{100}\right)}{180} = 0.044\ (base\ case) \quad \text{(A.4)}$$

$$H_2\left(\frac{COD\ H_2}{COD\ organic\ matter\ into\ DF}\right) = 0.044\times\frac{8}{1.067} = 0.33\ (base\ case) \quad \text{(A.5)}$$

$$Acids\ \left(\frac{kg\ acids}{kg\ organic\ matter\ into\ DF}\right) = \left(2-2.65\times Y_{X/S}\right)\times\frac{60}{180}\times\left(1-\frac{v}{100}\right) = 0.66\ (base\ case) \quad \text{(A.6)}$$

$$CO_2\left(\frac{kg\ CO_2}{kg\ organic\ matter\ into\ DF}\right) = \left(2-2.65\times Y_{X/S}\right)\times\frac{44}{180}\times\left(1-\frac{v}{100}\right) = 0.48\ (base\ case) \quad \text{(A.7)}$$

A.1.2.2 Conversions in anaerobic digestion stage

The AD stage used the following equations and numerical values for the microorganism yield ($Y_{X/S}$) and for the conversions. The value of $Y_{X/S}$ was assumed at a low value, according to the literature, the remaining equations were calculated from the COD balance of AD, as described in [A.3].

$$Y_{X/S}\ \left(\frac{COD\ microoganisms}{COD\ organic\ matter\ into\ DF}\right) = 0.05 \tag{A.8}$$

$$CH_4\left(\frac{kg\ CH_4}{kg\ organic\ matter\ into\ AD}\right) = $$
$$= \frac{\left(\frac{1-w}{100}\right)\times\left(\frac{1-Y_{X/S}}{4}\right)\times(0.66\times1.067+0.01\times(1-\frac{w}{100})\times1.42+\frac{1}{100}\times1.067)}{0.66+0.01\times\left(1-\frac{w}{100}\right)+\frac{w}{100}} = 0.25\ (base\ case) \tag{A.9}$$

$$CH_4\left(\frac{COD\ CH_4}{COD\ into\ AD}\right) = \frac{0.25\times4\times\left(0.66+0.01\times\left(1-\frac{w}{100}\right)+\frac{w}{100}\right)}{0.66\times1.067+0.01\times\left(1-\frac{w}{100}\right)\times1.42+\frac{w}{100}\times1.067} = 0.95\ (base\ case) \tag{A.10}$$

$$CH_4\left(\frac{COD\ CH_4}{COD\ into\ process}\right) = \frac{0.95\times\left(\frac{w}{100}+1.067\times0.66\times1.067+0.01\times\left(1-\frac{w}{100}\right)\times1.42\right)}{1.067} = 0.64\ (base\ case) \tag{A.11}$$

A.1.2.3 Conversions in steam gasification stage

The SG stage used the following equations and numerical values for the conversions, based on experimental data from a published study [A.5].

$$H_2\ \left(\frac{kg\ H_2}{kg\ organic\ matter\ into\ SG}\right) = 25\times\frac{2}{1000}\times\frac{x}{100} = 0.050\ (base\ case) \tag{A.12}$$

$$CO\ \left(\frac{kg\ CO}{kg\ organic\ matter\ into\ SG}\right) = 8\times\frac{28}{1000}\times\frac{x}{100} = 0.224\ (base\ case) \tag{A.13}$$

$$CO_2\ \left(\frac{kg\ CO_2}{kg\ organic\ matter\ into\ SG}\right) = 7\times\frac{44}{1000}\times\frac{x}{100} = 0.308\ (base\ case) \tag{A.14}$$

A.1.2.4 Conversions in plasma reforming stage

The conversions to H_2 and CO are taken from the stoichiometry of the reaction:

$$CH_4 + CO_2 \rightarrow 2H_2 + 2CO \tag{A.15}$$

$$H_2\ \left(\frac{kg\ H_2}{kg\ methane\ into\ PR}\right) = 0.25\times\frac{y}{100} = 0.25\ (base\ case) \tag{A.16}$$

$$CO\ \left(\frac{kg\ CO}{kg\ organic\ matter\ into\ PR}\right) = 3.5\times\frac{y}{100} = 3.5\ (base\ case) \tag{A.17}$$

A.1.2.5 Conversions in the water gas shift stage

The conversions in WGS to H_2 are taken from the stoichiometry of the equation below.

$$CO + H_2O \rightarrow H_2 + CO_2 \tag{A.18}$$

$$H_2\left(\frac{kg\ H_2}{kg\ CO}\right) = \frac{2}{28}\times\frac{z}{100} = 0.0714\ (base\ case) \tag{A.19}$$

A.2 Results

A.2.1 Base case

With reference to the base case, Figures A.1-A.3 show the contributions of the individual stages to the total hydrogen production, while Figures A.4-A.6 show the contributions to the energy consumption. The contributions are very similar for the considered types of feedstock, i.e. food waste (carbohydrates and lipids) and wastewater. With the assumptions of the base case, DF, AD/PR and WGS contribute almost equally to the hydrogen produced. Note that AD doesn’t produce any hydrogen directly, but the methane from AD is converted into hydrogen in the PR stage so the contribution of the AD and PR stages are combined in these graphs. The SG stage gives only a very little contribution to the hydrogen production (about 1 %), this is due to the assumptions of the base case for which almost all the organic matter is converted in the biological stages. As far as the contribution to the energy consumption is concerned, the stage that gives the highest energy consumption is the PR (53-59 %), while the biological stages give a minor contribution. Note that the SG stage gives a higher contribution to the energy consumption (6 %) than its contribution to the hydrogen production, because this stage is relatively more energy intensive than other stages.

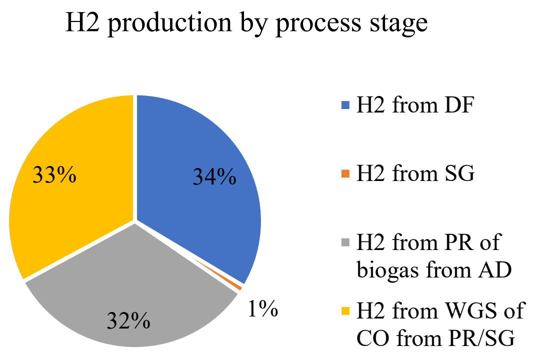


Figure A.1: H2 production for food waste (carbohydrates).

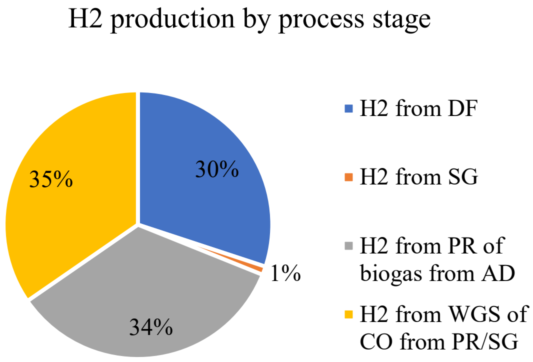


Figure A.2: H2 production for food waste (lipids).

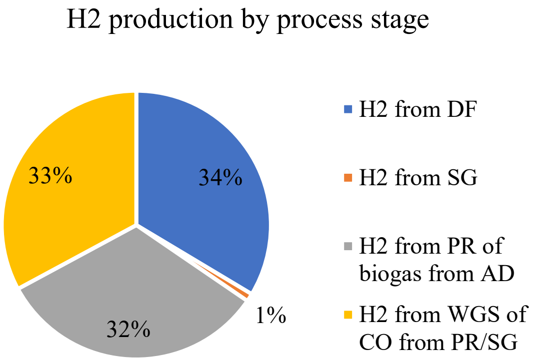


Figure A.3: H2 production for wastewater.

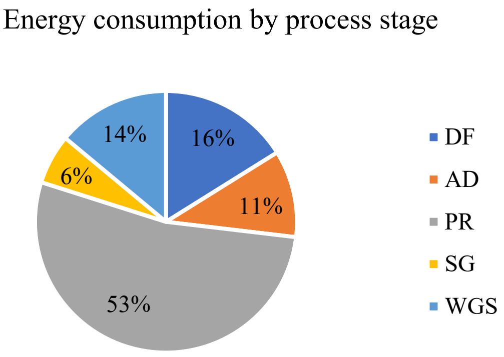


Figure A.4: Energy consumption for food waste (carbohydrates).

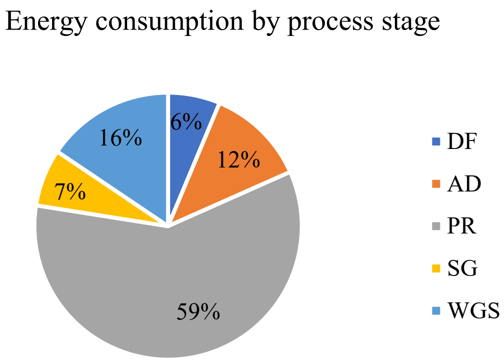


Figure A.5: Energy consumption for food waste (lipids).

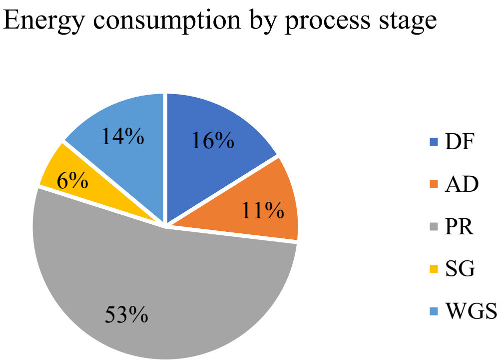


Figure A.6: Energy consumption for wastewater.

A.2.2 Effect of the main assumptions on the total hydrogen yield

This section reports how the total hydrogen yield is expected to vary as a function of the assumptions on the efficiency of each stage.

A.2.2.1 Effect of non-biodegradable organic matter in the dark fermentation stage

Figures A.7-A.11 illustrate the total H_2 yield for DF for all three cases (feedstock food waste made of carbohydrates or lipids and feedstock wastewater). The total H_2 yield does not vary significantly as the non-biodegradable fraction changes from 0-100% in all cases. This indicates that the DF stage does not affect H_2 production considerably. The reason for this is that any organic matter that is not biodegraded in the DF stages will move onto the AD stage which will then be converted to methane (and ultimately to hydrogen). However, as expected and as observed earlier, there is a higher total H_2 yield per kg or dry organic matter for lipids compared to carbohydrates and wastewater. Clearly, in all cases the hydrogen production per unit volume of waste treated is much higher for food waste than for wastewater due to the different concentration of organic matter.

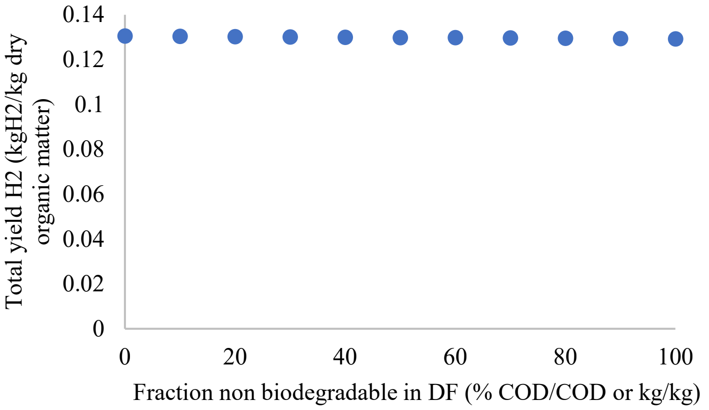


Figure A.7: Total H2 yield per kg of dry organic matter for food waste (carbohydrates) and wastewater.

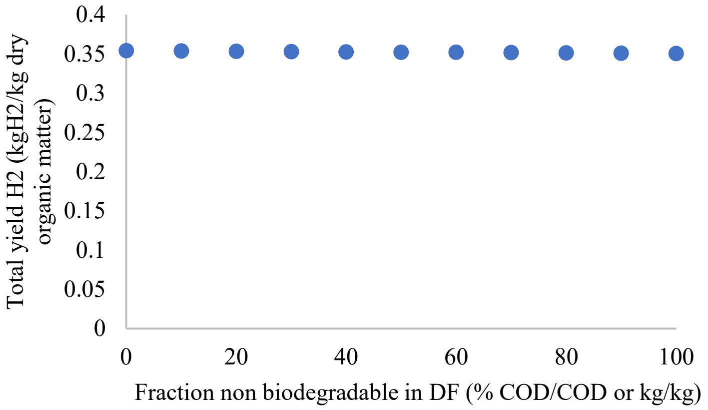


Figure A.8: Total H2 yield per kg of dry organic matter for food waste (lipids).

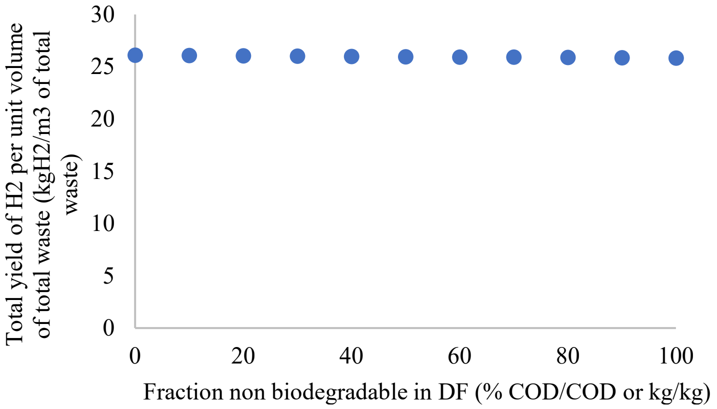


Figure A.9: Total H2 yield per m3 of total waste for food waste (carbohydrates).

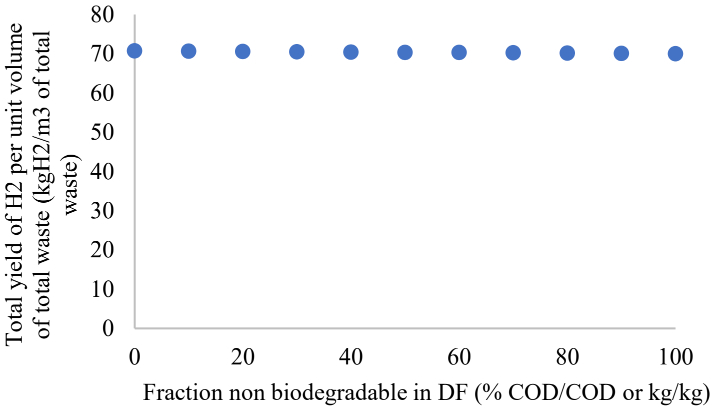


Figure A.10: Total H2 yield per m3 of total waste for food waste (lipids).

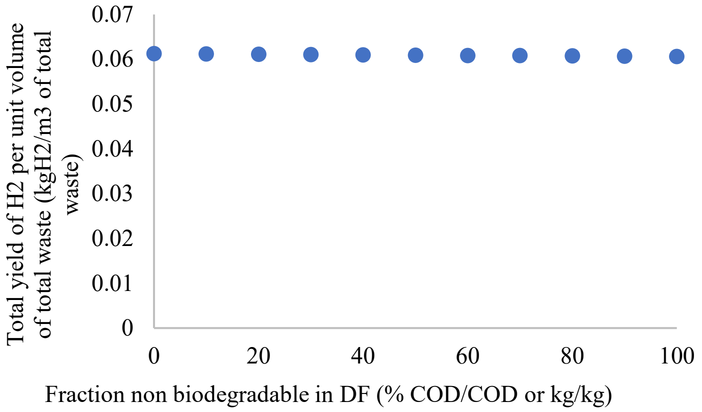


Figure A.11: Total H2 yield per m3 of total waste for wastewater.

A.2.2.2 Effect of non-biodegradable organic matter in the anaerobic digestion stage

Figures A.12-A.16 illustrate the total H_2 yield for AD for all the simulated cases. As the non-biodegradable fraction increases in AD, the total H_2 yield decreases steadily for all three cases. This is because as the non-biodegradable fraction increases, less methane is produced in this stage and therefore less H_2 is produced ultimately in the PR stage. Even though the residual organic matter after AD is converted in the SG stage, the hydrogen yield from SG is lower than from the combination of AD and PR, therefore the total hydrogen yield decreases as the fraction of non-biodegradable organic matter in AD increases. Overall, the AD stage affects the total H_2 production more than the DF stage for which the effect is very low (as seen in the previous section).

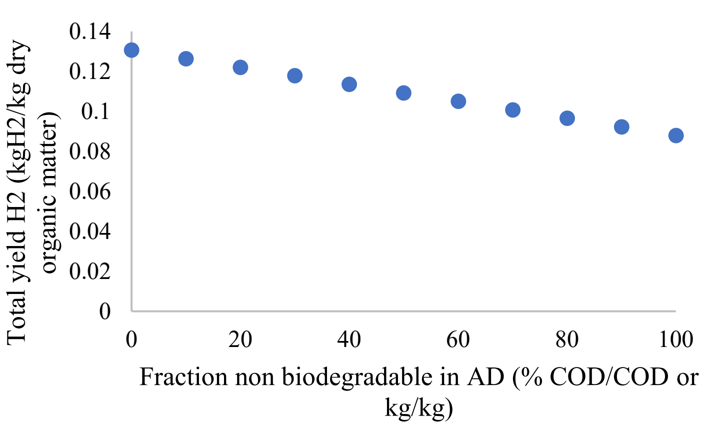


Figure A.12: Total H2 yield per kg of dry organic matter for food waste (carbohydrates) and wastewater.

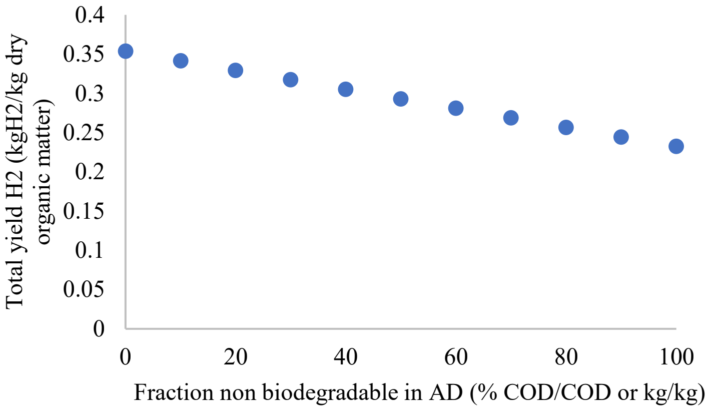


Figure A.13: Total H2 yield per kg of dry organic matter for food waste (lipids).

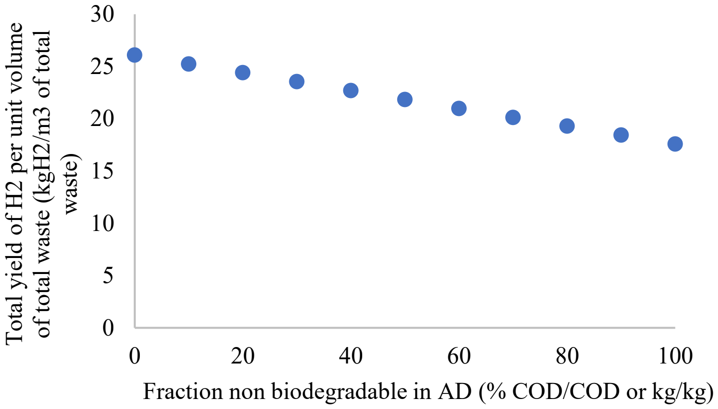


Figure A.14: Total H2 yield per m3 of total waste for food waste (carbohydrates).

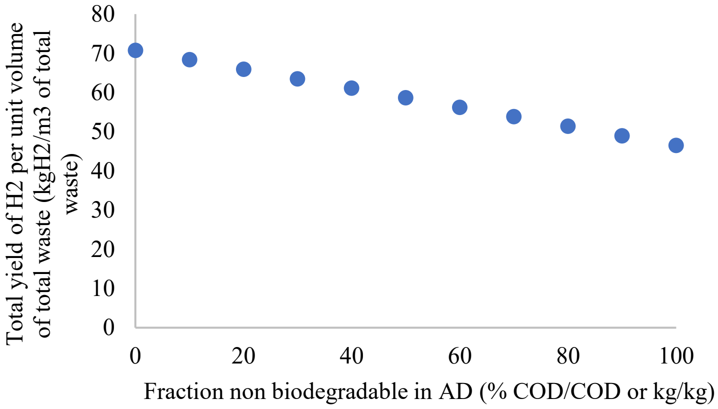


Figure A.15: Total H2 yield per m3 of total waste for food waste (lipids).

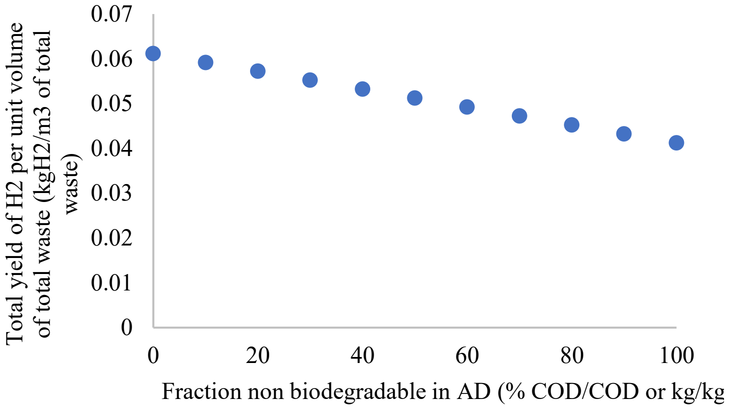


Figure A.16: Total H2 yield per m3 of total waste for wastewater.

A.2.2.3 Effect of the efficiency of the plasma reforming stage

Figures A.17-A.21 illustrate the total H_2 yield for PR for varying efficiency from 0-100% for all the simulated cases. As the efficiency of PR stage decreases, the total H_2 yield decreases. This is due to the loss of conversion in the PR stage and also to the consequent loss of CO production in this stage, which translates in reduced hydrogen production in the WGS stage. The effect of reduced efficiency in the PR stage is quantitatively more important than for other stages. Indeed, with no efficiency of the PR stage, the total hydrogen production reduces from 0.13 (100 % efficiency) to about 0.04 kg_{H2}/kg_{OM} while for example no efficiency in the AD stage still gives a total hydrogen yield of approximately 0.08 kg_{H2}/kg_{OM} (see previous section). The important effect of PR on the total hydrogen yield indicates the importance of optimising the performance of this stage.

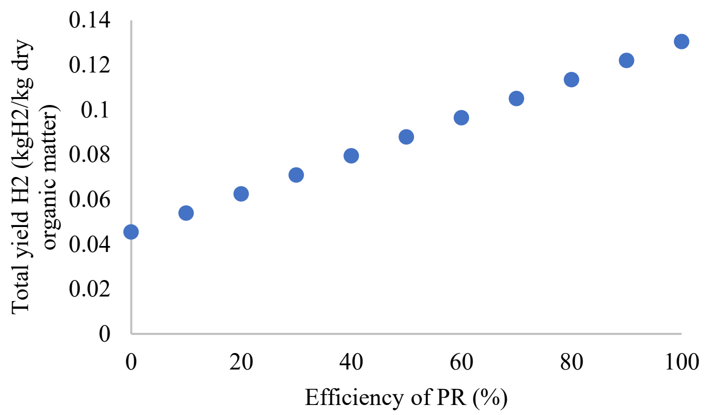


Figure A.17: Total H2 yield per kg of dry organic matter for food waste (carbohydrates) and wastewater.

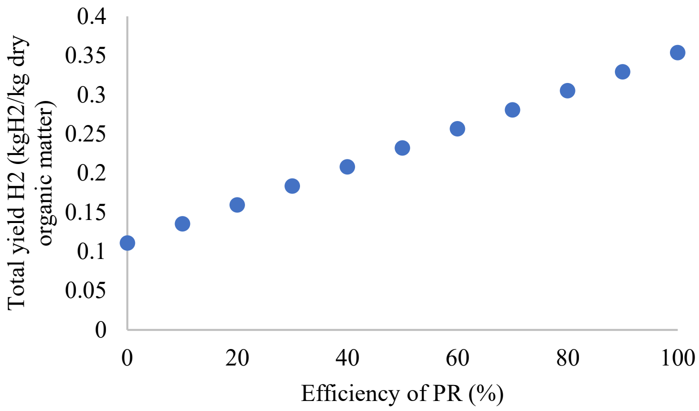


Figure A.18: Total H2 yield per kg of dry organic matter for food waste (lipids).

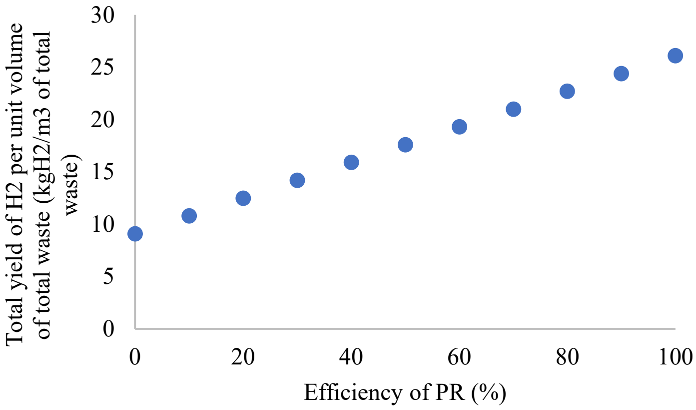


Figure A.19: Total H2 yield per m3 of total waste for food waste (carbohydrates).

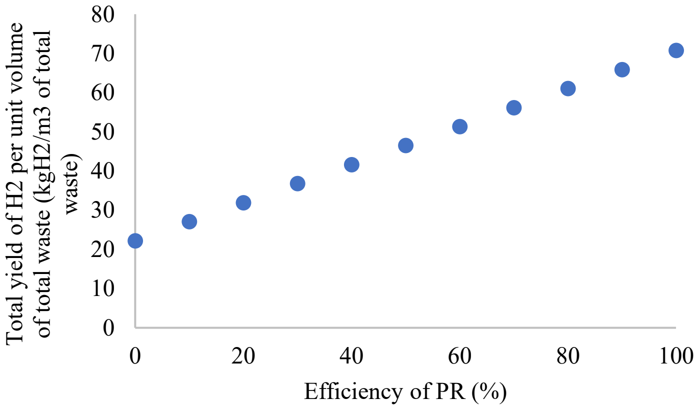


Figure A.20: Total H2 yield per m3 of total waste for food waste (lipids).

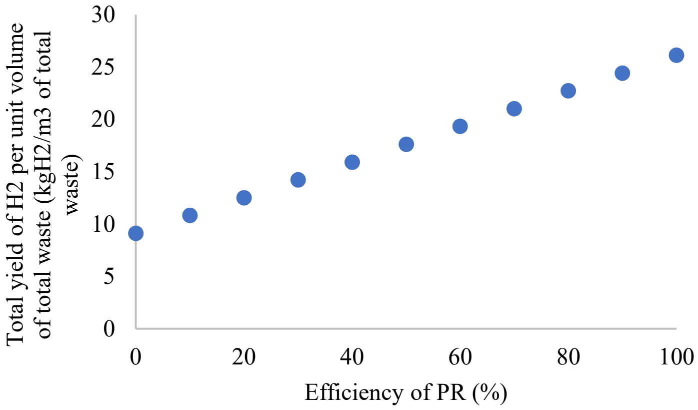


Figure A.21: Total H2 yield per m3 of total waste for wastewater.

A.2.2.4 Effect of the efficiency of the steam gasification stage

Figures A.22-A.26 illustrate the total H_2 yield for SG for varying efficiency from 0-100%. As seen in the figures, the total H_2 yield does not vary much throughout. This is because the simulations assume 100% efficiency of all the stages while varying the efficiency of the SG stage. This means that with 100% efficiency of the DF and AD stages, all the organic matter is biodegraded thus the SG stage only processes a very low amount of organic matter, corresponding to the microorganisms produced by AD. The effect of the SG stage with the assumption of only partial conversion in the AD stage is presented later in this report.

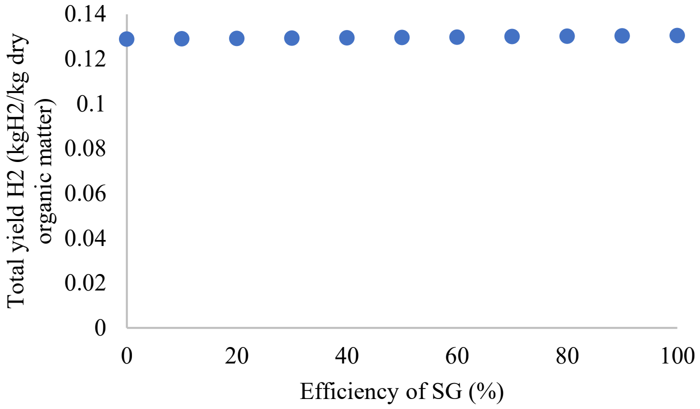


Figure A.22: Total H2 yield per kg of dry organic matter for food waste (carbohydrates) and wastewater.

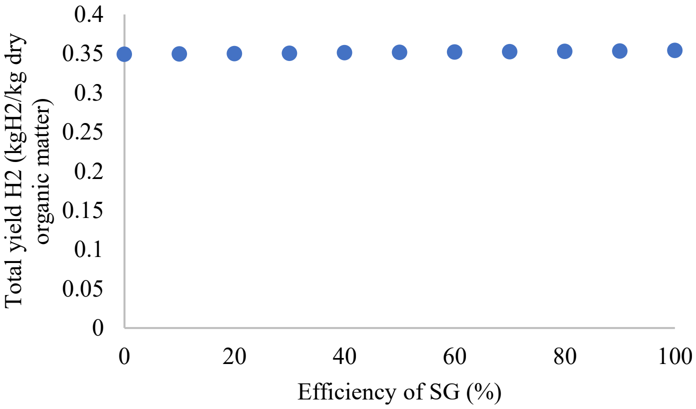


Figure A.23: Total H2 yield per kg of dry organic matter for food waste (lipids).

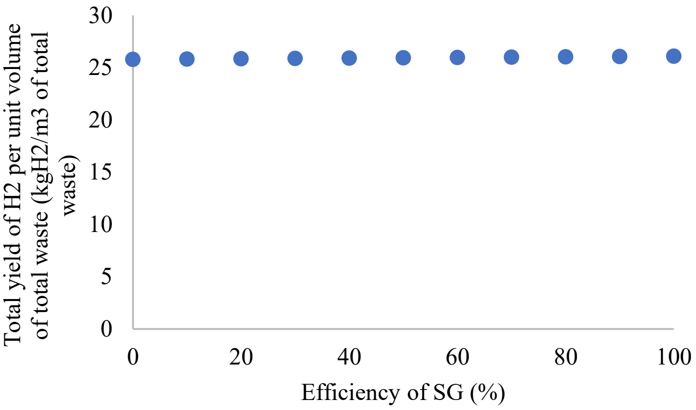


Figure A.24: Total H2 yield per m3 of total waste for food waste (carbohydrates).

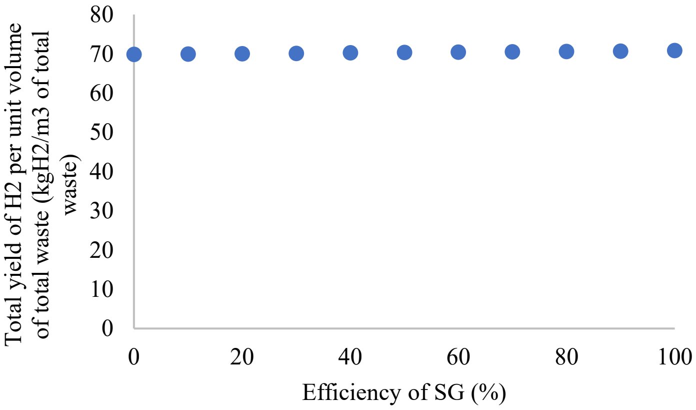


Figure A.25: Total H2 yield per m3 of total waste for food waste (lipids).

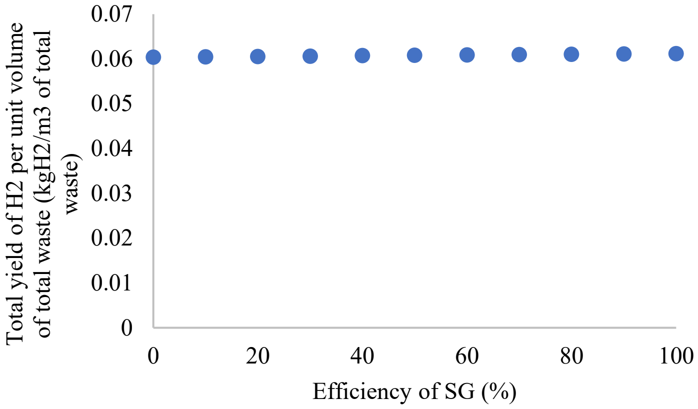


Figure A.26: Total H2 yield per m3 of total waste for wastewater.

A.2.2.5 Effect of the efficiency of the water gas shift stage

Figures A.27-A.31 show the effect of the WGS stage on the total hydrogen production. With decreasing efficiency in WGS, the total H_2 yield decreases. This is because less of the CO produced from the PR and SG stages is converted to H_2 and CO_2. Quantitatively, the effect of the WGS efficiency is significant but less important than for the PR stage. Indeed, the total hydrogen yield decreases from 0.13 (100 % efficiency) to approximately 0.09 (no efficiency of the WGS) kg_{H2}/kg_{OM} for the assumption of the feedstock composed by carbohydrates.

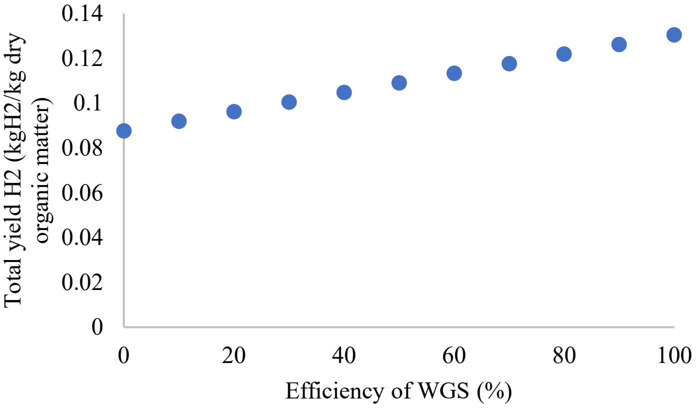


Figure A.27: Total H2 yield per kg of dry organic matter for food waste (carbohydrates) and wastewater.

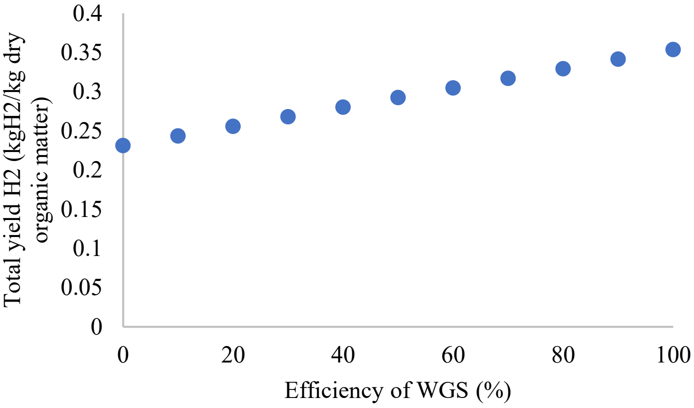


Figure A.28: Total H2 yield per kg of dry organic matter for food waste (lipids).

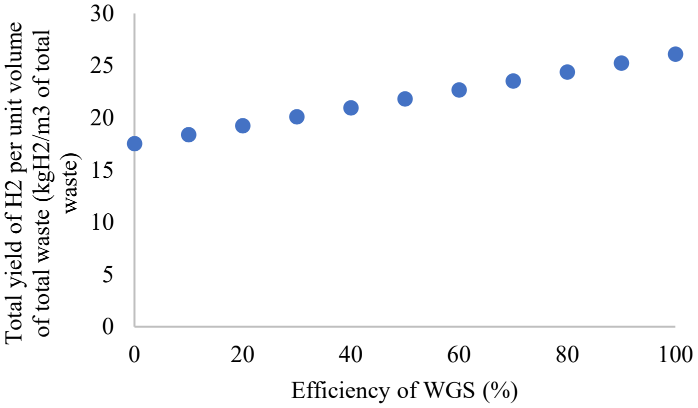


Figure A.29: Total H2 yield per m3 of total waste for food waste (carbohydrates).

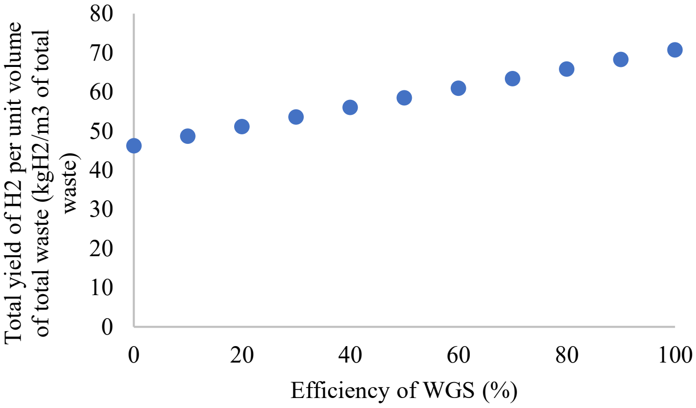


Figure A.30: Total H2 yield per m3 of total waste for food waste (lipids).

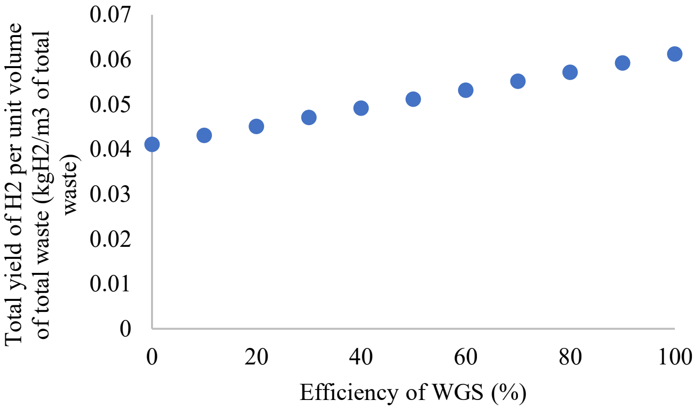


Figure A.31: Total H2 yield per m3 of total waste for wastewater.

A.2.2.6 50% efficiency at all stages

In the previous simulations, we have assumed that the efficiency of each stage varied while the efficiency of the other stages remained at 100 %. In this section we simulated the total hydrogen yield assuming that all stages are operating at 50% efficiency. The results are shown in Table A.7. As seen, there is a drop in the total H_2 yield compared to the base case yields in all cases. The yield decreases significantly, to about 40 % of the base case, e.g. 0.054 vs 0.13 kg_{H2}/kg_{OM} for food waste made of carbohydrates. This again indicates the importance of optimising the yield of all stages to maximise the total hydrogen yield from the process.

Table A.7: Total H_2 yield with 50% efficiency in all stages.

	Base case total yield H2 (kgH$_2$/kg dry organic matter)	**50% efficiency for all stages, total yield H_2 (kgH$_2$/kg dry organic matter)**
Food waste (carbohydrates)	0.13	0.054
Food waste (lipids)	0.35	0.13
Wastewater	0.13	0.054

A.2.2.7 Steam gasification with 50% non-biodegradable organic matter in dark fermentation and anaerobic digestion

Figures A.32-A.36 illustrate the total H_2 yield when the efficiency of the SG stage is varied from 0-100% while maintaining the efficiency of the DF and AD stages at 50%. This was investigated because in the previous simulations (section A.2.2.4) just varying the SG stage does not produce a noticeable change in the total H_2 yield as all the organic matter was assumed to be biodegraded in the DF and AD stages. Figures A.32-A.36 show that, with 50% efficiency of the DF and AD stages, the hydrogen yield is lower than for the base case for any efficiency of the SG stage, as expected. If the efficiency of SG is lower than 100 %, then the hydrogen yield decreases significantly, because of the loss of conversion to hydrogen and carbon monoxide in this stage. The results in this section indicate that SG too can have an important effect on the total hydrogen yield, therefore it is important to optimise this stage too.

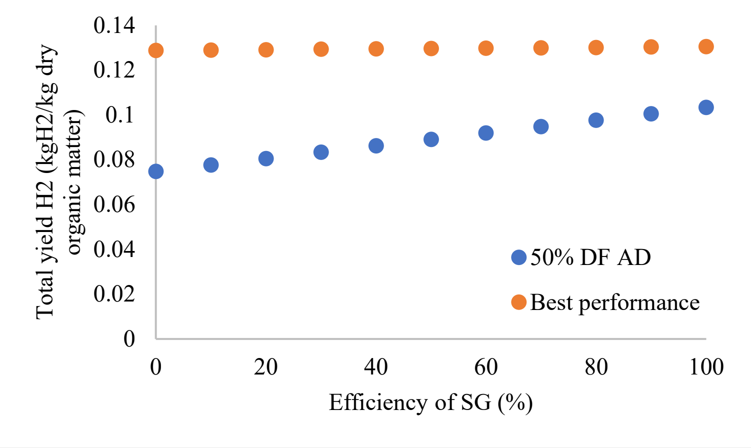


Figure A.32: Total H2 yield per kg of dry organic matter for food waste (carbohydrates) and wastewater.

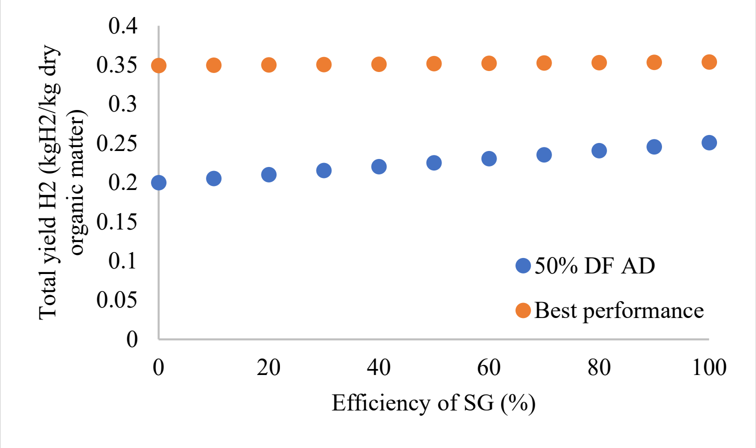


Figure A.33: Total H2 yield per kg of dry organic matter for food waste (lipids).

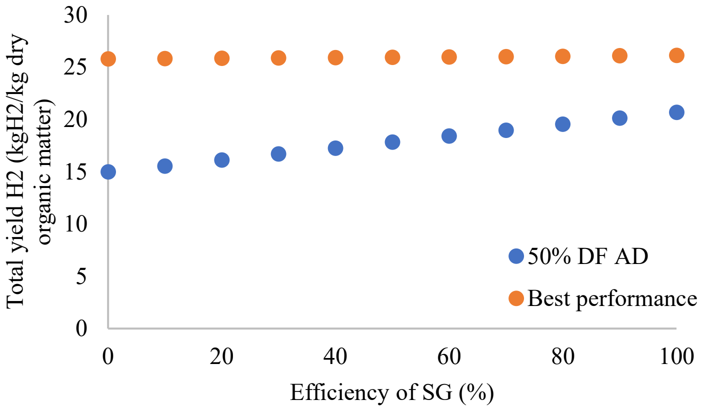


Figure A.34: Total H2 yield per m3 of total waste for food waste (carbohydrates).

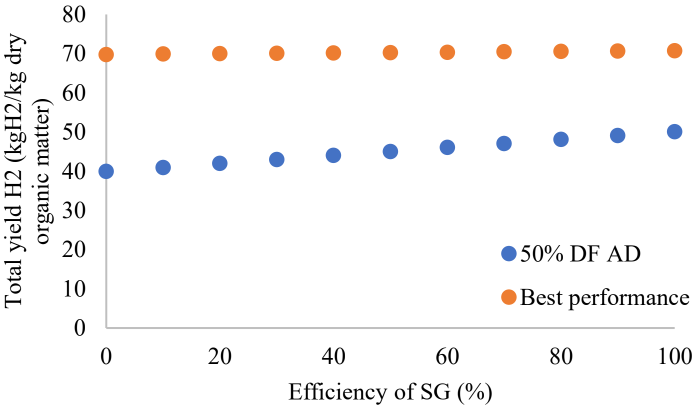


Figure A.35: Total H2 yield per m3 of total waste for food waste (lipids).

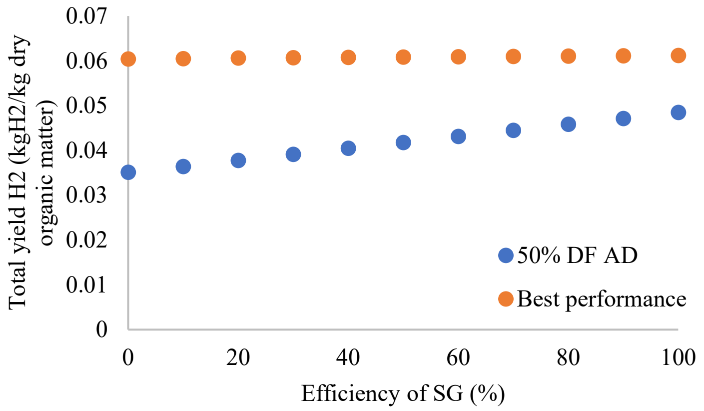


Figure A.36: Total H2 yield per m3 of total waste for wastewater.

A.2.3 Effect of the main assumptions on the total energy consumption

Similarly as section A.2.2, this section simulates the effect of the assumptions on the efficiency of each stage on the process performance, this time considering the total energy consumption.

A.2.3.1 Effect of non-biodegradable organic matter in the dark fermentation stage

Figures A.37-A.39 illustrate the total energy consumption as a function of the conversion efficiency in the DF stage. As seen in the figures, the energy consumption increases as the non-biodegradable fraction in DF increases, with the lowest energy consumption being when all organic matter is biodegraded in the DF stage. This is because as the non-biodegradable fraction in DF increases, less H_2 is produced in the DF stage and therefore more methane is produced in the AD stage. Therefore, more methane has to be converted into H_2 in the PR stage, which is more energy intensive than the biological stages, causing an increase in the total energy consumption by the process. This section shows that it is important to optimise the conversion in the DF stage even though, as shown in section A.2.2.1, the DF has only modest effect on the total hydrogen yield from the process.

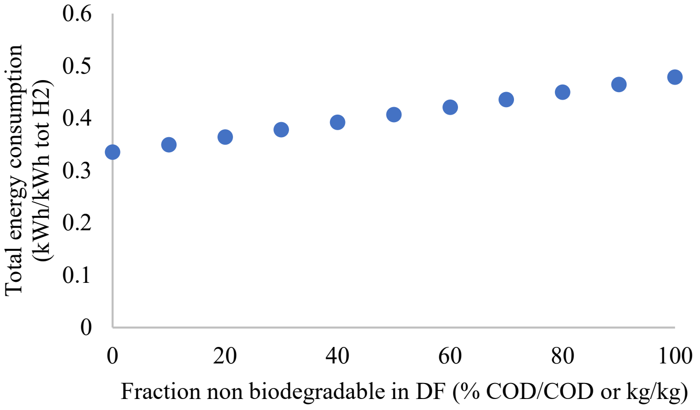


Figure A.37: Total energy consumption per kWh total H2 for food waste (carbohydrates).

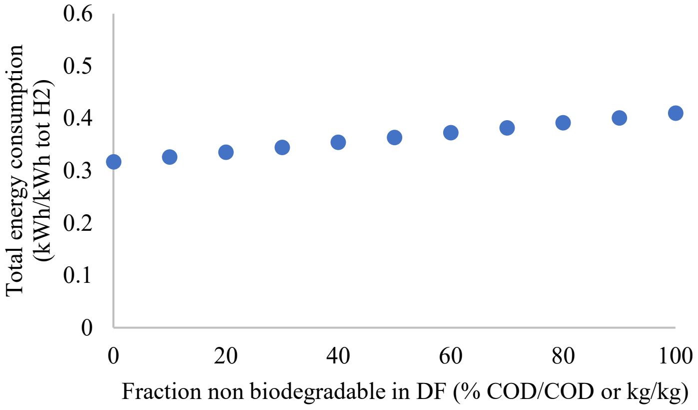


Figure A.38: Total energy consumption per kWh total H2 for food waste (lipids).

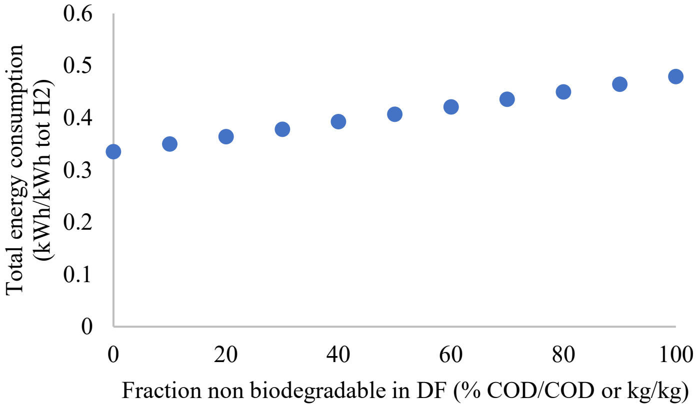


Figure A.39: Total energy consumption per kWh total H2 for wastewater.

A.2.3.2 Effect of non-biodegradable organic matter in the anaerobic digestion stage

Figure A.40-A.42 show the total energy consumption by varying the non-biodegradable fraction in the AD stage. As seen from the figures, the total energy consumption increases as the non-biodegradable fraction increases. This increase is significant, for example the energy consumption for feedstock made of food waste (carbohydrates) increases from approximately 0.4 to approximately 1.0 kWh/kWh$_{H2}$ as the non-biodegradable fraction increases from 0 to 100 %. This important effect of AD on the total energy consumption is because the organic matter that is not biodegraded in this stage would need to be converted in the SG stage to produce H_2 and CO. However, SG is energy intensive, causing the total energy consumption to increase. Furthermore, the CO from SG is then further converted to H2 using the WGS stage, which is also energy intensive, and therefore contributes to increasing the total energy consumption of the process when the performance of AD reduces. This section shows the importance of optimising the conversion in the AD stage.

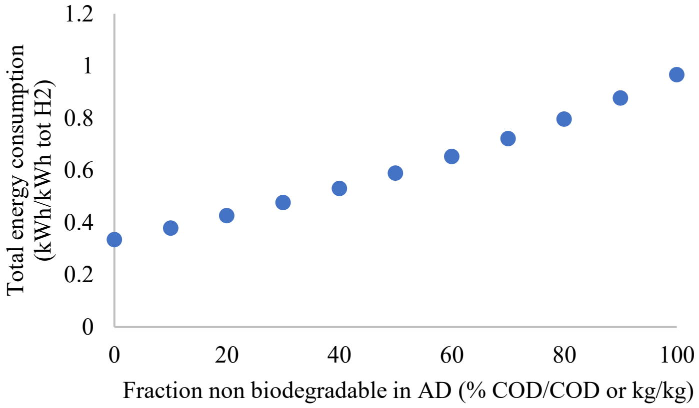


Figure A.40: Total energy consumption per kWh total H2 for food waste (carbohydrates).

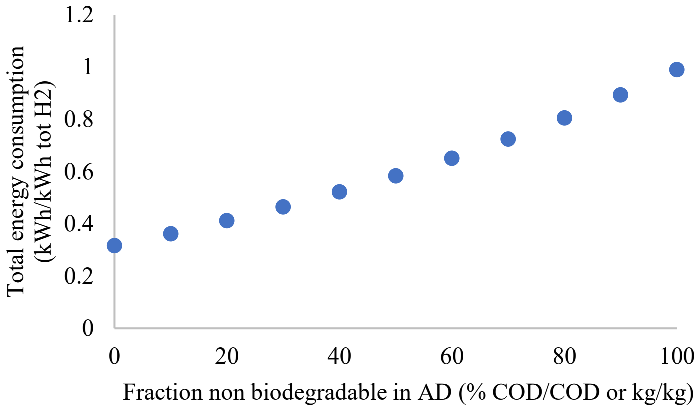


Figure A.41: Total energy consumption per kWh total H2 for food waste (lipids).

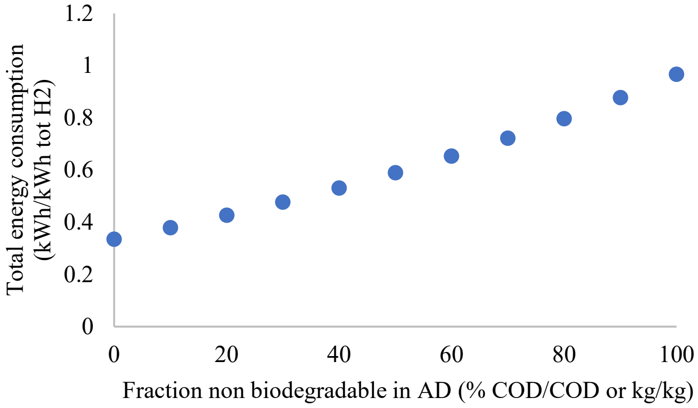


Figure A.42: Total energy consumption per kWh total H2 for wastewater.

A.2.3.3 Effect of the efficiency of the plasma reforming stage

Figures A.43-A.45 show how the total energy consumption varies with the efficiency of the PR stage. Similar as for the biological stages, the total energy consumption increases with decreases efficiency of PR. This is because lower efficiency of the PR stage corresponds to lower hydrogen production and therefore to higher energy consumption per unit hydrogen. The effect of the PR stage on energy consumption is considerable, as the energy consumption increases from less than 0.4 over 0.8 kWh/kWh$_{H2}$, which again confirms the importance of optimising this stage.

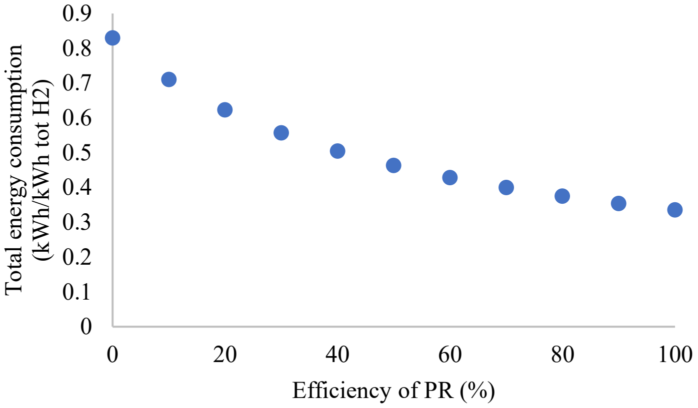


Figure A.43: Total energy consumption per kWh total H2 for food waste (carbohydrates).

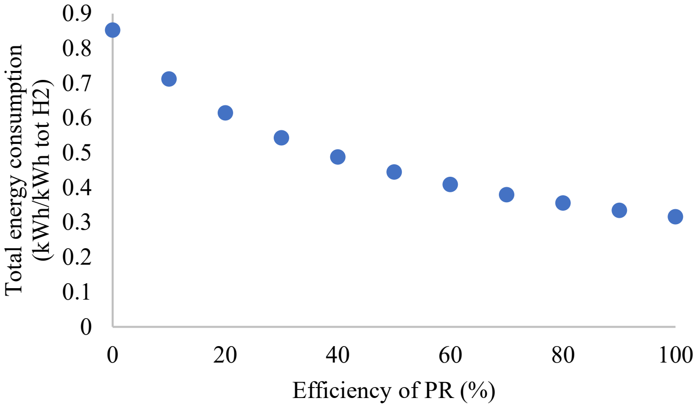


Figure A.44: Total energy consumption per kWh total H2 for food waste (lipids).

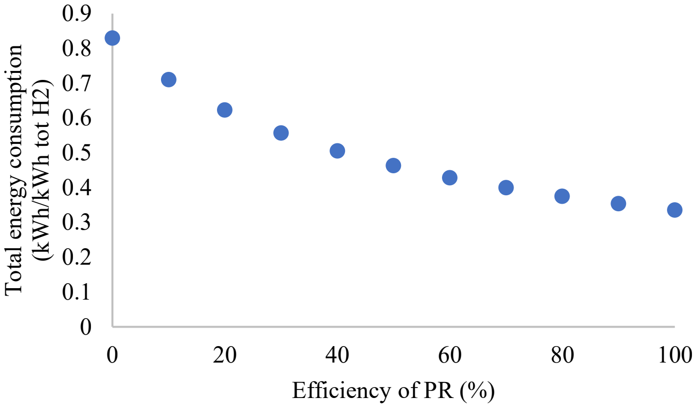


Figure A.45: Total energy consumption per kWh total H2 for wastewater.

A.2.3.4 Effect of the efficiency of the steam gasification stage

Figures A.47-A.49 illustrates the total energy consumption as a function of the efficiency of the SG stage. As predicted, the total energy consumption does not vary noticeably as the efficiency of the SG changes from 0-100%. As mentioned previously, under the assumptions of this simulation, the DF and AD stages are operating at 100% efficiency which results in all the organic matter to be biodegraded in the DF and AD stages. Therefore, the SG stage only has very little organic matter to react to produce H_2, hence the energy consumption is not much affected by the efficiency of this stage.

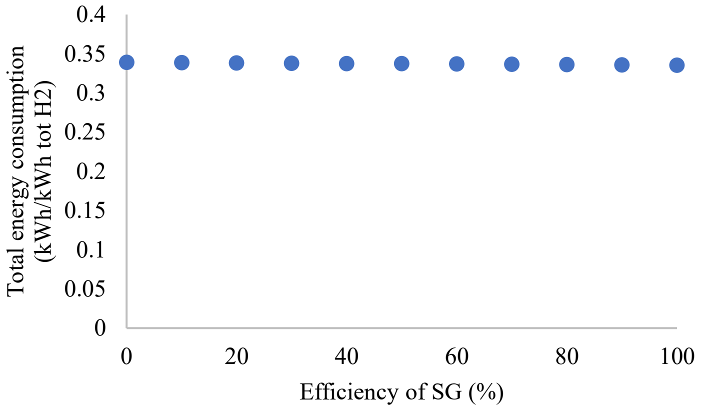


Figure A.47: Total energy consumption per kWh total H2 for food waste (carbohydrates).

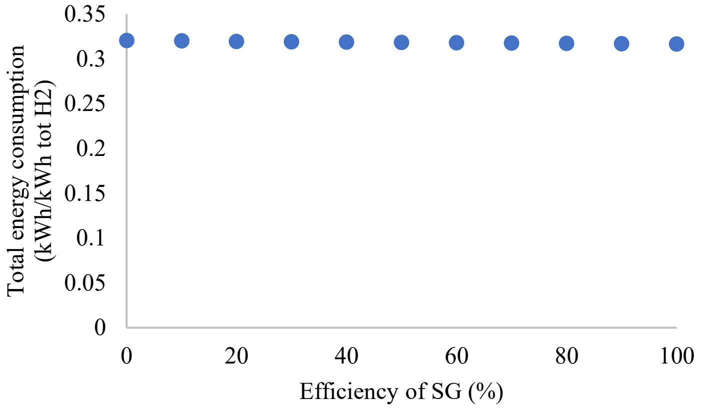


Figure A.48: Total energy consumption per kWh total H2 for food waste (lipids).

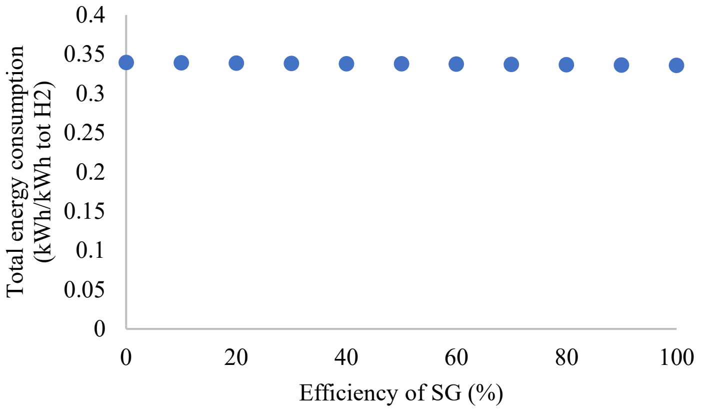


Figure A.49: Total energy consumption per kWh total H2 for wastewater.

A.2.3.5 Effect of the efficiency of the water gas shift stage

Figures A.50-A.52 show the total energy consumption for varying efficiency in WGS. As the efficiency of WGS decreases, the total energy consumption decreases. As observed for other stages, this is due to the fact that the total hydrogen production decreases as the WGS efficiency decreases, therefore the unit energy consumption increases. Quantitatively, the effect of reduced efficiency of WGS is less important that reduced efficiency of the PR stage, as the PR stage gives a higher contribution to the total hydrogen production.

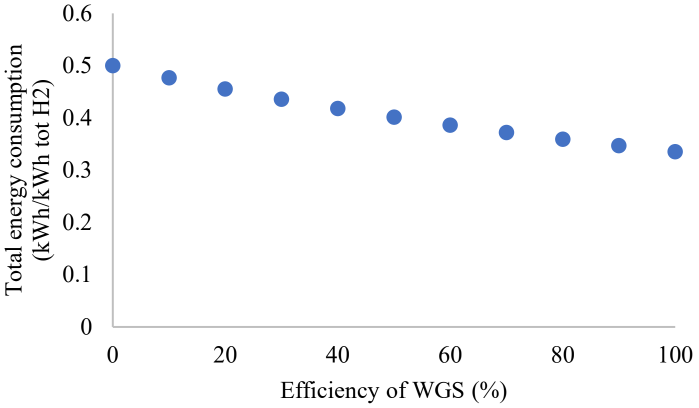


Figure A.50: Total energy consumption per kWh total H2 for food waste (carbohydrates).

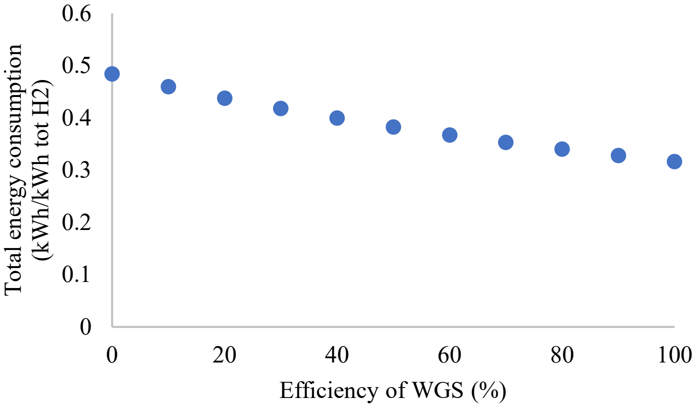


Figure A.51: Total energy consumption per kWh total H2 for food waste (lipids).

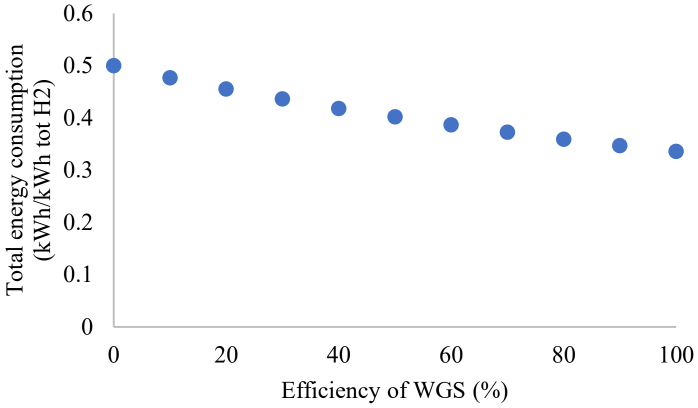


Figure A.52: Total energy consumption per kWh total H2 for wastewater.

A.2.3.6 50% efficiency at all stages

In the previous sections the efficiency of each stage was varied while assuming that all other stages remained at 100 % efficiency, as for the base case. In contrast, Table A.8 gives the total energy consumption when all stages are operating at 50 % efficiency. As seen, there is an increase in the total energy consumption compared to the base case in all cases. This is expected and confirms the importance of optimising all stages to reduce the energy consumption of the process.

Table A.8: Total energy consumption with 50 % efficiency in all

	Base case total energy consumption (kWh/kWh tot H2)	**50 % efficiency for all stages, total energy consumption (kWh/kWh tot H2)**
Food waste (carbohydrates)	0.335	1.40
Food waste (lipids)	0.317	1.12
Wastewater	0.335	1.40

A.2.3.7 Double the energy consumption at each stage

So far, the simulations assumed a fixed unit energy consumption for each stage, according to Table A.2. The effect of doubling the energy consumption of each stage on the total energy consumption was investigated (Figures A.53-A.55). As evident from the graphs, doubling the energy consumption at the PR stage gives the highest total energy consumption than the rest of the stages (for all cases). This is because PR is an energy intensive stage and requires more energy than the other stages. All the simulations in this section have been done using the base case assumptions on the conversions of each stage.

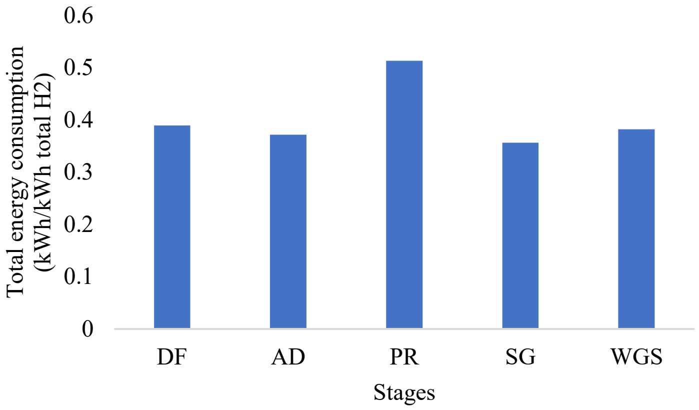


Figure A.53: Double the energy consumption for food waste (carbohydrates).

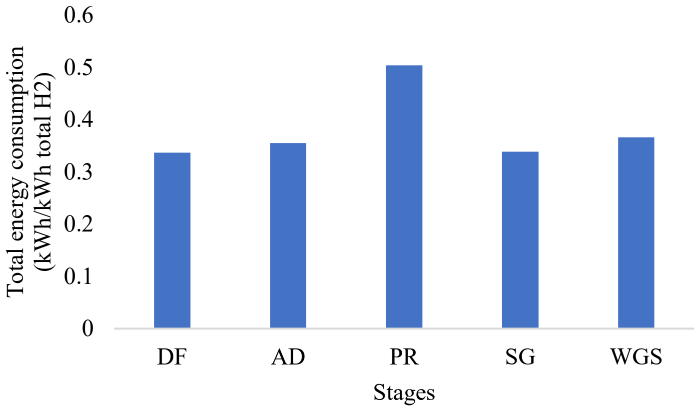


Figure A.54: Double the energy consumption for food waste (lipids).

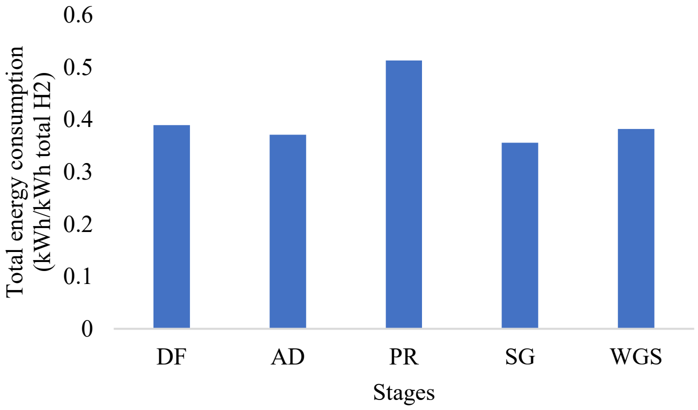


Figure A.55: Double the energy consumption for wastewater.

A.2.3.8 Steam gasification with 50% non-biodegradable organic matter in dark fermentation and anaerobic digestion

Figures A.56-A.58 illustrate the total energy consumption when the efficiency of the SG stage is varied from 0-100% while maintaining the efficiency of the DF and AD stages at 50%. This was investigated because just varying the SG stage does not produce a noticeable change in the total energy consumption as all the organic matter is biodegraded in the DF and AD stages. All the above figures show that the total energy consumption increases with decreasing efficiency of SG. This increase in energy consumption is significant, reaching over 1.0 kWh/kWhH2 for zero efficiency of the SG stage. These results indicate the importance of optimising the SG stage to reduce the energy consumption of the process.

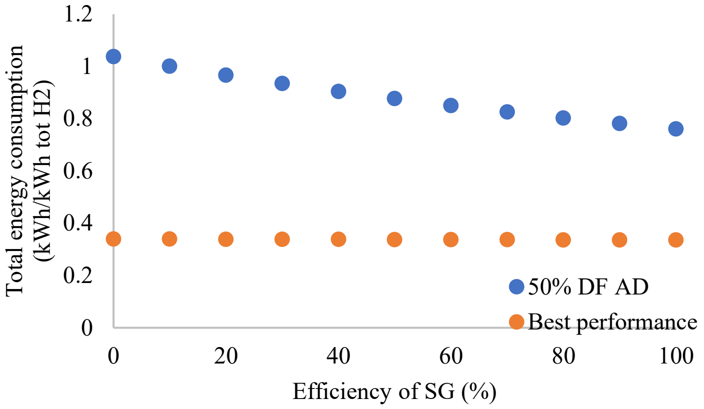


Figure A.56: Total energy consumption for food waste (carbohydrates).

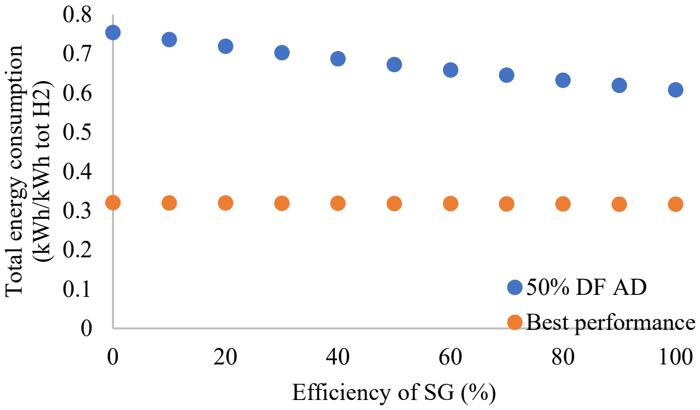


Figure A.57: Total energy consumption for food waste (lipids).

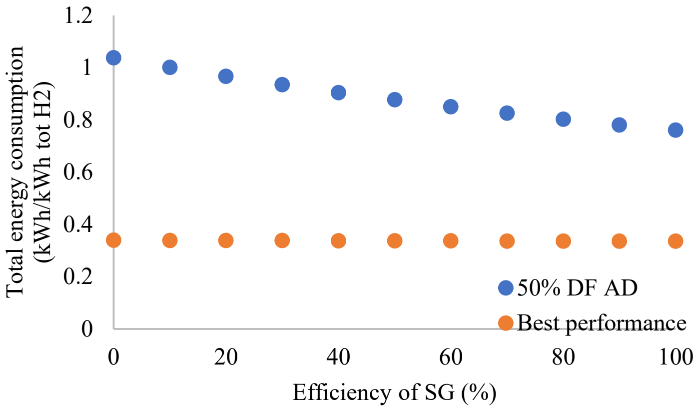


Figure A.58: Total energy consumption for wastewater.

A.2.4 Effect of the main assumptions on the total water consumption

In this section we investigated the effect of the efficiency of each stage on the total water consumption. The approach is the same followed in sections A.2.2 and A.2.3 for the hydrogen yield and the energy consumption.

A.2.4.1 Effect of non-biodegradable organic matter in the dark fermentation stage

Figures A.59-A.61 show how the total water consumption is affected by the efficiency of the DF stage. The total water consumption increases with increasing the non-biodegradable fraction in the DF stage. This is because the higher the non-biodegradable fraction, the less organic matter is biodegraded in the DF stage and the more in the AD stage. This results in less hydrogen produced in DF and more methane produced in AD. The methane from AD is converted into CO by PR and then the CO is converted into CO2 in the WGS reaction, which requires water. Therefore, ultimately lower efficiency in DF corresponds to higher water consumption.

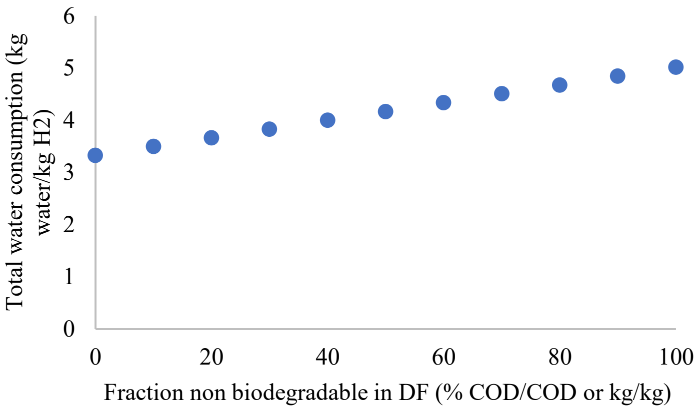


Figure A.59: Total water consumption for food waste (carbohydrates).

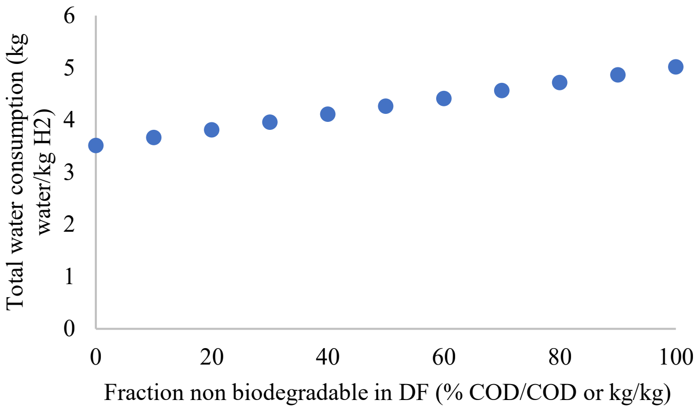


Figure A.60: Total water consumption for food waste (lipids).

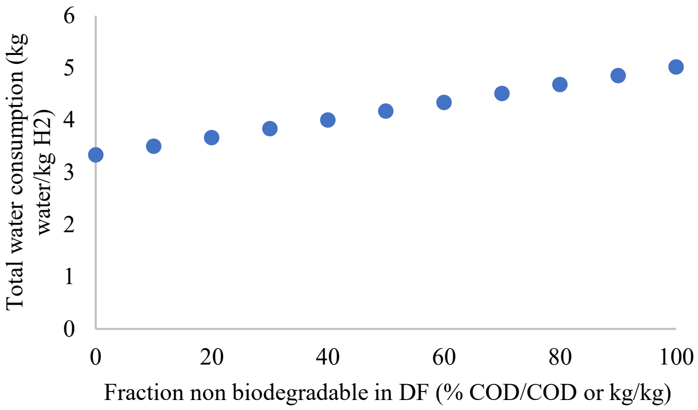


Figure A.61: Total water consumption for wastewater.

A.2.4.2 Effect of non-biodegradable organic matter in the anaerobic digestion stage

Figures A.62-A.64 show how the total water consumption is affected by the efficiency of the AD stage. The effect on the total water consumption of the AD stage is similar to the DF fermentation stage where, as the non-biodegradable fraction increases the total water consumption increases. This is because higher the non-biodegradable fraction, the less organic matter is biodegraded in the AD stages resulting in the organic matter being reacted in the SG stage to produce H2. SG requires water and therefore the water consumption increases. Note that, quantitatively, the effect of AD efficiency on water consumption is very considerable, e.g. the calculated water consumption increases from approximately 3 to 18 kg/kg$_{H2}$ when the non-biodegradable fraction increases from 0 to 100 %.

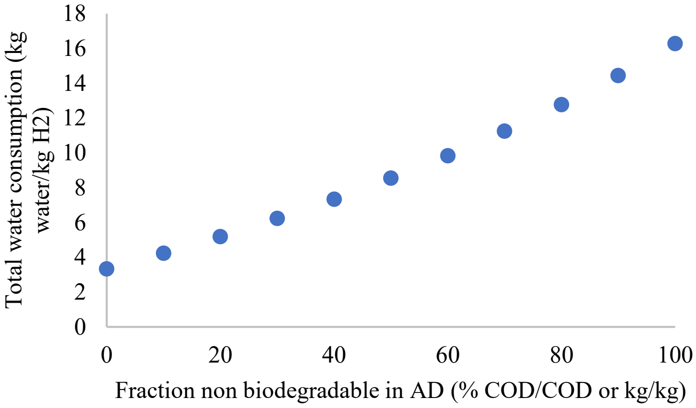


Figure A.62: Total water consumption for food waste (carbohydrates).

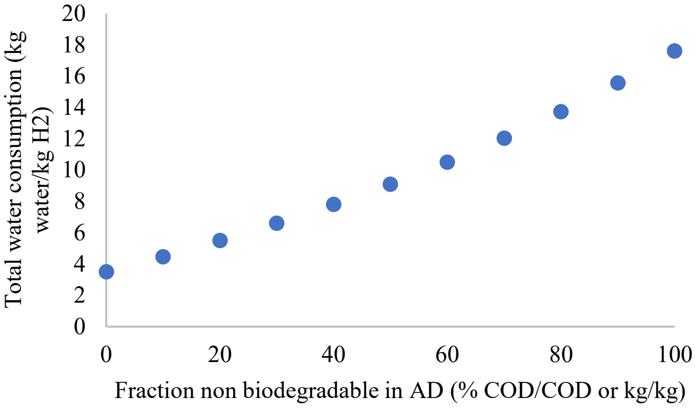


Figure A.63: Total water consumption for food waste (lipids).

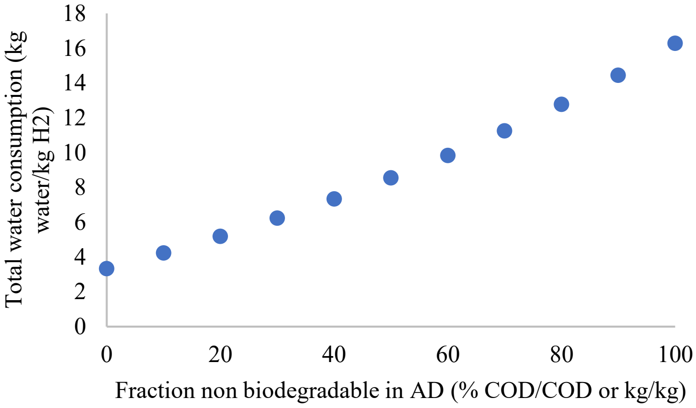


Figure A.64: Total water consumption for wastewater.

A.2.4.3 Effect of the efficiency of the plasma reforming stage

Figures A.65-A.67 show the effect of PR stage efficiency on the total water consumption. The total water consumption decreases with decreasing efficiency in PR. This is because with decreasing efficiency, less CO is produced and therefore the next step of WGS requires less water. Obviously, lower efficiency in PR, although it reduces the water consumption, is not to be desired because it significantly decreases the hydrogen yield for the whole process.

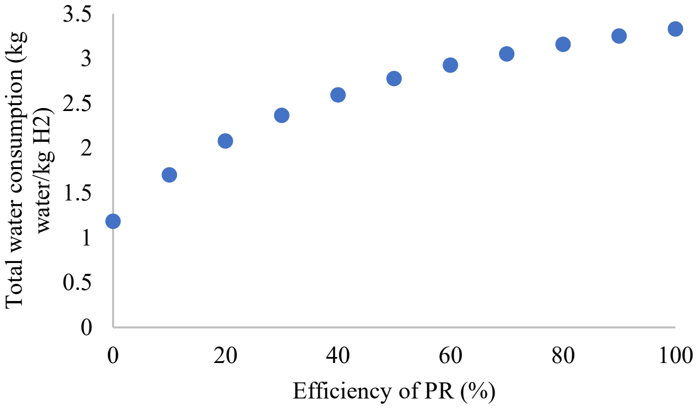


Figure A.65: Total water consumption for food waste (carbohydrates).

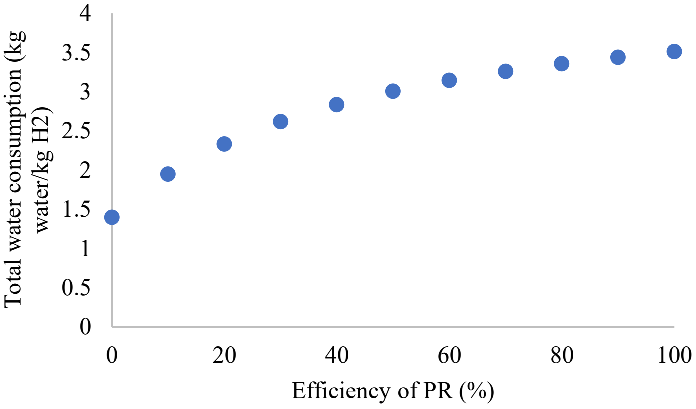


Figure A.66: Total water consumption for food waste (lipids).

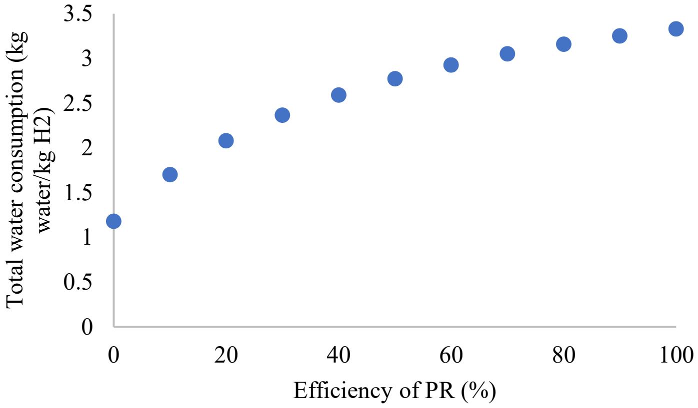


Figure A.67: Total water consumption for wastewater.

A.2.4.4 Effect of the efficiency of the steam gasification stage

Figures A.68-A.70 illustrates the effect of the SG efficiency on the total water consumption. There isn't a noticeable effect in the water consumption. This is because these simulations assume the base case efficiency for all other stages, which translates in very little organic matter to be processed in the SG stage, as discussed earlier.

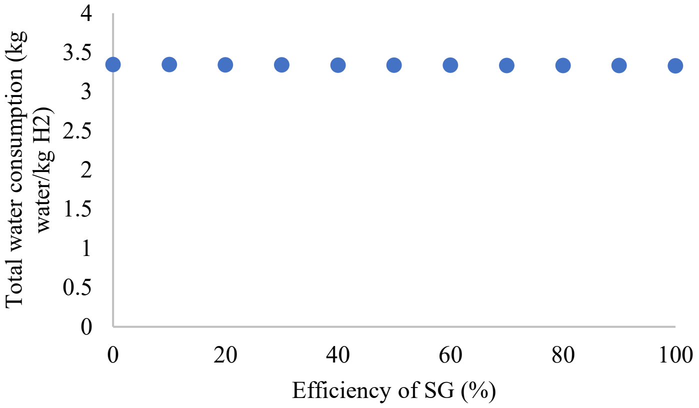


Figure A.68: Total water consumption for food waste (carbohydrates).

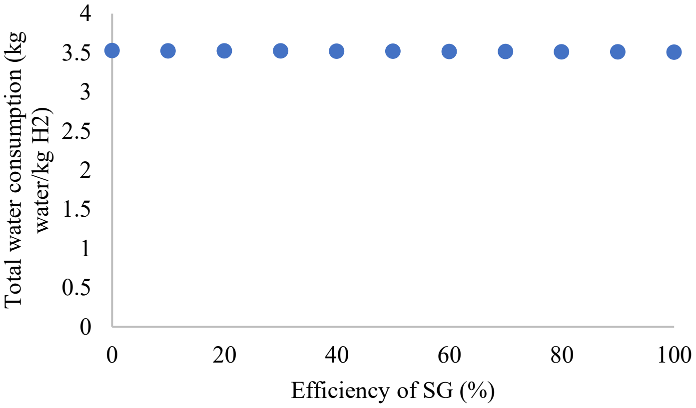


Figure A.69: Total water consumption for food waste (lipids).

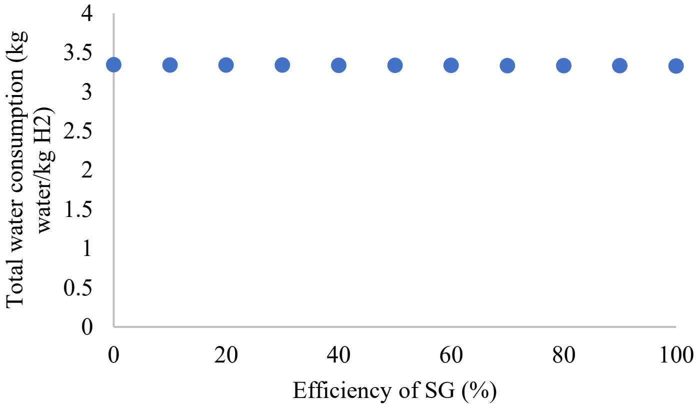


Figure A.70: Total water consumption for wastewater.

A.2.4.5 Effect of the efficiency of the water gas shift stage

Figures A.71-A.73 show the effect of the efficiency of the WGS stage on the total water consumption. As the efficiency of the WGS decreases, the water consumption per unit hydrogen produced increases. This is because lower efficiency of WGS corresponds to less hydrogen production with a higher unit water consumption.

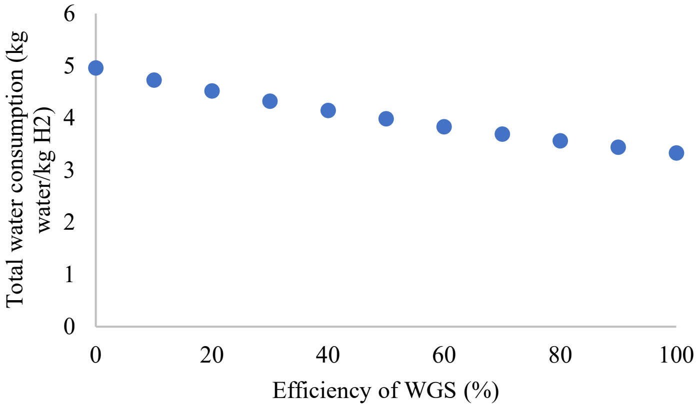


Figure A.71: Total water consumption for food waste (carbohydrates).

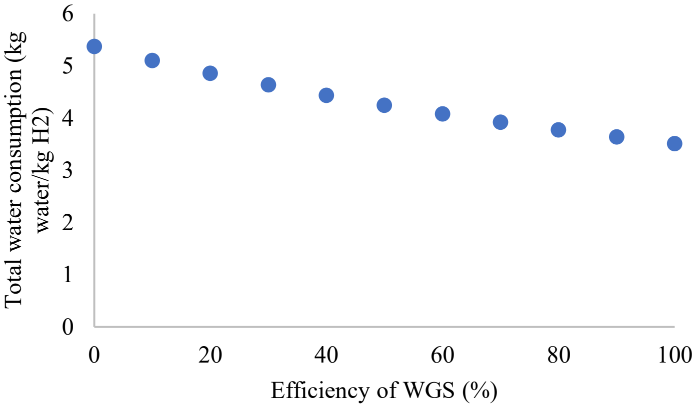


Figure A.72: Total water consumption for food waste (lipids).

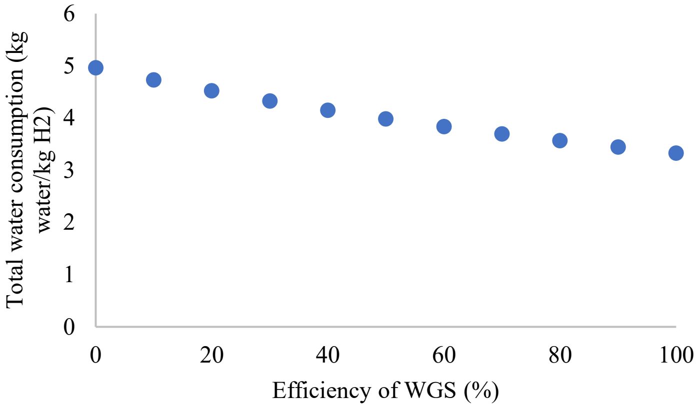


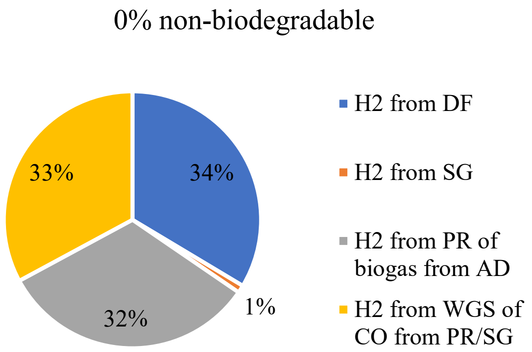
Figure A.73: Total water consumption for wastewater.

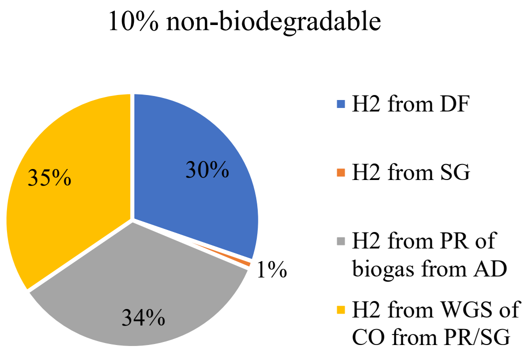
A.2.5 Hydrogen production by process stage with food waste (carbohydrates)

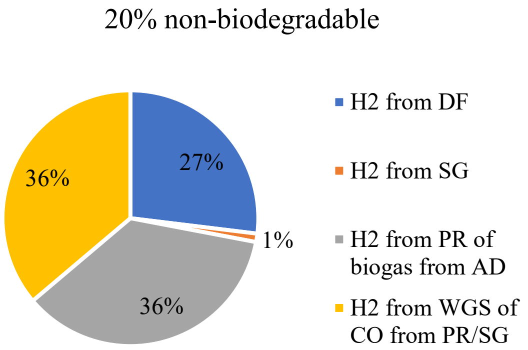
The following graphs illustrates the simulations for food waste assuming carbohydrates composition (COD factor 1.067). The graphs show the contribution of each stage to the total hydrogen production for different values of the efficiency of each stage. When the efficiency of each stage was varied, the efficiency of all other stages was assumed to remain the same as assumed for the base case. Note that the results shown in this section also apply to the case of wastewater feedstock, as the organic matter in wastewater was assumed to be composed of carbohydrates.

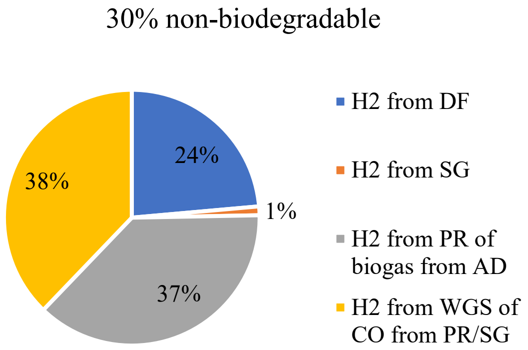
A.2.5.1 Dark fermentation

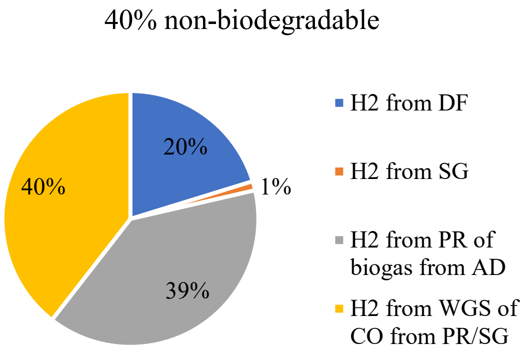
Figure A.74 shows the contributions of each stage to the total hydrogen production as a function of the conversion efficiency in the DF stage. As the conversion efficiency decreases (higher fraction of non-biodegradable organic matter) the contribution of DF decreases, as expected, with a corresponding increase in the role of WGS and PR. This is due to the increasing fraction of organic matter which is converted in AD, due to the loss of efficiency of the DF stage. Higher contribution of the PR and WGS stages is undesirable, because these stages are more energy intensive than DF, which in turn causes a higher energy consumption, as also shown earlier.

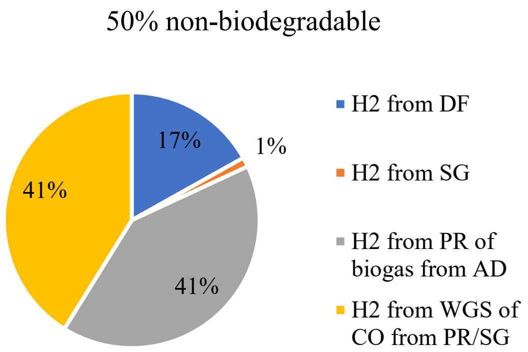

0% non-biodegradable
34%
1%
32%
33%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG

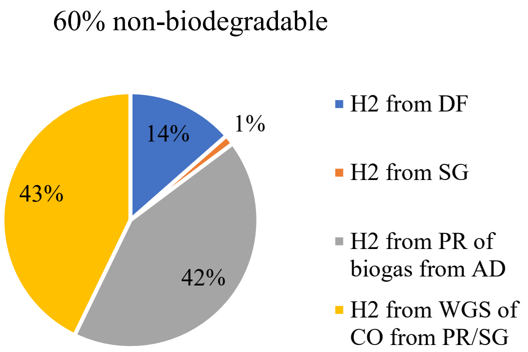

10% non-biodegradable
30%
1%
34%
35%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG

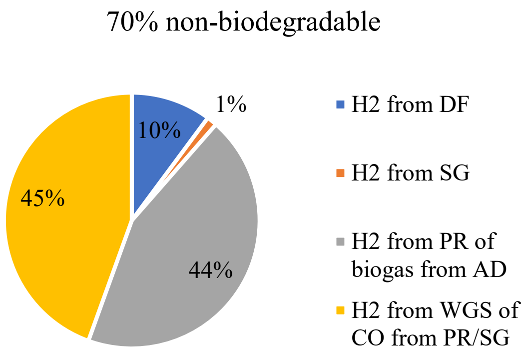

20% non-biodegradable
27%
1%
36%
36%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG


30% non-biodegradable
24%
1%
37%
38%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG


40% non-biodegradable
20%
1%
39%
40%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG


50% non-biodegradable
17%
1%
41%
41%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG


60% non-biodegradable
14%
1%
42%
43%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG


70% non-biodegradable
10%
1%
44%
45%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG

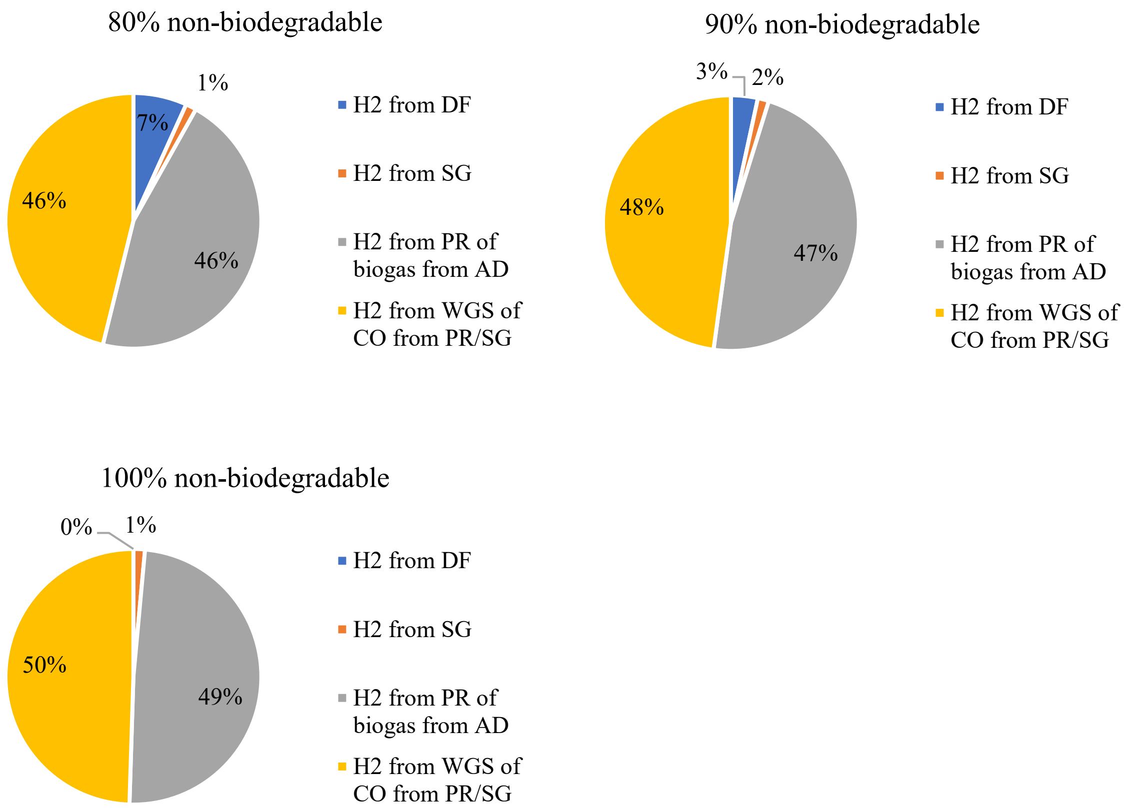
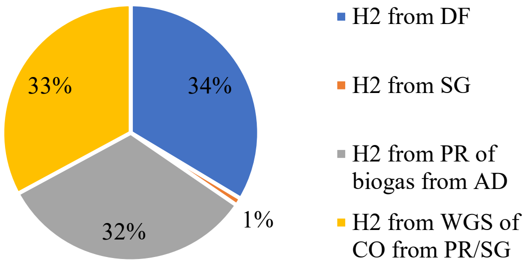


Figure A.74. Effect of the assumptions on the non-biodegradable fraction of the organic matter in DF on the contribution of each stage to total hydrogen production

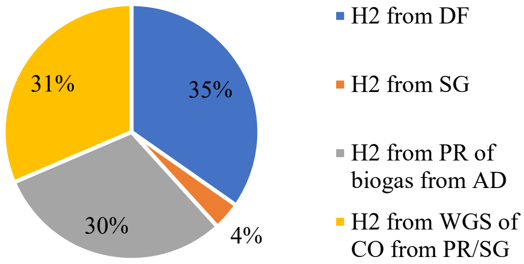
A.2.5.2 Anaerobic digestion

Figure A.75 shows the contributions of each stage to the total hydrogen production as a function of the conversion efficiency in the AD stage. As the conversion efficiency decreases (higher fraction of non-biodegradable organic matter) the contribution of PR decreases. This is because PR processes the methane from AD and lower conversions in AD mean lower methane available for PR. Corresponding to the lower role of PR, the role of WGS also decreases because of the lower production of CO from PR. Higher non-biodegradable fraction in AD gives a higher role to SG, which converts the non-biodegradable fraction. Higher contribution of the SG stage is undesirable, because this stage is more energy intensive and therefore the process will have higher energy consumption, as also shown earlier.

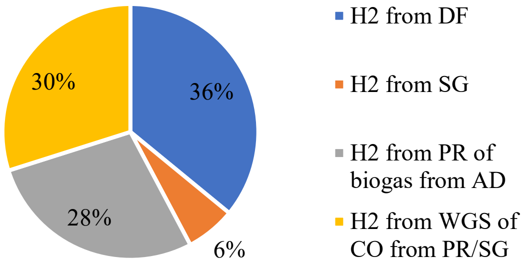
0% non-biodegradable



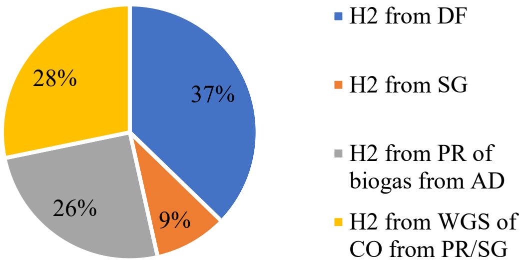
10% non-biodegradable



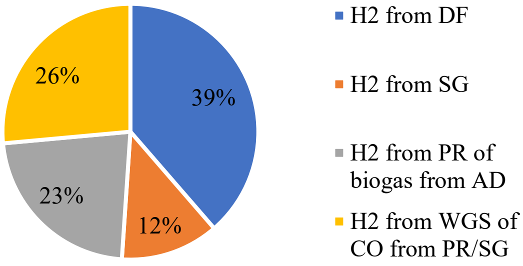
20% non-biodegradable



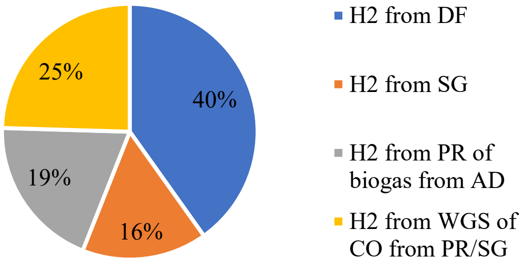
30% non-biodegradable



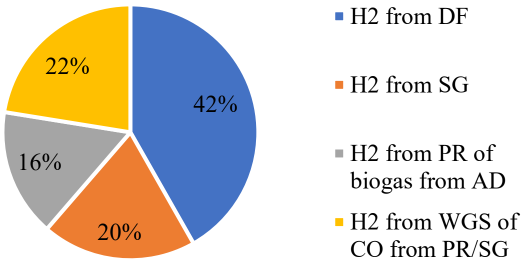
40% non-biodegradable



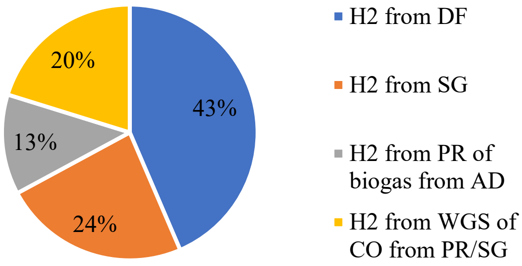
50% non-biodegradable

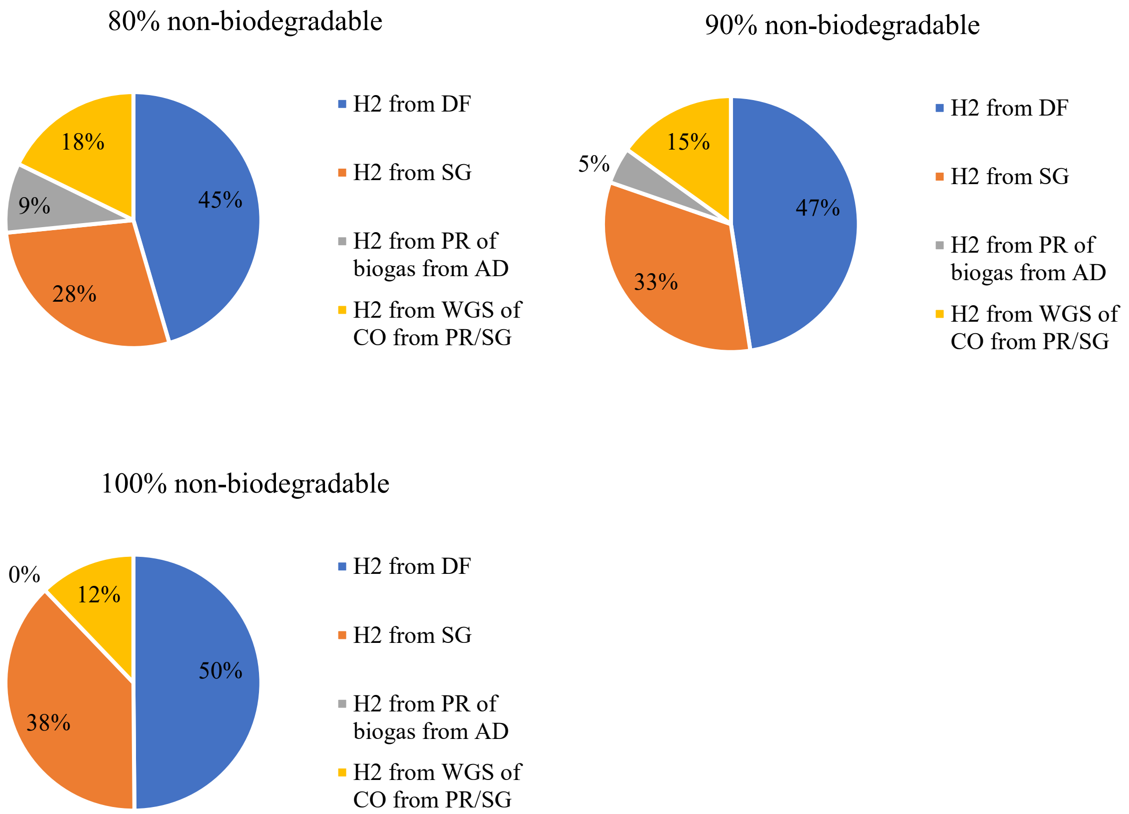


60% non-biodegradable



70% non-biodegradable




80% non-biodegradable

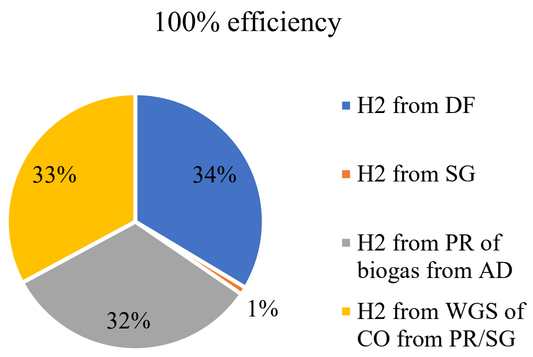
90% non-biodegradable

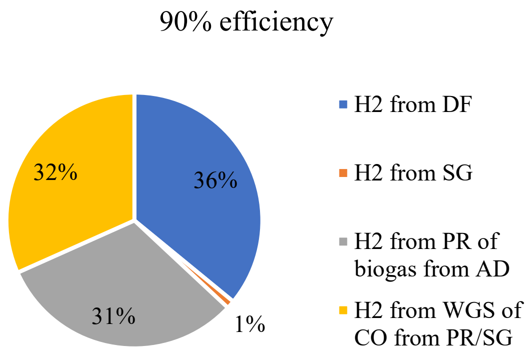
100% non-biodegradable

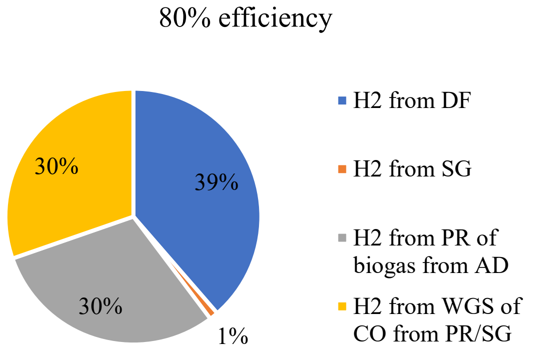
Figure A.75. Effect of the assumptions on the non-biodegradable fraction of the organic matter in AD on the contribution of each stage to total hydrogen production

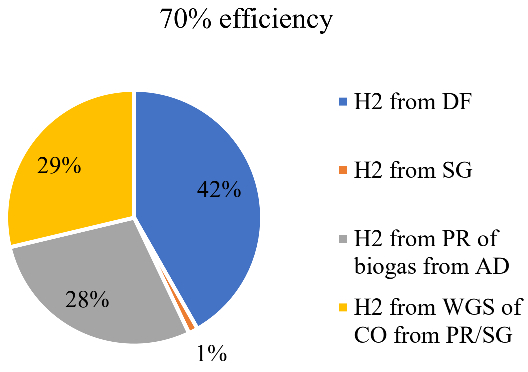
A.2.5.3 Plasma reforming

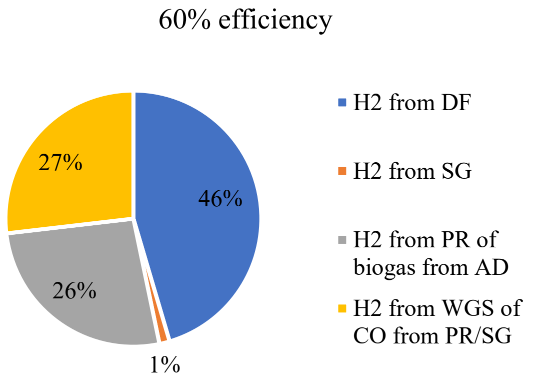
Figure A.76 shows the contributions of each stage to the total hydrogen production as a function of the conversion efficiency in the PR stage. As the conversion efficiency in PR decreases, the role of PR and WGS in the total hydrogen production decreases. The lower role of WGS is due to the reduction in the CO production from PR. In the extreme case of zero efficiency in the PR stage, almost all the hydrogen will be produced by DF, however this will be a relatively low value as shown in previous sections.

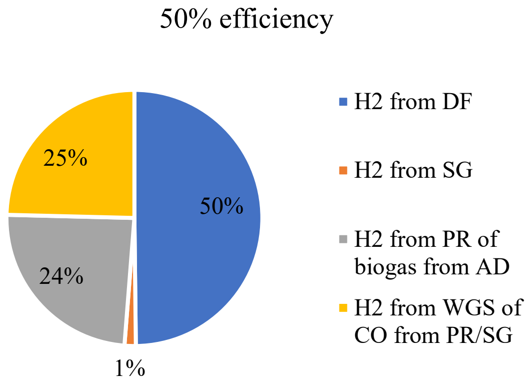

100% efficiency
33%
34%
32%
1%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG

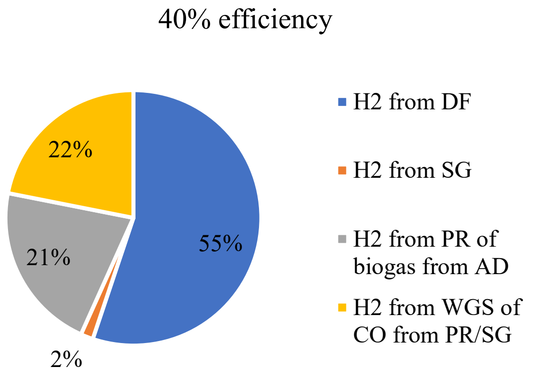

90% efficiency
32%
36%
31%
1%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG

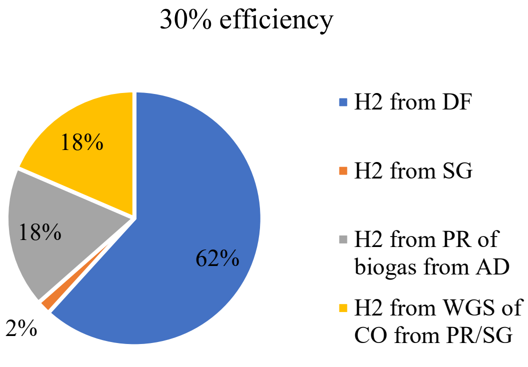

80% efficiency
30%
39%
30%
1%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG


70% efficiency
29%
42%
28%
1%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG


60% efficiency
27%
46%
26%
1%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG


50% efficiency
25%
50%
24%
1%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG


40% efficiency
22%
55%
21%
2%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG


30% efficiency
18%
18%
62%
2%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG

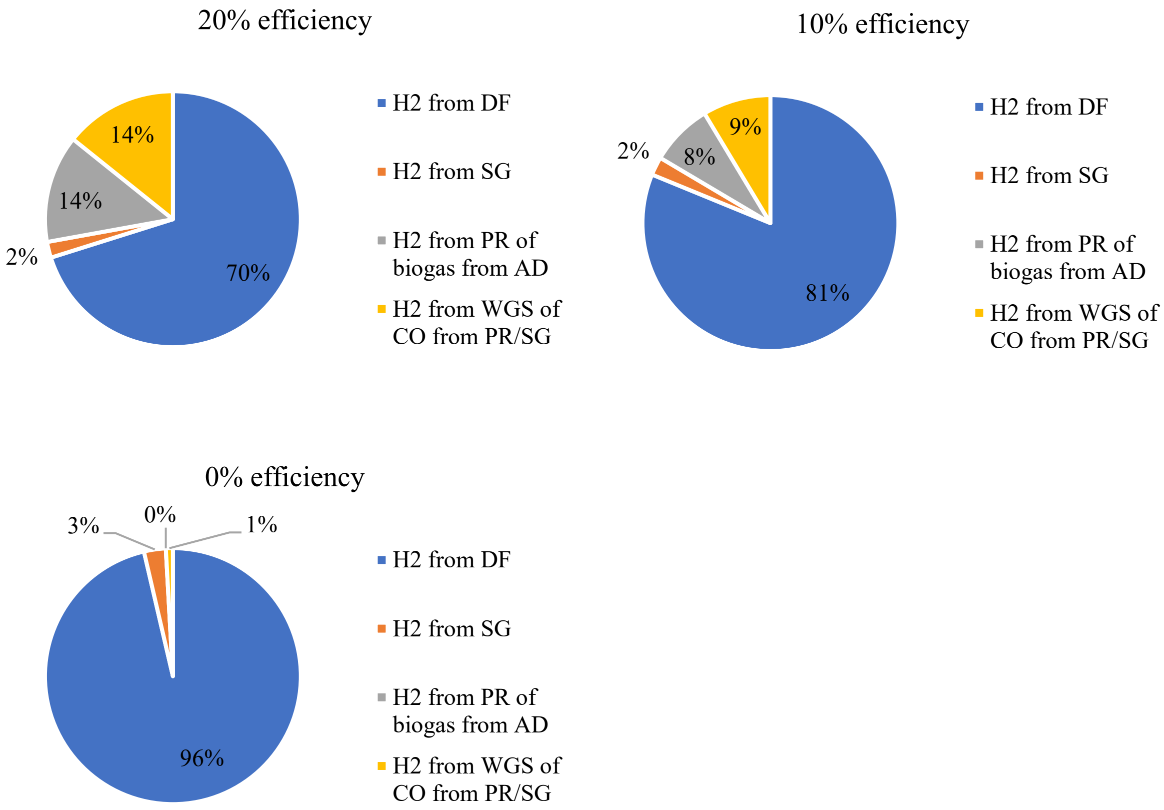
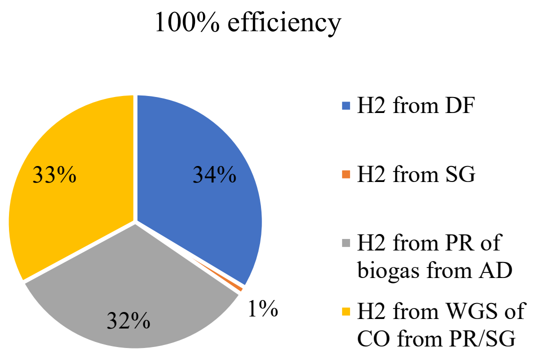
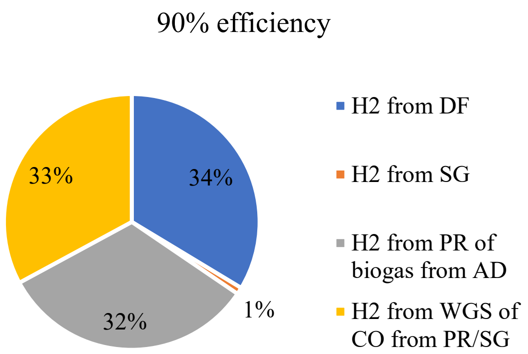


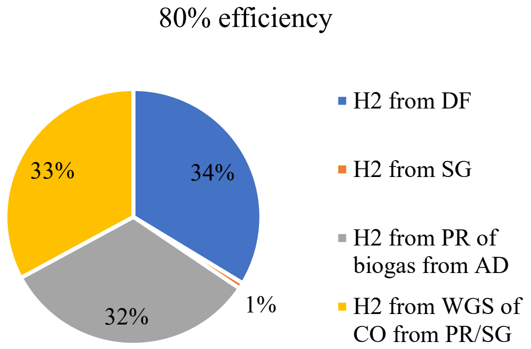
Figure A.76. Effect of the assumptions on the efficiency of the PR stage on the contribution of each stage to total hydrogen production

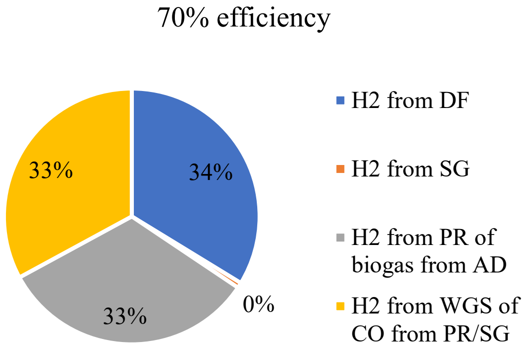
A.2.5.4 Steam gasification

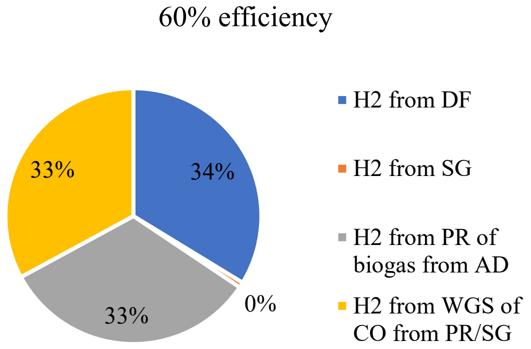
Figure A.77 shows the contributions of each stage to the total hydrogen production as a function of the conversion efficiency in the SG stage. Under the base case assumptions of these simulations, the role of SG is very low in all cases, because of the very high conversion of the organic matter in AD. Therefore, under these assumptions the conversion efficiency in SG doesn’t affect the contributions of the other stages to the total hydrogen production.

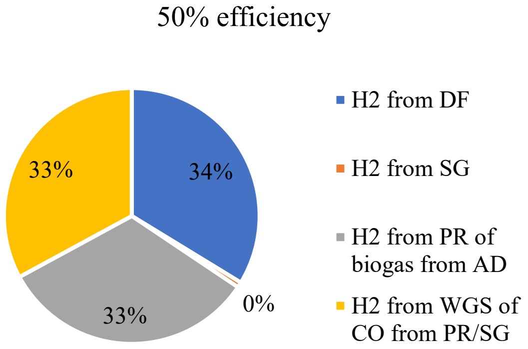

100% efficiency
34%
1%
32%
33%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG

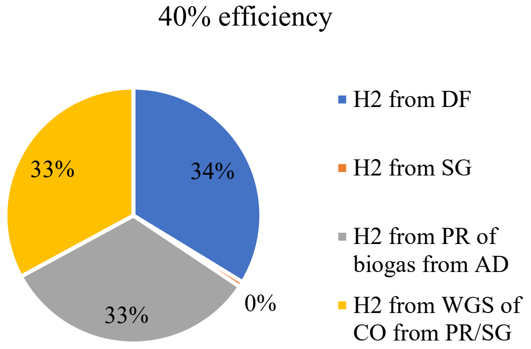

90% efficiency
34%
1%
32%
33%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG

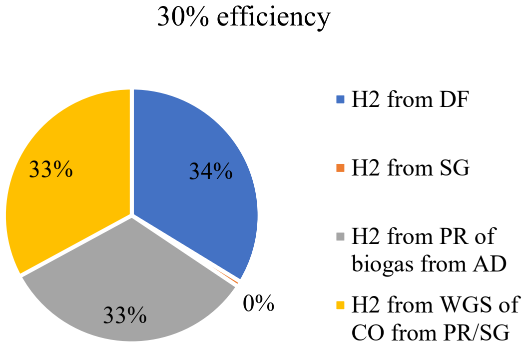

80% efficiency
34%
1%
32%
33%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG


70% efficiency
34%
0%
33%
33%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG


60% efficiency
34%
0%
33%
33%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG


50% efficiency
34%
0%
33%
33%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG


40% efficiency
34%
0%
33%
33%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG


30% efficiency
34%
0%
33%
33%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG

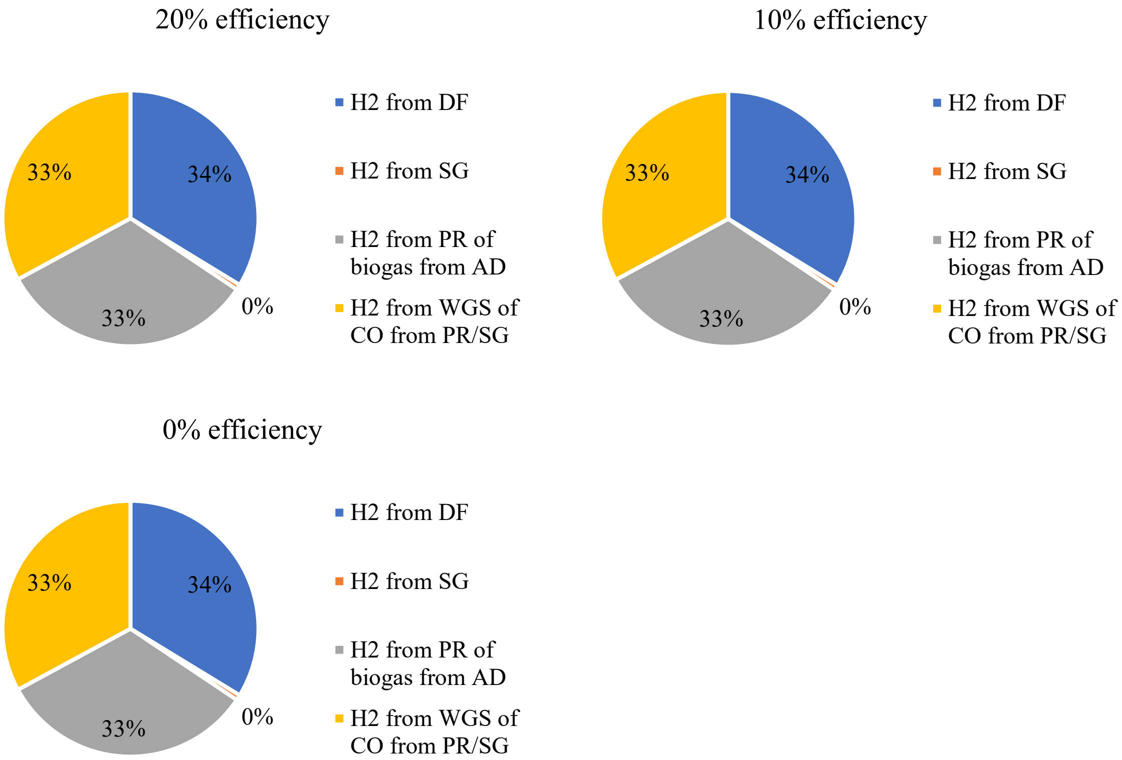
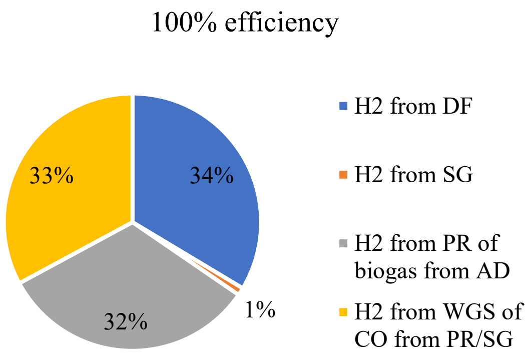
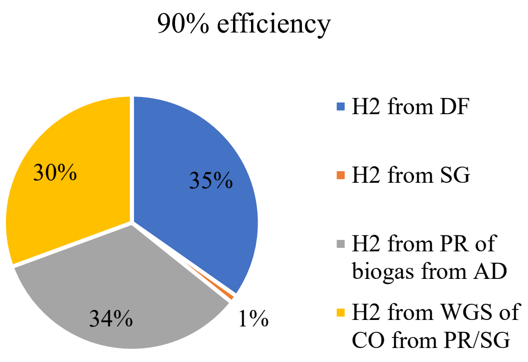


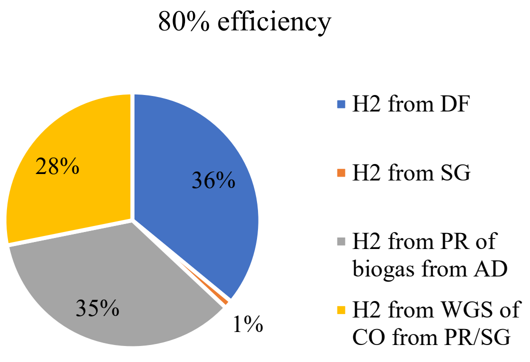
Figure A.77. Effect of the assumptions on the efficiency of the SG stage on the contribution of each stage to total hydrogen production

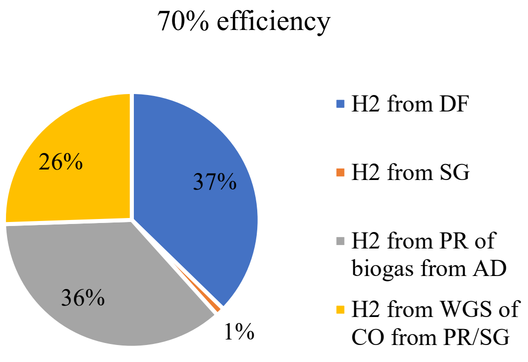
A.2.5.5 Water gas shift

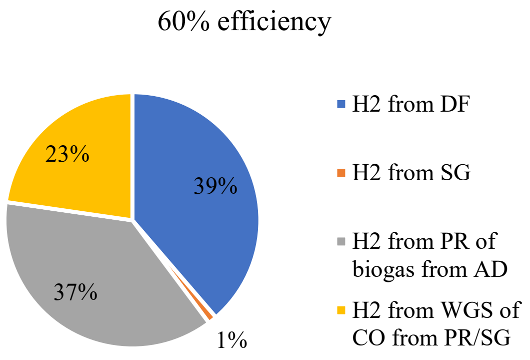
Figure A.78 shows the contributions of each stage to the total hydrogen production as a function of the conversion efficiency in the WGS stage. As the efficiency of the WGS decreases, the role of PR and DF increases because, with the assumptions of the base case, these stages are the main producers of hydrogen in the absence or with lower efficiency of the WGS reaction.

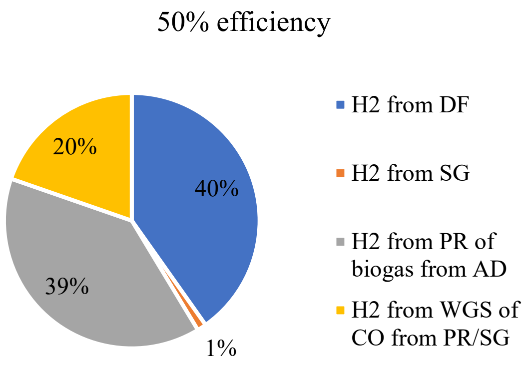

100% efficiency
34%
1%
32%
33%
■ H2 from DF
■ H2 from SG
■ H2 from PR of biogas from AD
■ H2 from WGS of CO from PR/SG

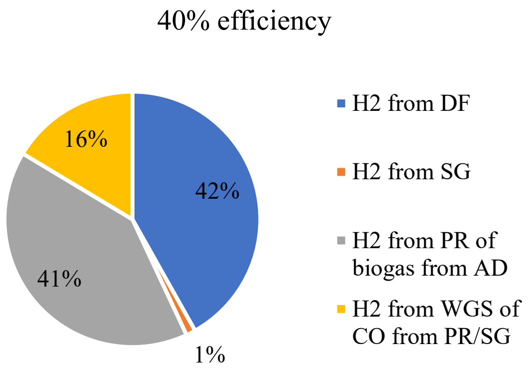

90% efficiency
35%
1%
34%
30%
■ H2 from DF
■ H2 from SG
■ H2 from PR of biogas from AD
■ H2 from WGS of CO from PR/SG

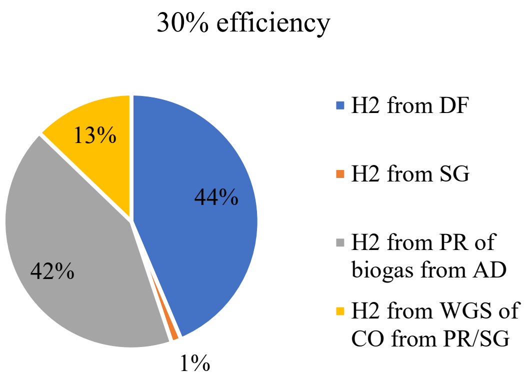

80% efficiency
36%
1%
35%
28%
■ H2 from DF
■ H2 from SG
■ H2 from PR of biogas from AD
■ H2 from WGS of CO from PR/SG


70% efficiency
37%
1%
36%
26%
■ H2 from DF
■ H2 from SG
■ H2 from PR of biogas from AD
■ H2 from WGS of CO from PR/SG


60% efficiency
39%
1%
37%
23%
■ H2 from DF
■ H2 from SG
■ H2 from PR of biogas from AD
■ H2 from WGS of CO from PR/SG


50% efficiency
40%
1%
39%
20%
■ H2 from DF
■ H2 from SG
■ H2 from PR of biogas from AD
■ H2 from WGS of CO from PR/SG


40% efficiency
42%
1%
41%
16%
■ H2 from DF
■ H2 from SG
■ H2 from PR of biogas from AD
■ H2 from WGS of CO from PR/SG


30% efficiency
44%
1%
42%
13%
■ H2 from DF
■ H2 from SG
■ H2 from PR of biogas from AD
■ H2 from WGS of CO from PR/SG

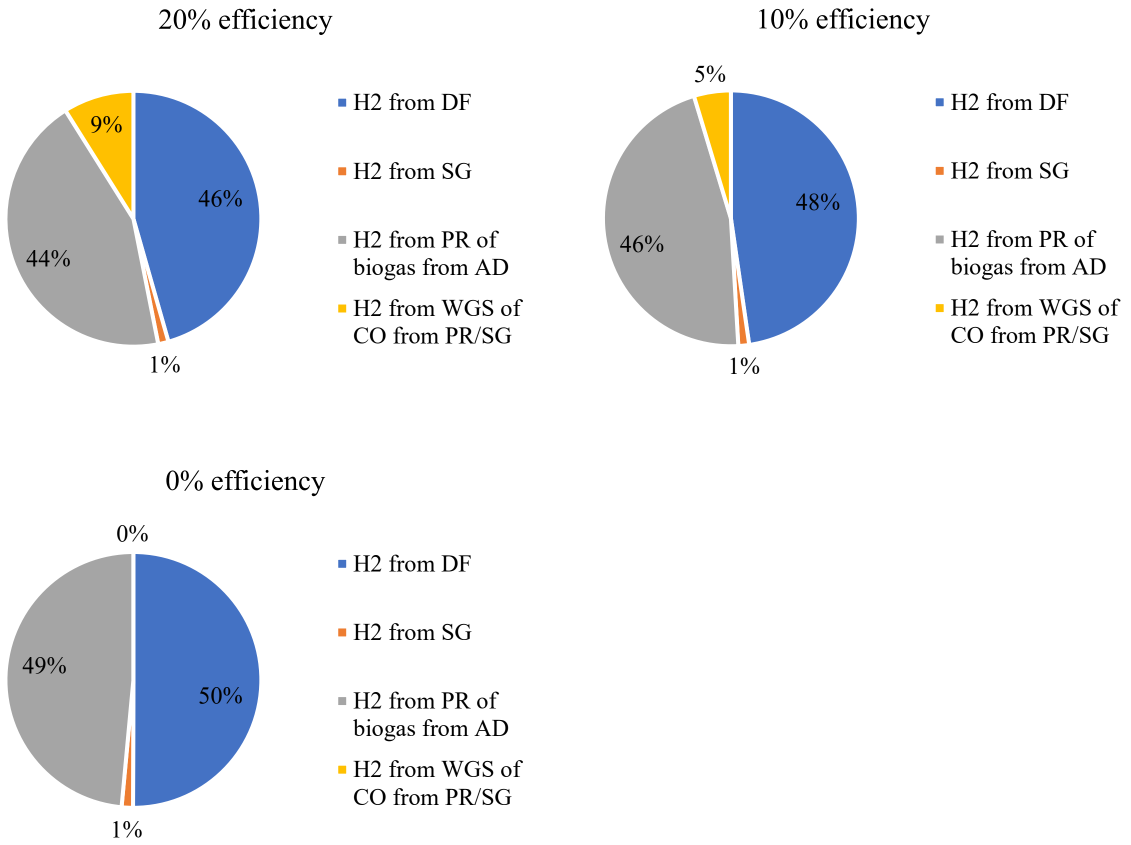


Figure A.78. Effect of the assumptions on the efficiency of the WGS stage on the contribution of each stage to total hydrogen production

A.2.5.6 50% efficiency at all stages

Figure A.79 shows the contribution of each stage to the total hydrogen production under the assumption that the efficiency of each stage is 50 % of the base case. Compared to the contributions for the base case (Figure A.1) the main difference is the higher role of SG, which is due to the higher amount of organic matter leaving AD and which is then converted in the SG stage. Note that with 50 % efficiency of each stage the total hydrogen production is significantly lower than for the base case, as reported earlier.

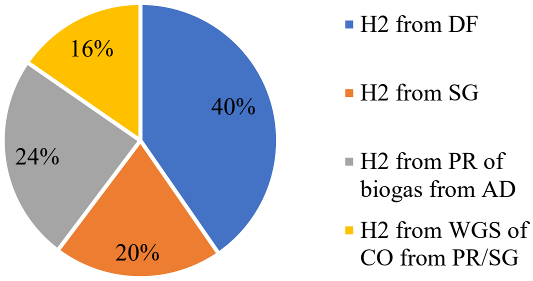
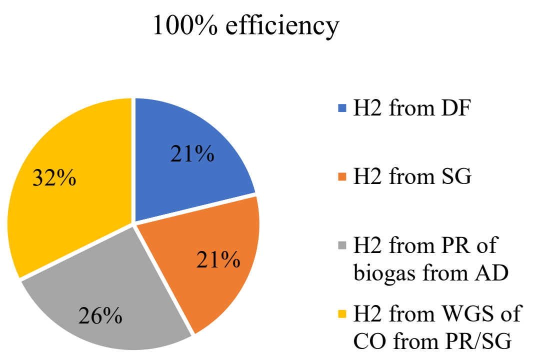
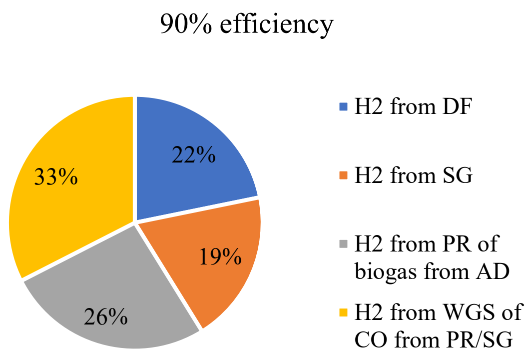


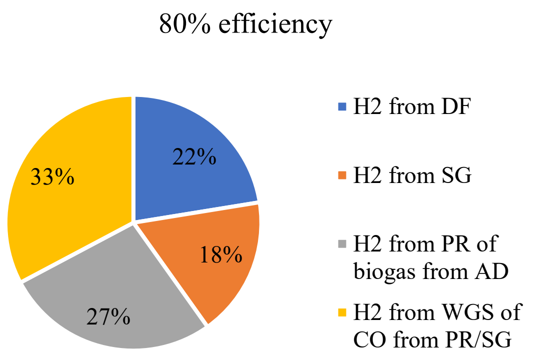
Figure A.79. Contribution of each stage to total hydrogen production for an efficiency of each stage of 50 %.

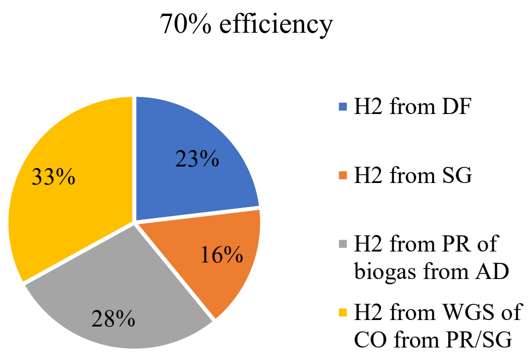
A.2.5.7 Steam gasification with 50% non-biodegradable organic matter in dark fermentation and anaerobic digestion

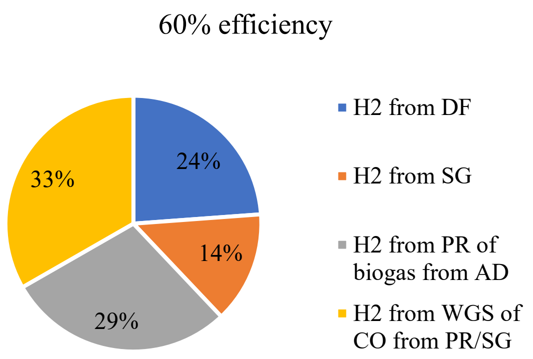
Figure A.80 shows how the assumptions on the efficiency of the SG stage influence the contributions of each stage to the total hydrogen production, under the assumption of 50 % efficiency of the biological stages. The main effect is that, as the efficiency of SG reduces, the role of DF and PR increases of importance, however the total hydrogen production reduces as observed earlier.

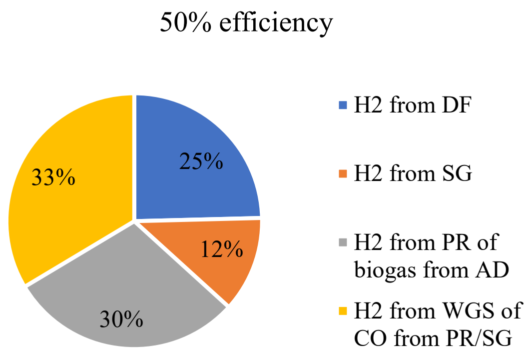

100% efficiency
21%
21%
26%
32%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG

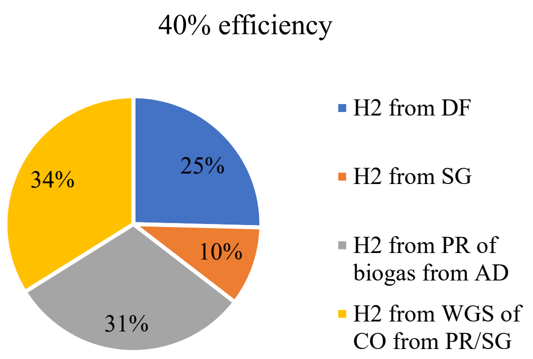

90% efficiency
22%
19%
26%
33%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG

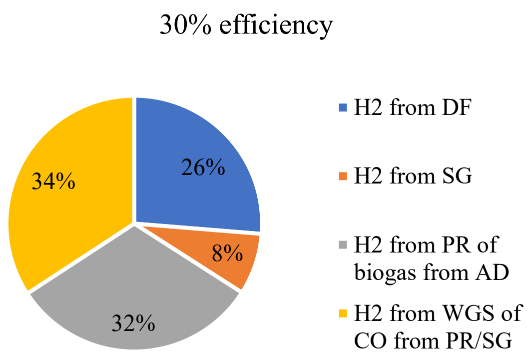

80% efficiency
22%
18%
27%
33%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG


70% efficiency
23%
16%
28%
33%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG


60% efficiency
24%
14%
29%
33%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG


50% efficiency
25%
12%
30%
33%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG


40% efficiency
25%
10%
31%
34%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG


30% efficiency
26%
8%
32%
34%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG

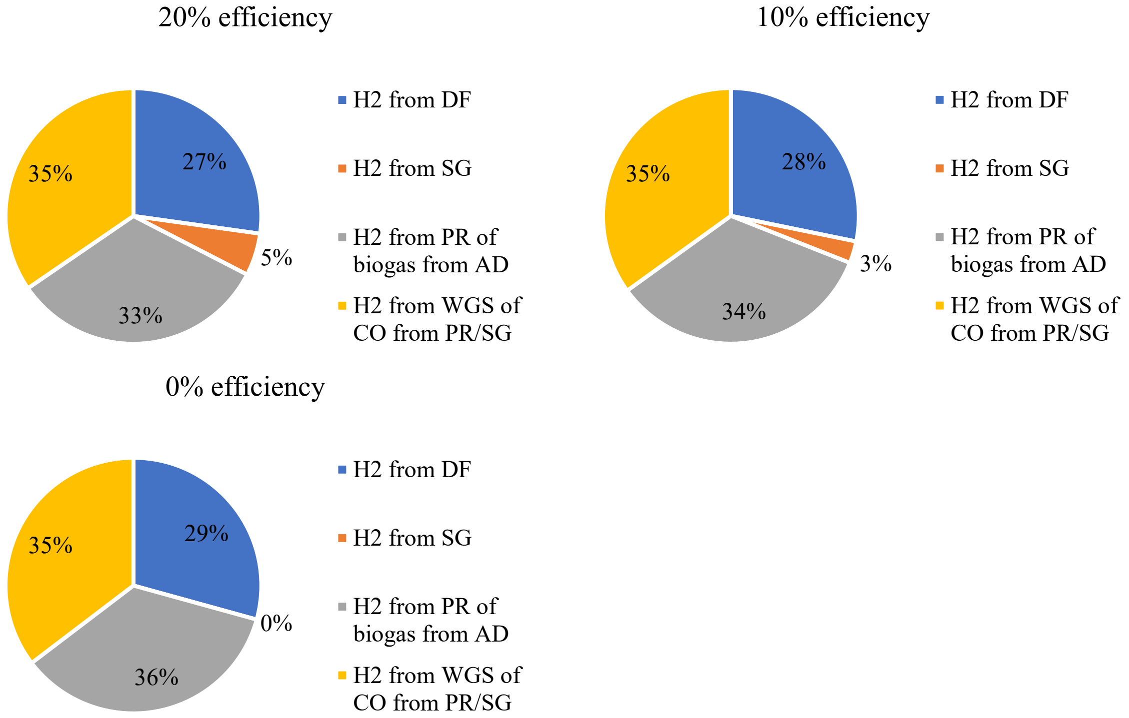


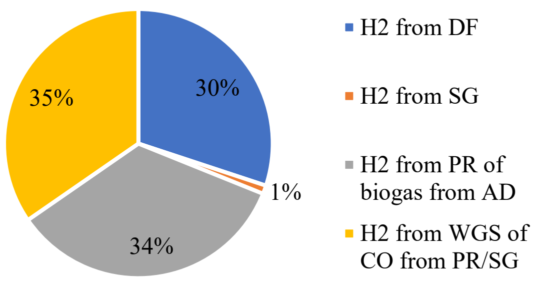
Figure A.80. Effect of the assumptions on the efficiency of the SG stage on the contribution of each stage to total hydrogen production, assuming 50 % efficiency for the biological stages.

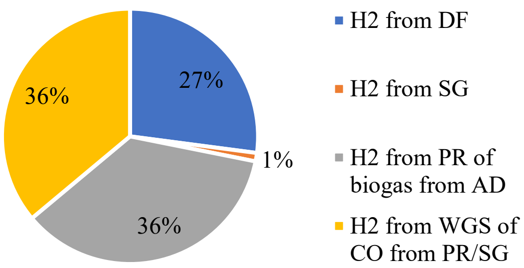
A.2.6 Hydrogen production by process stage with food waste (lipids)

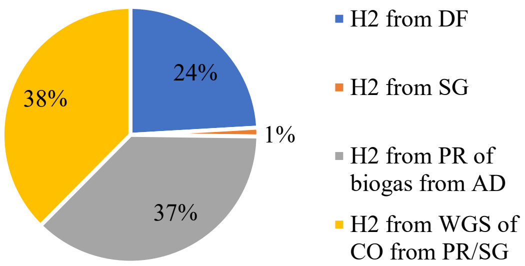
This section shows the contributions of each stage to the total hydrogen production under the assumption that the organic matter is composed of lipids with the same empirical formula as oleic acid. These assumptions are explained in sections 1 and A.1. Apart from the chemical composition of the organic matter, the other assumptions and the presentation of the results are the same as in Section A.2.5. Generally, the trends observed are similar to those observed with carbohydrate feedstock in Section A.2.5.

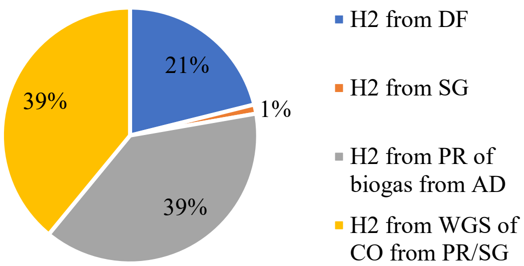
A.2.6.1 Dark fermentation

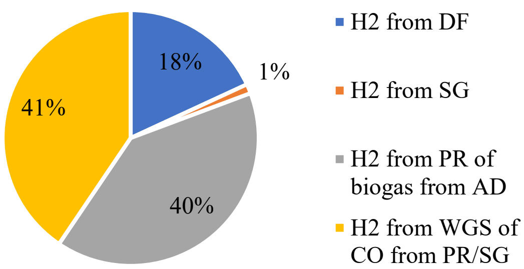
Figure A.81 shows the contributions of each stage to the total hydrogen production as a function of the conversion efficiency in the DF stage. The results are similar, although not identical, as those reported in section A.2.5.1 for an organic matter composed of carbohydrates. As the conversion efficiency decreases (higher fraction of non-biodegradable organic matter) the contribution of DF decreases, as expected, with a corresponding increase in the role of WGS and PR. Comparing Figure A.81 with Figure A.74, it can be noted that the contribution of DF when the organic matter is made of lipids is slightly lower than when the organic matter is made of carbohydrates. This is due to the different empirical formula of carbohydrates and lipids, which cause a slightly higher role of AD in the energy conversion of the feedstock.

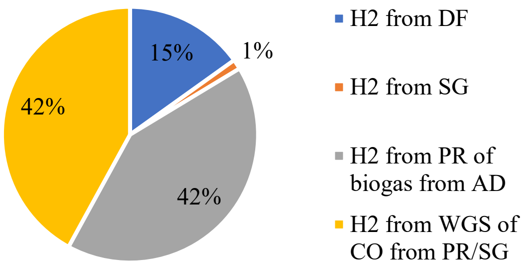

0% non-biodegradable

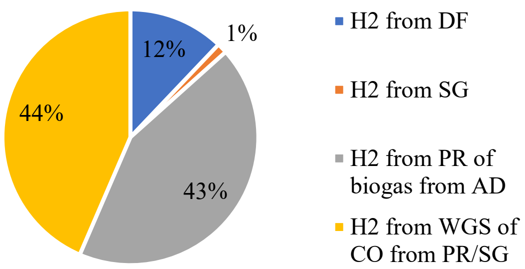

10% non-biodegradable

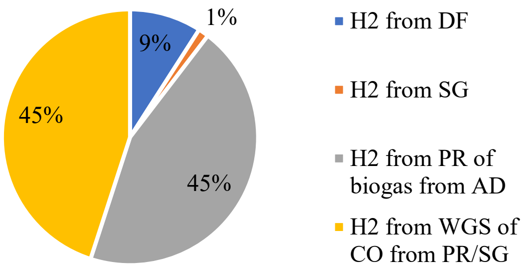

20% non-biodegradable


30% non-biodegradable


40% non-biodegradable


50% non-biodegradable


60% non-biodegradable


70% non-biodegradable

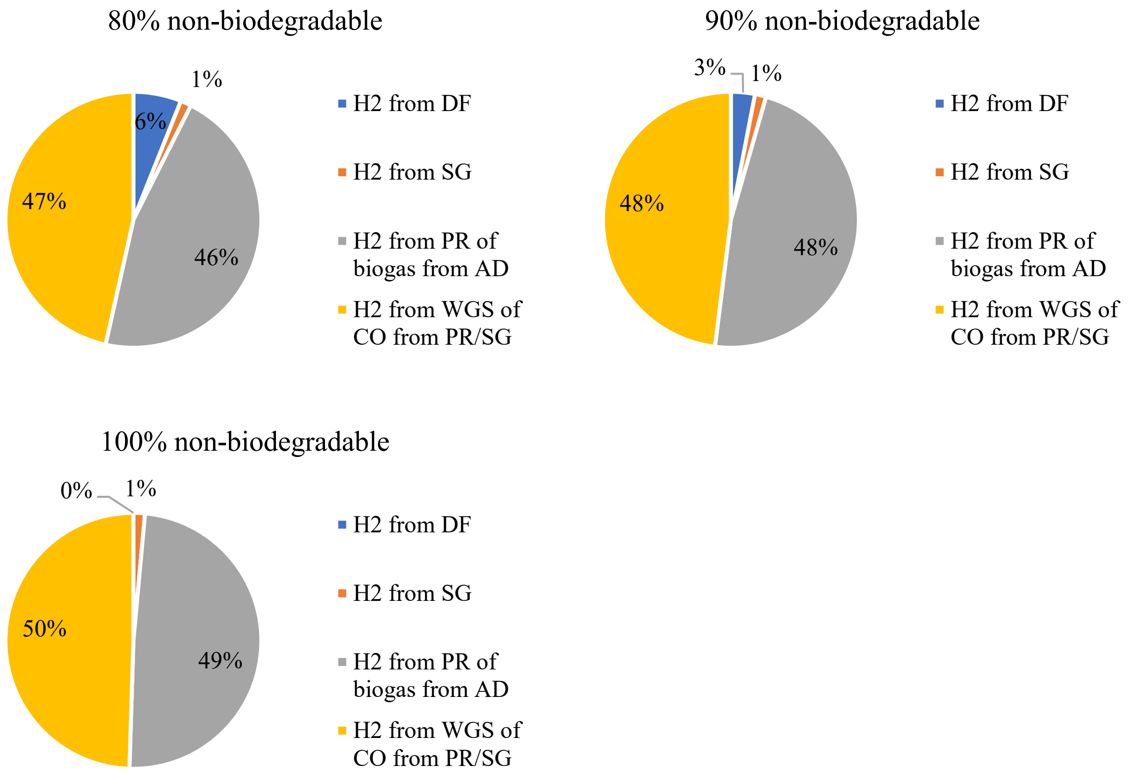
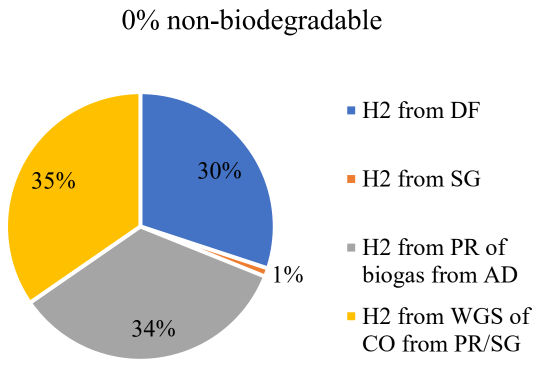
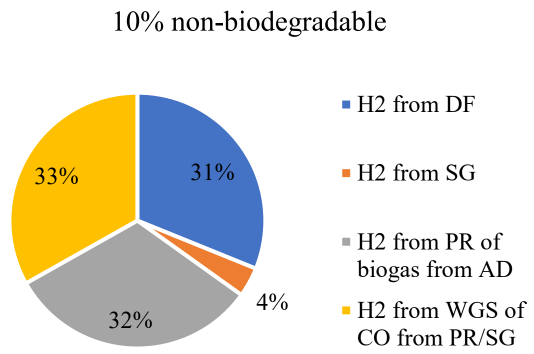


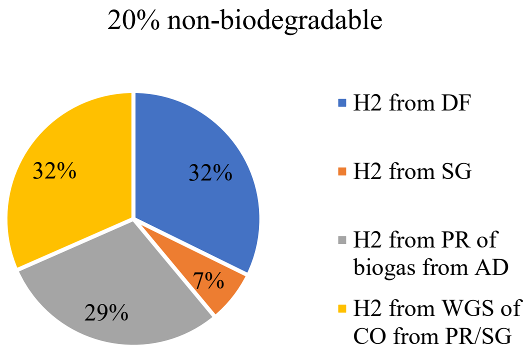
Figure A.81. Effect of the assumptions on the non-biodegradable fraction of the organic matter in DF on the contribution of each stage to total hydrogen production (organic matter made of lipids).

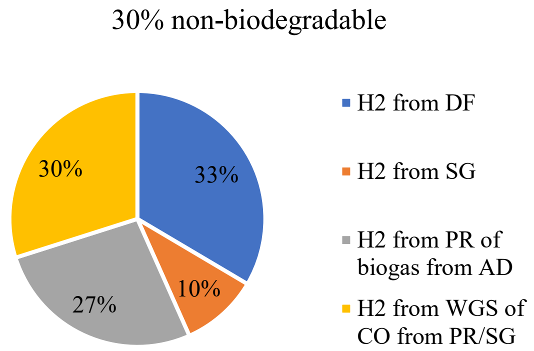
A.2.6.2 Anaerobic digestion

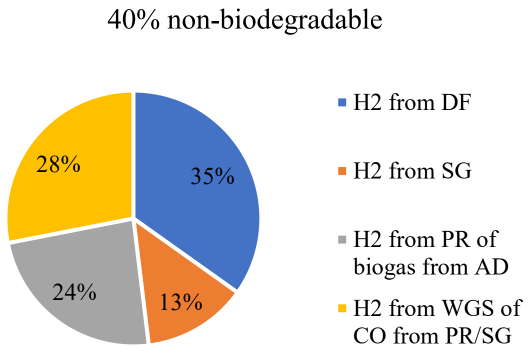
Figure A.82 shows the contributions of each stage to the total hydrogen production as a function of the conversion efficiency in the AD stage. The results are similar, although not identical, as those reported in section A.2.5.2 for an organic matter composed of carbohydrates. As the conversion efficiency decreases (higher fraction of non-biodegradable organic matter) the contribution of AD/PR decreases, as expected, with a corresponding increase in the role of SG. Comparing Figure A.82 with Figure A.75 which refers to organic matter made of carbohydrates, it can be observed the slightly higher role of SG when the organic matter is made of lipids. This is due to the chemistry of the DF and AD reactions for lipids and carbohydrates, based on which a slightly higher fraction of the influent organic matter leaves the DF stages with lipid than with carbohydrate feedstock.

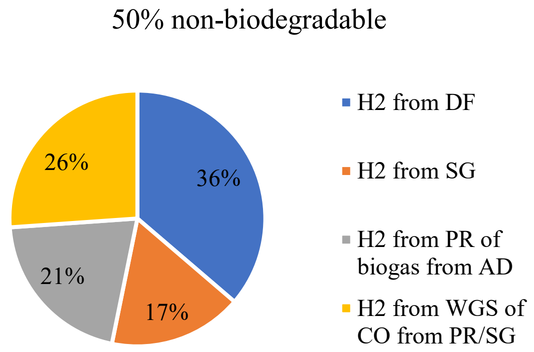

0% non-biodegradable
35%
30%
1%
34%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG

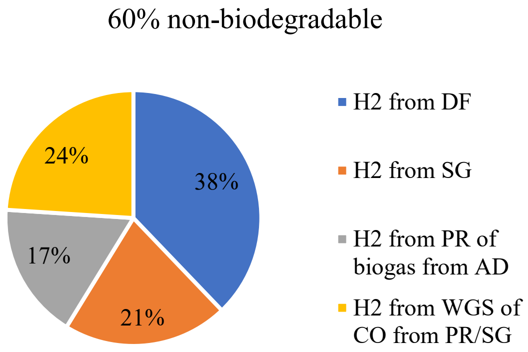

10% non-biodegradable
33%
31%
4%
32%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG

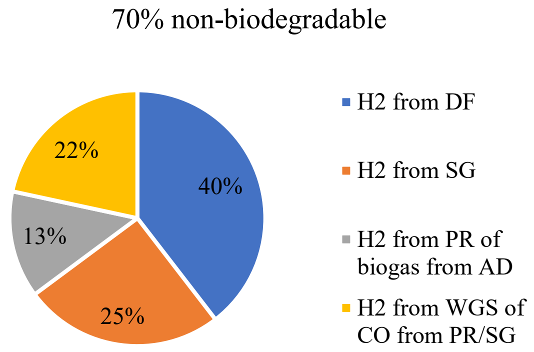

20% non-biodegradable
32%
32%
7%
29%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG


30% non-biodegradable
30%
33%
10%
27%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG


40% non-biodegradable
28%
35%
24%
13%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG


50% non-biodegradable
26%
36%
21%
17%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG


60% non-biodegradable
24%
38%
17%
21%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG


70% non-biodegradable
22%
40%
13%
25%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG

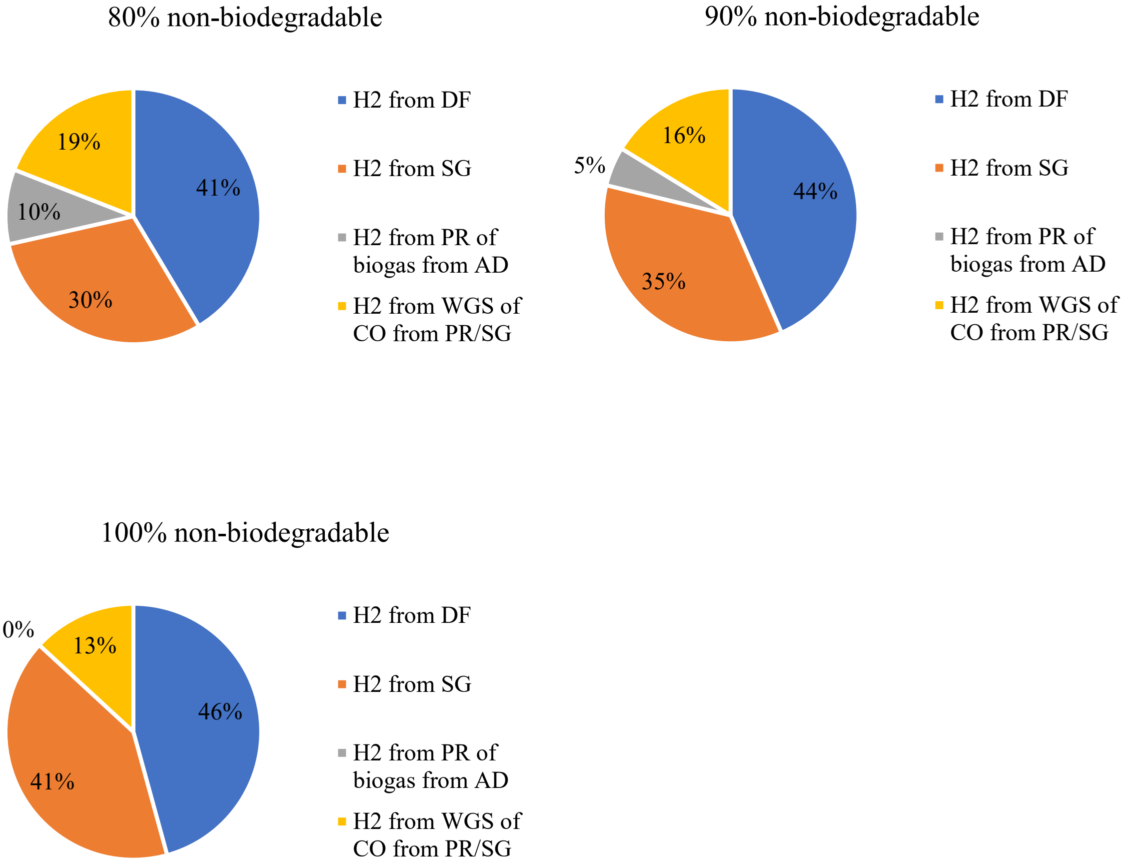
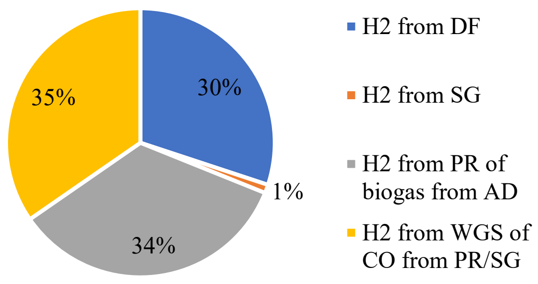


Figure A.82. Effect of the assumptions on the non-biodegradable fraction of the organic matter in AD on the contribution of each stage to total hydrogen production (organic matter made of lipids).

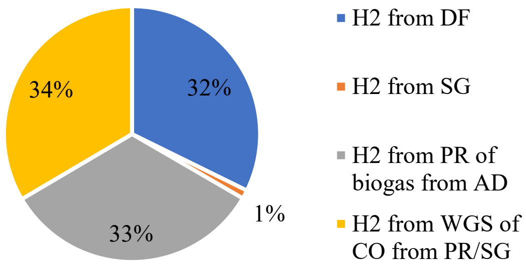
A.2.6.3 Plasma reforming

Figure A.83 shows the contributions of each stage to the total hydrogen production as a function of the conversion efficiency in the PR stage. The results are similar to those reported in Section A.2.5.3 for carbohydrate feedstock and the same observations can also be made here.

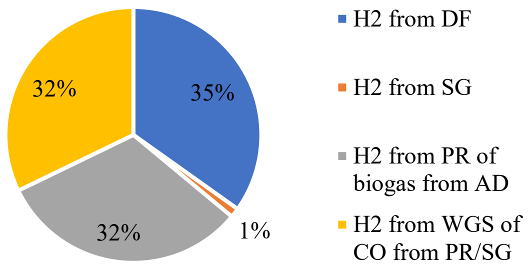
100% efficiency



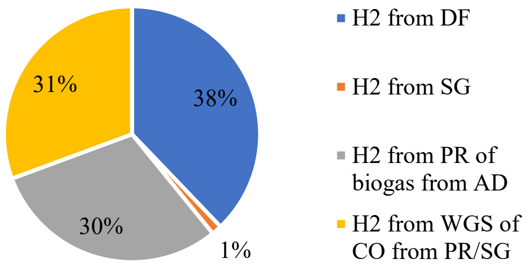
90% efficiency



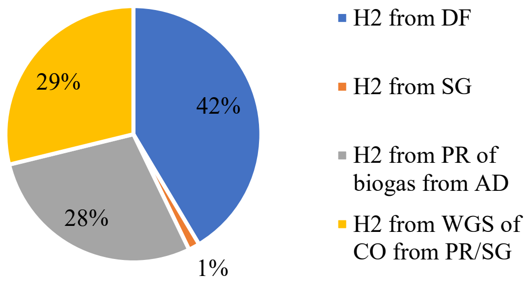
80% efficiency



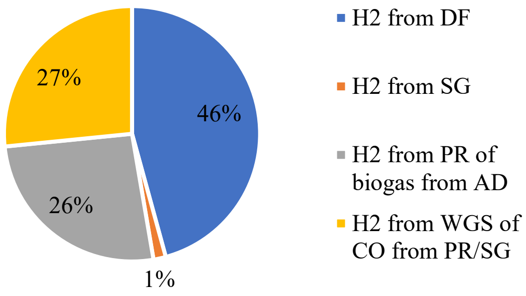
70% efficiency



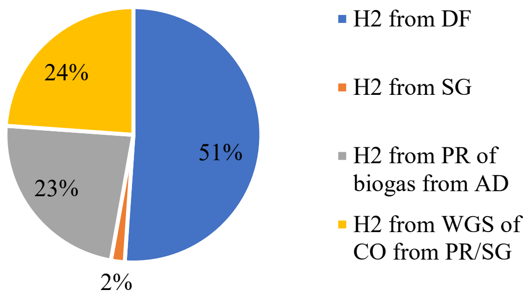
60% efficiency



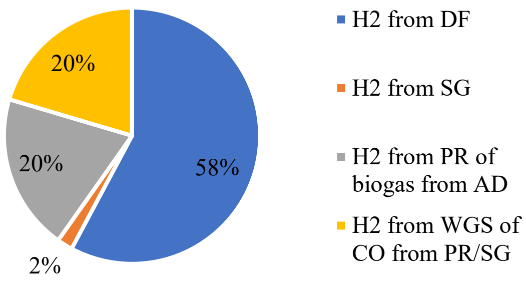
50% efficiency



40% efficiency



30% efficiency



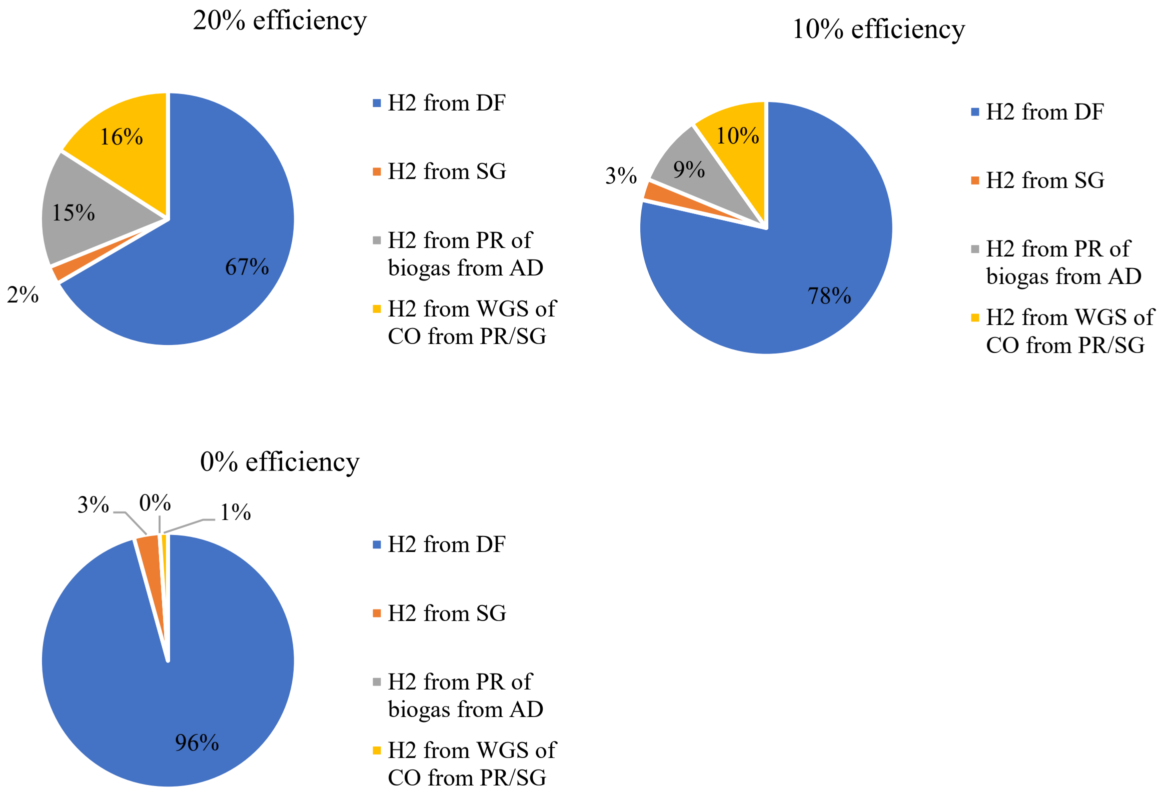
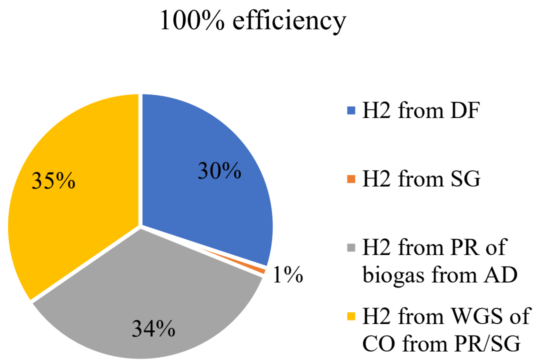
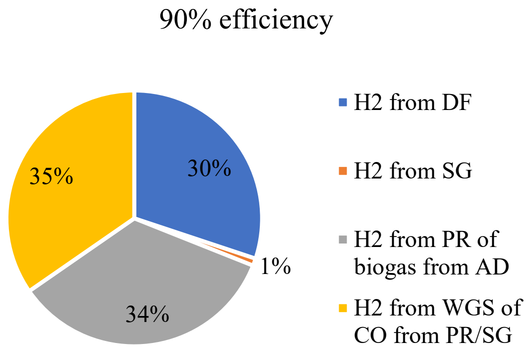


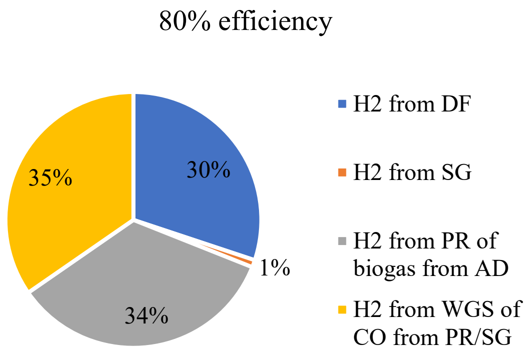
Figure A.83. Effect of the assumptions on the efficiency of PR on the contribution of each stage to total hydrogen production (organic matter made of lipids).

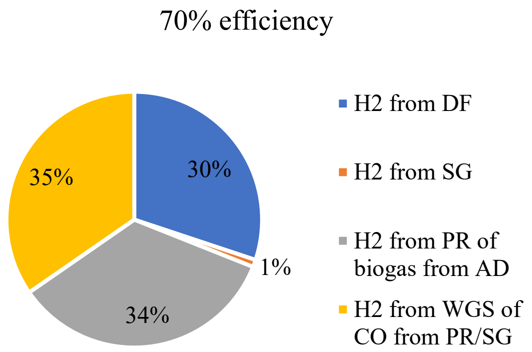
A.2.6.4 Steam gasification

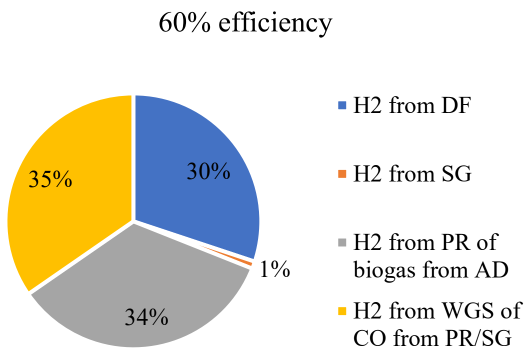
Figure A.84 shows the contributions of each stage to the total hydrogen production as a function of the conversion efficiency in the SG stage. The results are similar to those reported in Section A.2.5.4 for carbohydrate feedstock, with the slight difference in the role of DF and AD, which derives from the different empirical formula of carbohydrates and lipids as observed above.

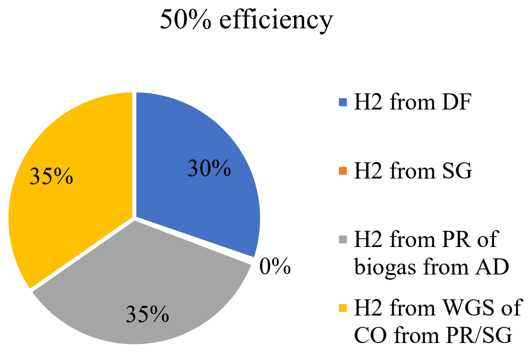

100% efficiency
35%
30%
1%
34%
■ H2 from DF
■ H2 from SG
■ H2 from PR of biogas from AD
■ H2 from WGS of CO from PR/SG

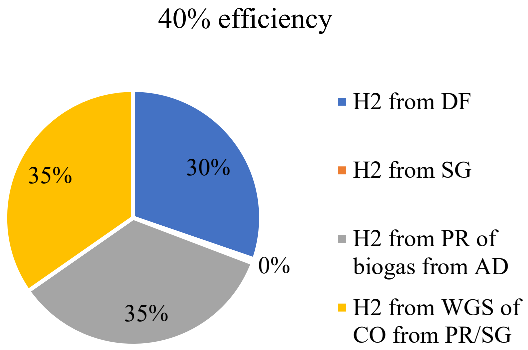

90% efficiency
35%
30%
1%
34%
■ H2 from DF
■ H2 from SG
■ H2 from PR of biogas from AD
■ H2 from WGS of CO from PR/SG

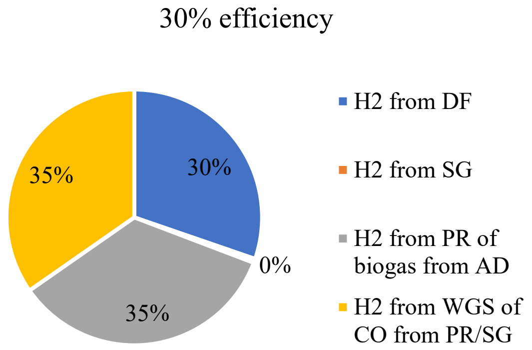

80% efficiency
35%
30%
1%
34%
■ H2 from DF
■ H2 from SG
■ H2 from PR of biogas from AD
■ H2 from WGS of CO from PR/SG


70% efficiency
35%
30%
1%
34%
■ H2 from DF
■ H2 from SG
■ H2 from PR of biogas from AD
■ H2 from WGS of CO from PR/SG


60% efficiency
35%
30%
1%
34%
■ H2 from DF
■ H2 from SG
■ H2 from PR of biogas from AD
■ H2 from WGS of CO from PR/SG


50% efficiency
35%
30%
0%
35%
■ H2 from DF
■ H2 from SG
■ H2 from PR of biogas from AD
■ H2 from WGS of CO from PR/SG


40% efficiency
35%
30%
0%
35%
■ H2 from DF
■ H2 from SG
■ H2 from PR of biogas from AD
■ H2 from WGS of CO from PR/SG


30% efficiency
35%
30%
0%
35%
■ H2 from DF
■ H2 from SG
■ H2 from PR of biogas from AD
■ H2 from WGS of CO from PR/SG

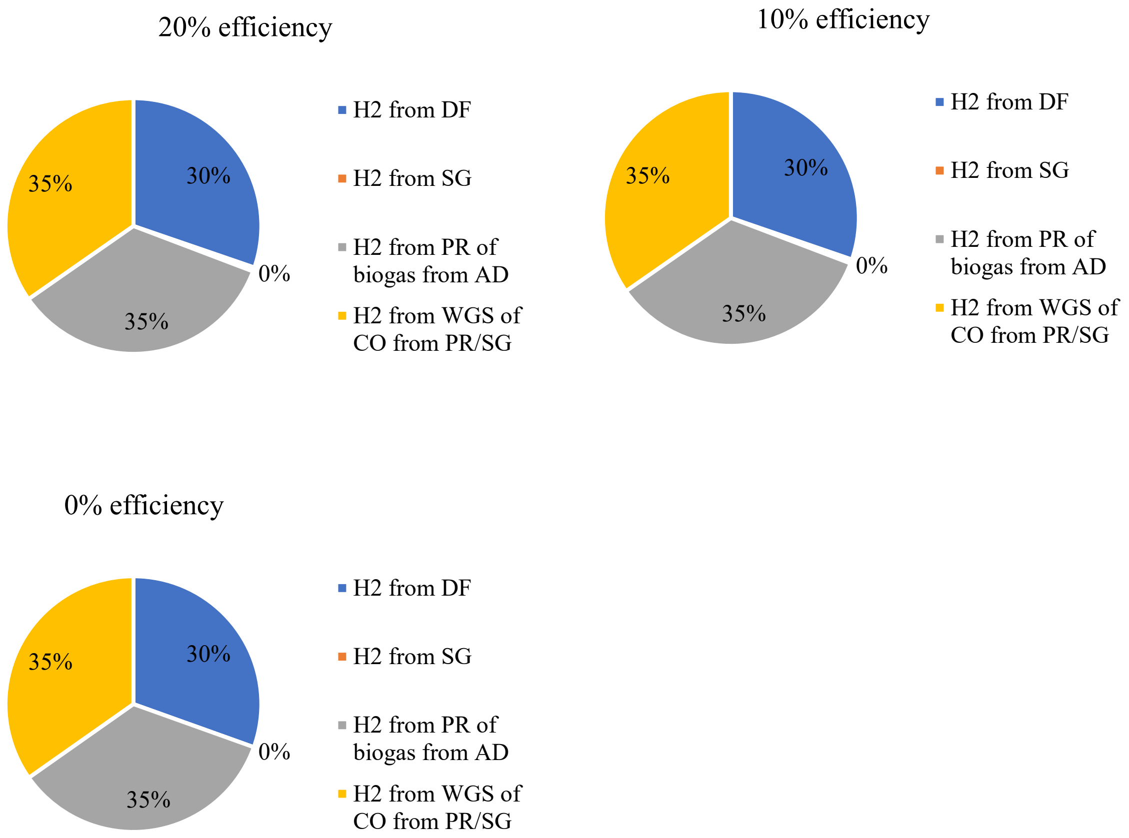
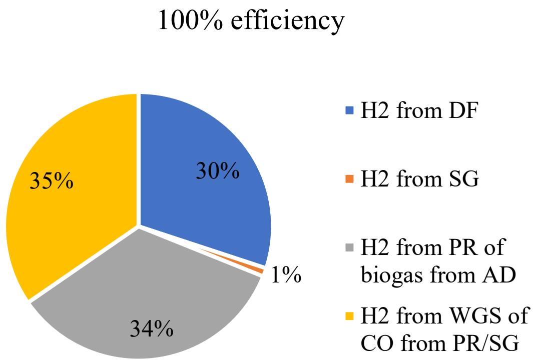
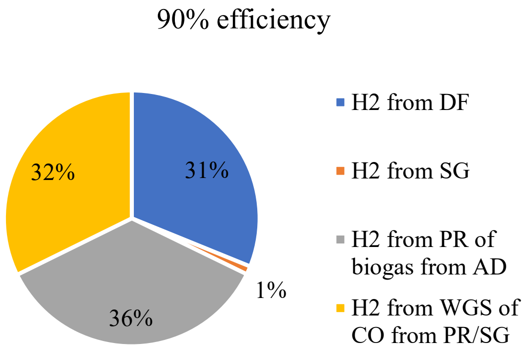


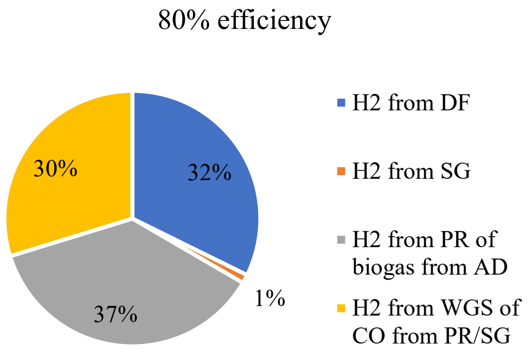
Figure A.84. Effect of the assumptions on the efficiency of SG on the contribution of each stage to total hydrogen production (organic matter made of lipids).

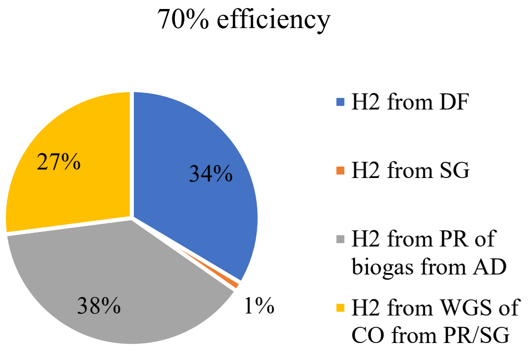
A.2.6.5 Water gas shift

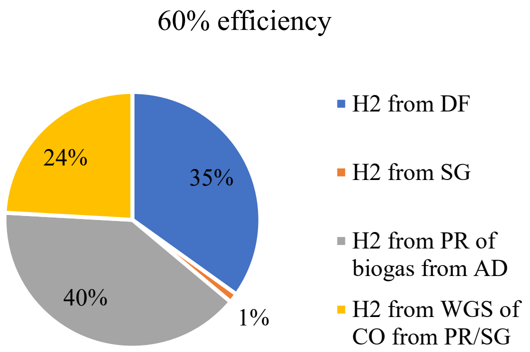
Figure A.85 shows the contributions of each stage to the total hydrogen production as a function of the conversion efficiency in the WGS stage. The observed trends are similar to those reported in Section A.2.5.5 for carbohydrate feedstock and the same observations can also be made here.

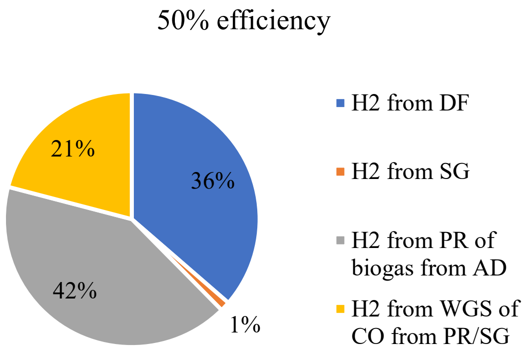

100% efficiency
35%
30%
1%
34%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG

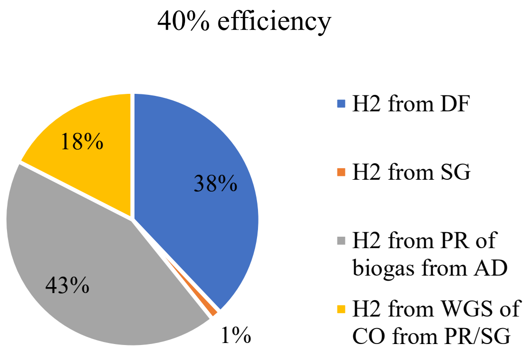

90% efficiency
32%
31%
1%
36%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG

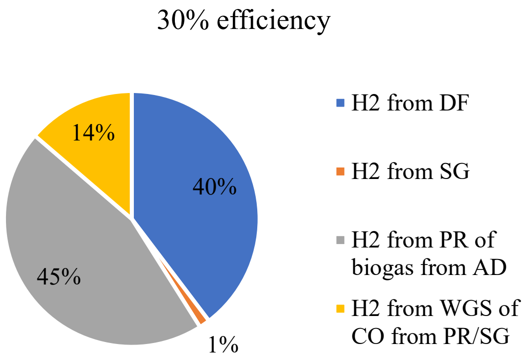

80% efficiency
30%
32%
1%
37%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG


70% efficiency
27%
34%
1%
38%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG


60% efficiency
24%
35%
1%
40%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG


50% efficiency
21%
36%
1%
42%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG


40% efficiency
18%
38%
1%
43%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG


30% efficiency
14%
40%
1%
45%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG

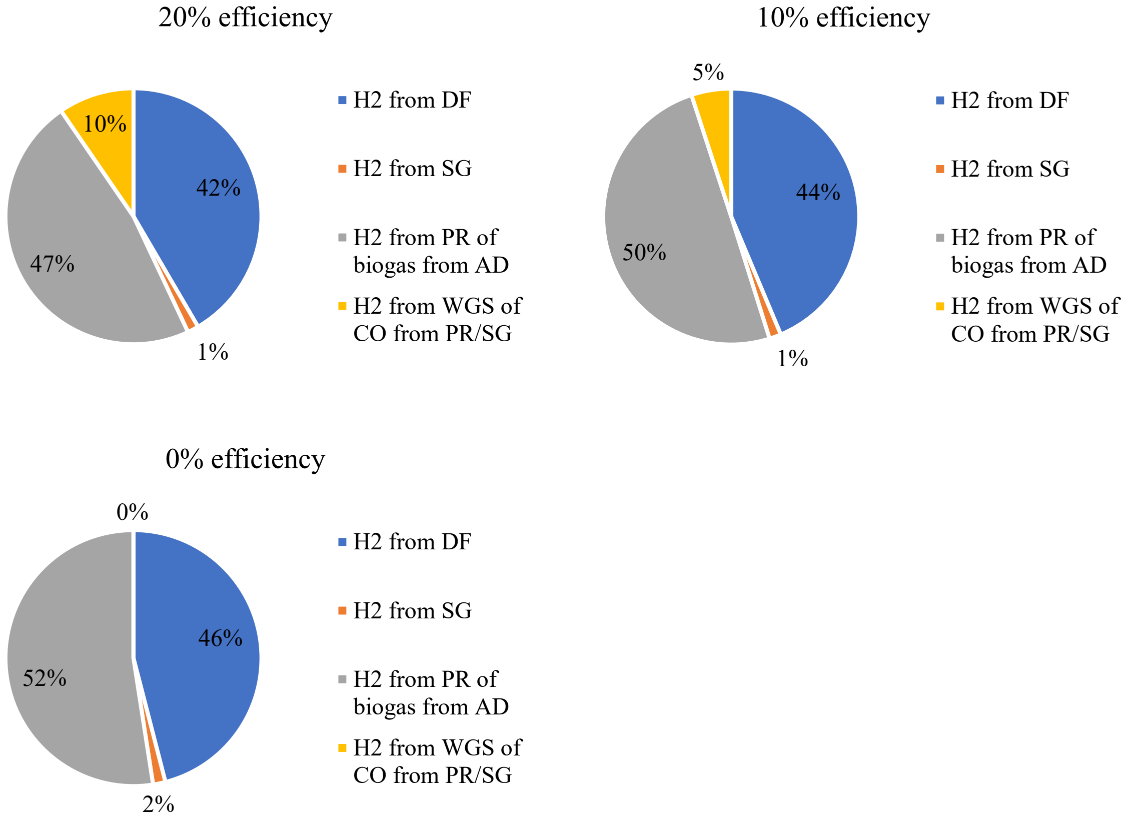


Figure A.85. Effect of the assumptions on the efficiency of WGS on the contribution of each stage to total hydrogen production (organic matter made of lipids).

A.2.6.6 50% efficiency at all stages

Figure A.86 shows the contribution of each stage to the total hydrogen production when the efficiency of each stage is 50 % than what was assumed for the base case. The results are similar to those reported in Section A.2.5.6 and in Figure A.79 for the carbohydrate feed, with a slightly higher role of PR/AD for the lipid feed, which is due to the different empirical formula of lipid and carbohydrates, as observed in previous sections.

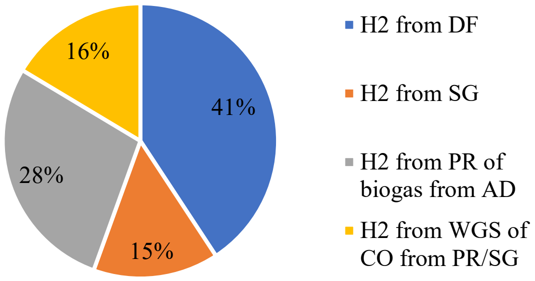
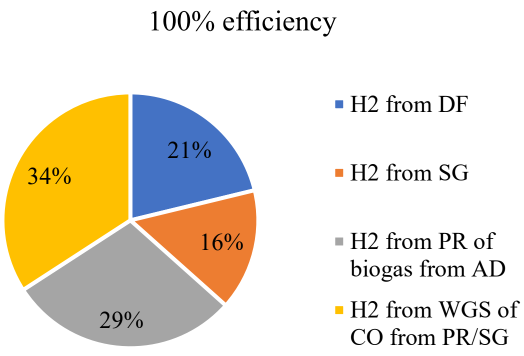
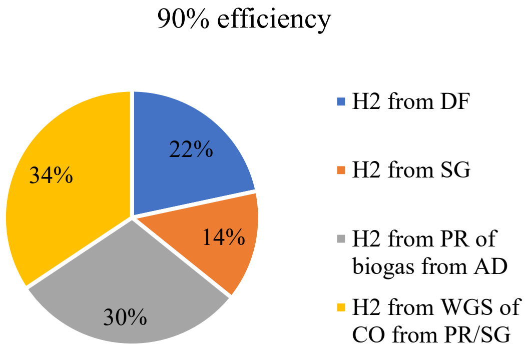


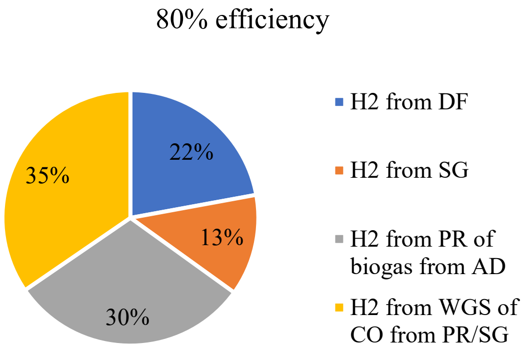
Figure A.86. Contribution of each stage to the total hydrogen production when the efficiency of each stage is 50 % than the assumed efficiency for the base case (organic matter made of lipids).

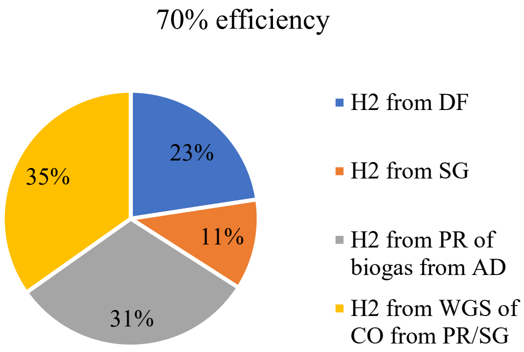
A.2.6.7 Steam gasification with 50% non-biodegradable organic matter in dark fermentation and anaerobic digestion

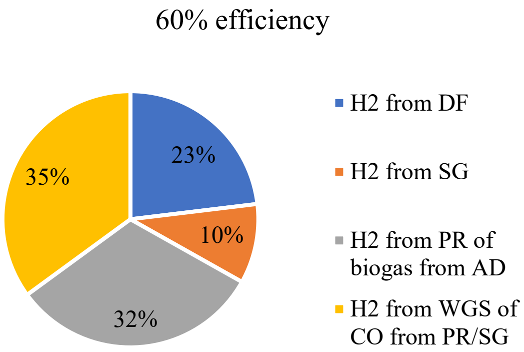
Similarly to what reported for carbohydrate feedstock in Section A.2.5.7 and in Figure A.80, Figure A.87 shows how the assumptions on the efficiency of the SG stage influence the contributions of each stage to the total hydrogen production, under the assumption of 50 % efficiency of the biological stages with lipid feedstock. The trends are similar to what reported in Section A.2.5.7 and the same conclusions can be drawn.

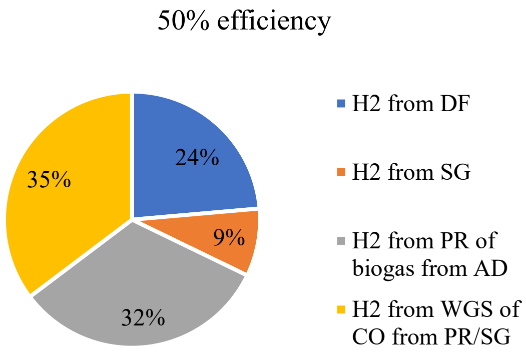

100% efficiency
21%
16%
29%
34%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG

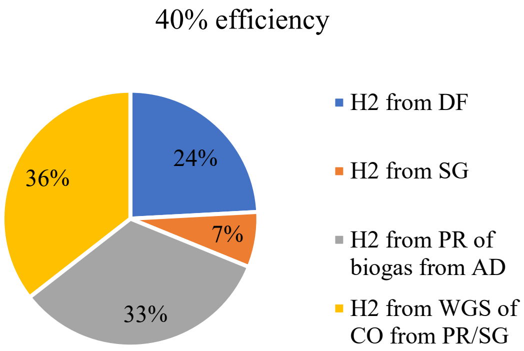

90% efficiency
22%
14%
30%
34%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG

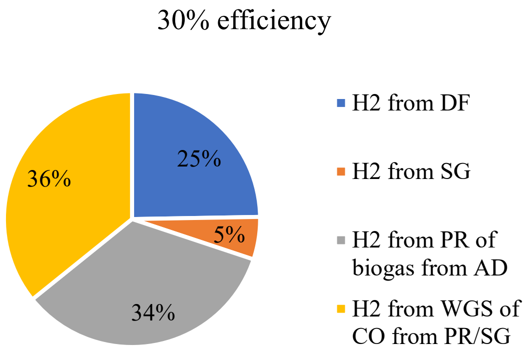

80% efficiency
22%
13%
30%
35%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG


70% efficiency
23%
11%
31%
35%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG


60% efficiency
23%
10%
32%
35%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG


50% efficiency
24%
9%
32%
35%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG


40% efficiency
24%
7%
33%
36%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG


30% efficiency
25%
5%
34%
36%
H2 from DF
H2 from SG
H2 from PR of biogas from AD
H2 from WGS of CO from PR/SG

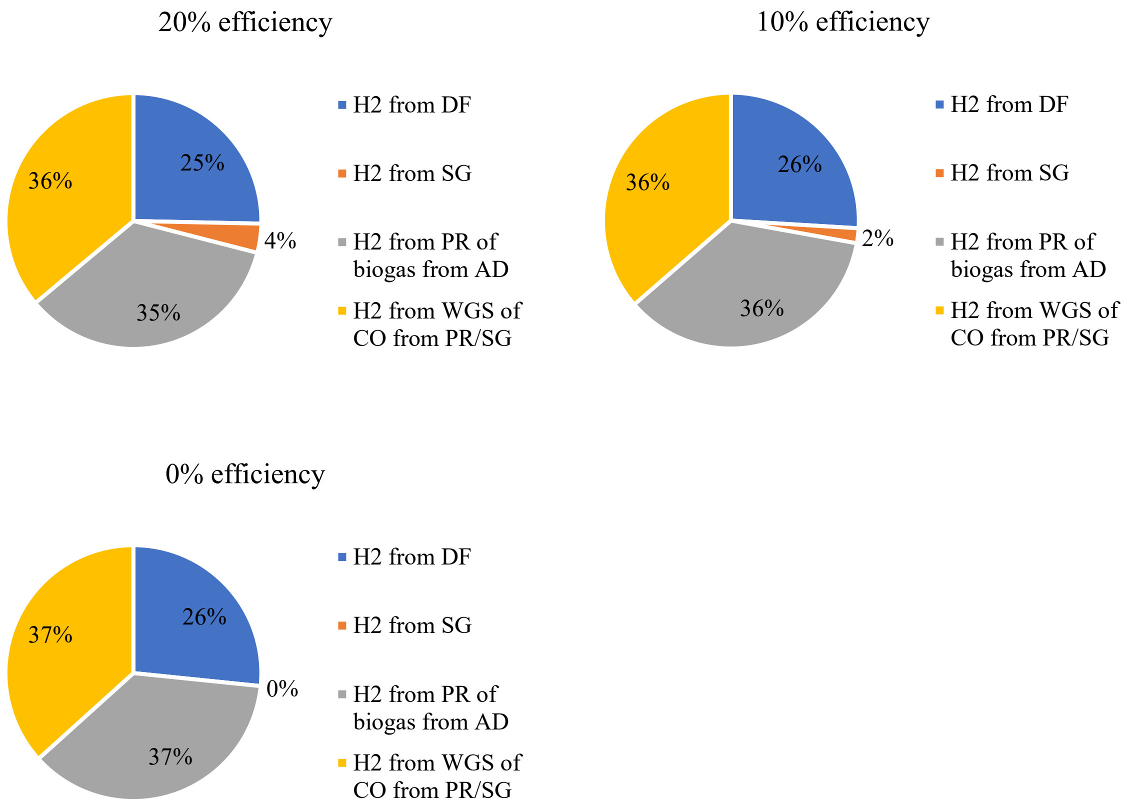


Figure A.87. Effect of the assumptions on the efficiency of the SG stage on the contribution of each stage to total hydrogen production, assuming 50 % efficiency for the biological stages (organic matter made of lipids).

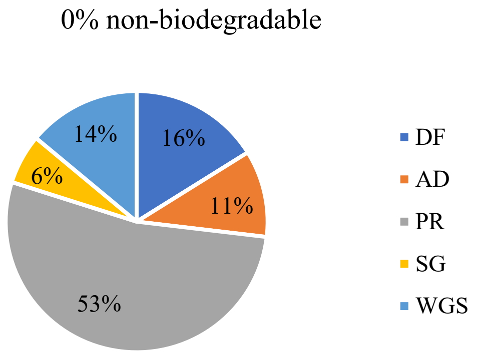
A.2.7 Energy consumption by process stage for food waste (carbohydrates)

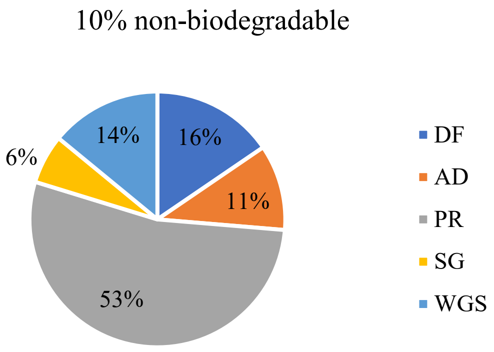
This section shows the individual contribution of each process stage to the total energy consumption of the process. Each subsection reports the fraction of the total energy consumption due to each stage, for different values of the efficiency of the stage named in the subsection title.

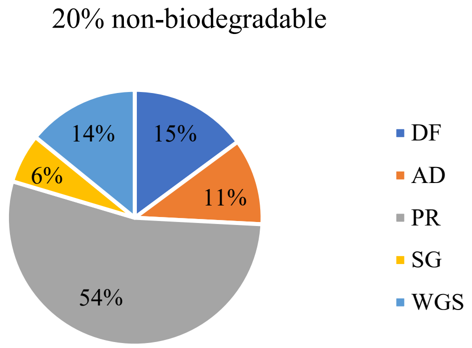
The following graphs illustrates the simulations for food waste assuming carbohydrates composition (COD factor 1.067). Note that the results shown in this section are also valid for the simulations of wastewater feedstock, as the composition of wastewater was assumed to be carbohydrates.

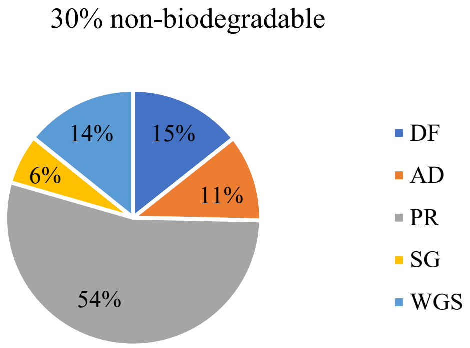
A.2.7.1 Dark fermentation

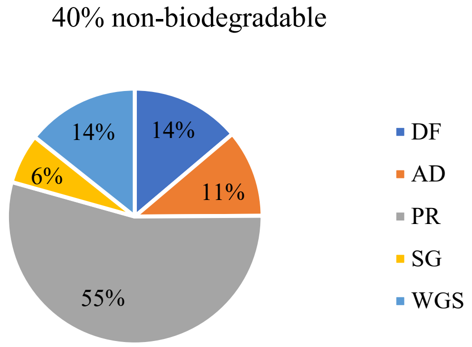
Figure A.88 shows the contribution of each stage to the total energy consumption of the process as a function of the non-biodegradable fraction of the organic matter in the DF stage. The figure shows only a very little effect of the efficiency of the DF stage, with a small increase in the role of PR due to the slightly larger production of methane in the AD stage.

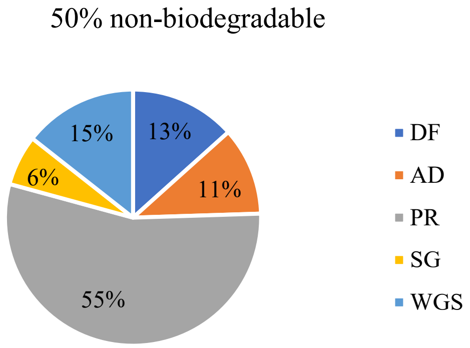

0% non-biodegradable
16%
11%
53%
6%
14%
DF
AD
PR
SG
WGS

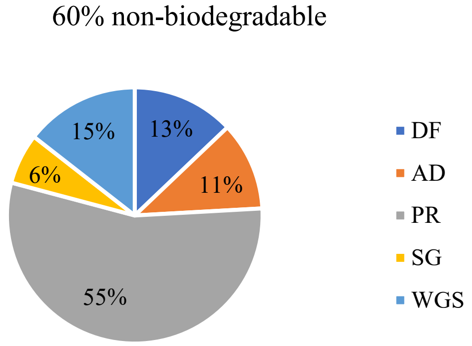

10% non-biodegradable
16%
11%
53%
6%
14%
DF
AD
PR
SG
WGS

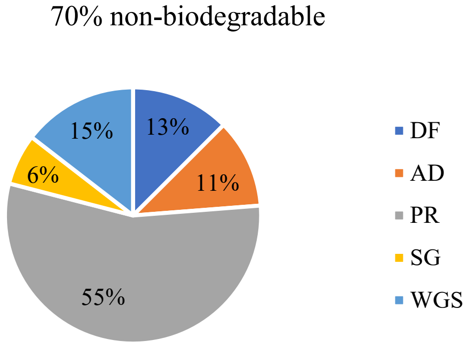

20% non-biodegradable
15%
11%
54%
6%
14%
DF
AD
PR
SG
WGS


30% non-biodegradable
15%
11%
54%
6%
14%
DF
AD
PR
SG
WGS


40% non-biodegradable
14%
11%
55%
6%
14%
DF
AD
PR
SG
WGS


50% non-biodegradable
13%
11%
55%
6%
15%
DF
AD
PR
SG
WGS


60% non-biodegradable
13%
11%
55%
6%
15%
DF
AD
PR
SG
WGS


70% non-biodegradable
13%
11%
55%
6%
15%
DF
AD
PR
SG
WGS

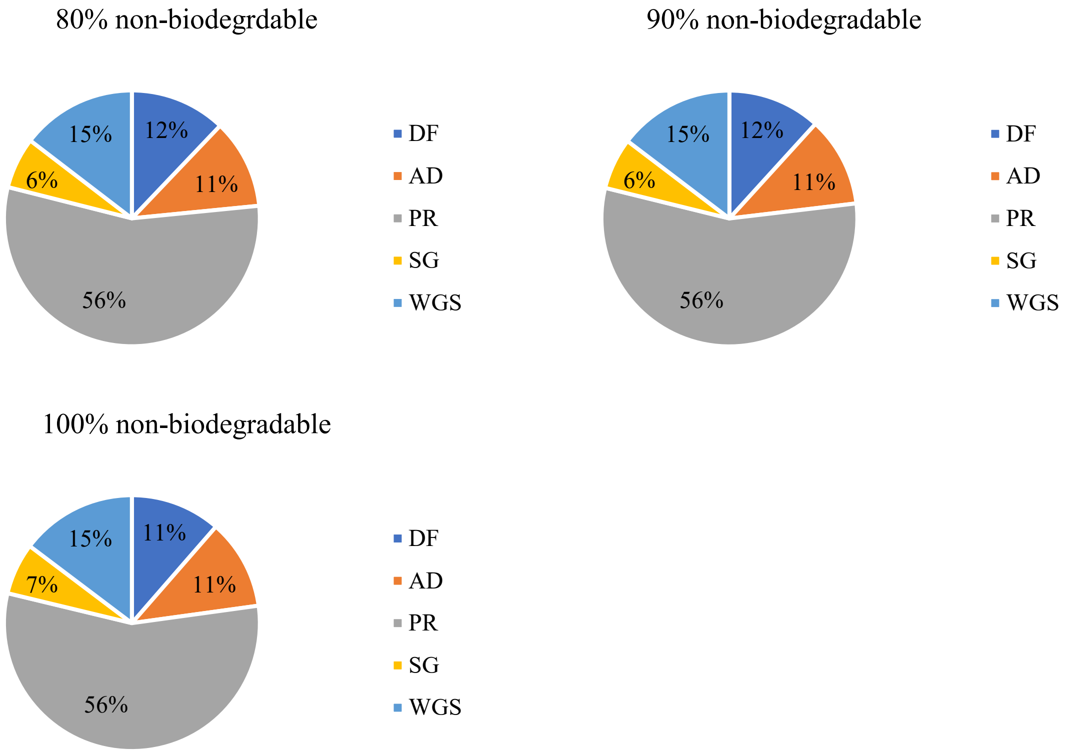
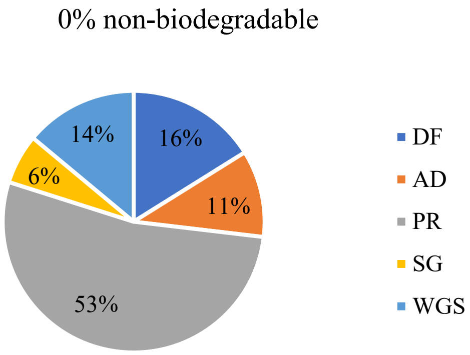
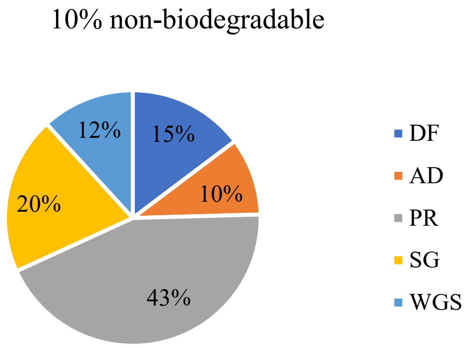


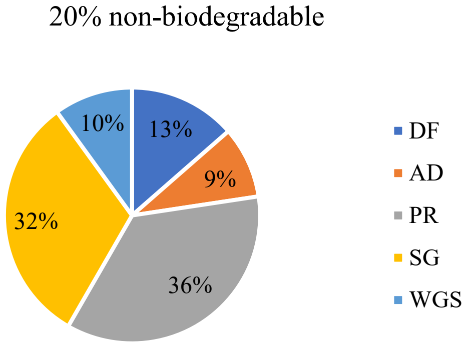
Figure A.88. Effect of the assumptions on the efficiency of the DF stage (non-biodegradable fraction in the feedstock) on the contribution of each stage to total energy consumption

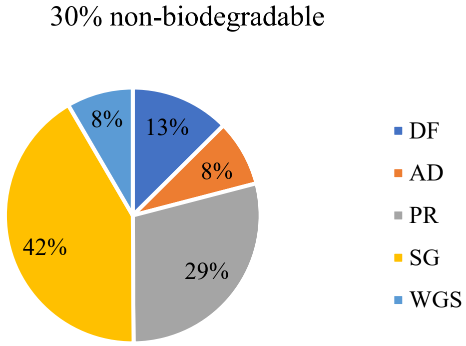
A.2.7.2 Anaerobic digestion

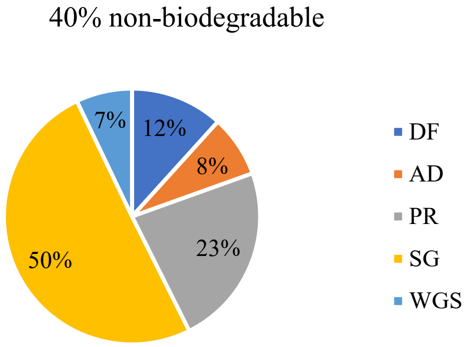
Figure A.89 shows the contribution of each stage to the total energy consumption of the process as a function of the non-biodegradable fraction of the organic matter in the AD stage. The figure shows a very large increase of the role of the SG stage. This is due to the fact that, as the efficiency of AD decreases (larger fraction of non-biodegradable organic matter), more organic matter needs to be processed in the SG stage, with a consequent higher consumption of steam and higher contribution of this stage to the total energy consumption.

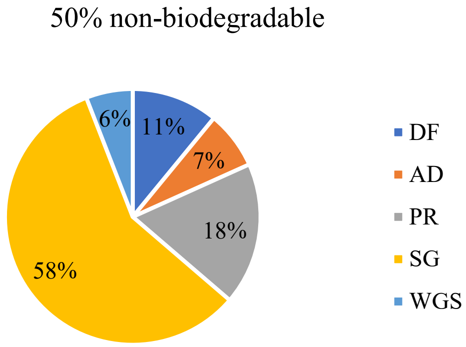

0% non-biodegradable
16%
11%
53%
6%
14%
DF
AD
PR
SG
WGS

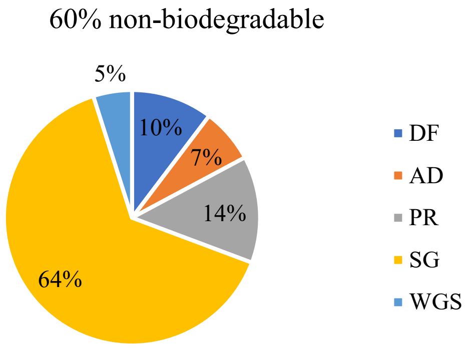

10% non-biodegradable
15%
10%
43%
20%
12%
DF
AD
PR
SG
WGS

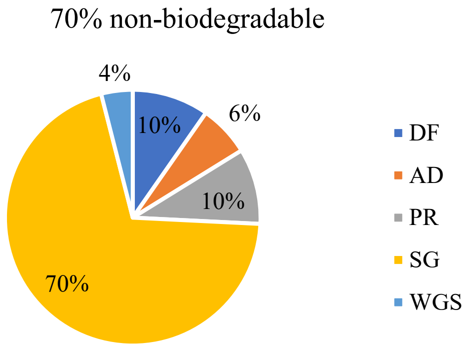

20% non-biodegradable
13%
9%
36%
32%
10%
DF
AD
PR
SG
WGS


30% non-biodegradable
13%
8%
29%
42%
8%
DF
AD
PR
SG
WGS


40% non-biodegradable
12%
8%
23%
50%
7%
DF
AD
PR
SG
WGS


50% non-biodegradable
11%
7%
18%
58%
6%
DF
AD
PR
SG
WGS


60% non-biodegradable
10%
7%
14%
64%
5%
DF
AD
PR
SG
WGS


70% non-biodegradable
10%
6%
10%
70%
4%
DF
AD
PR
SG
WGS

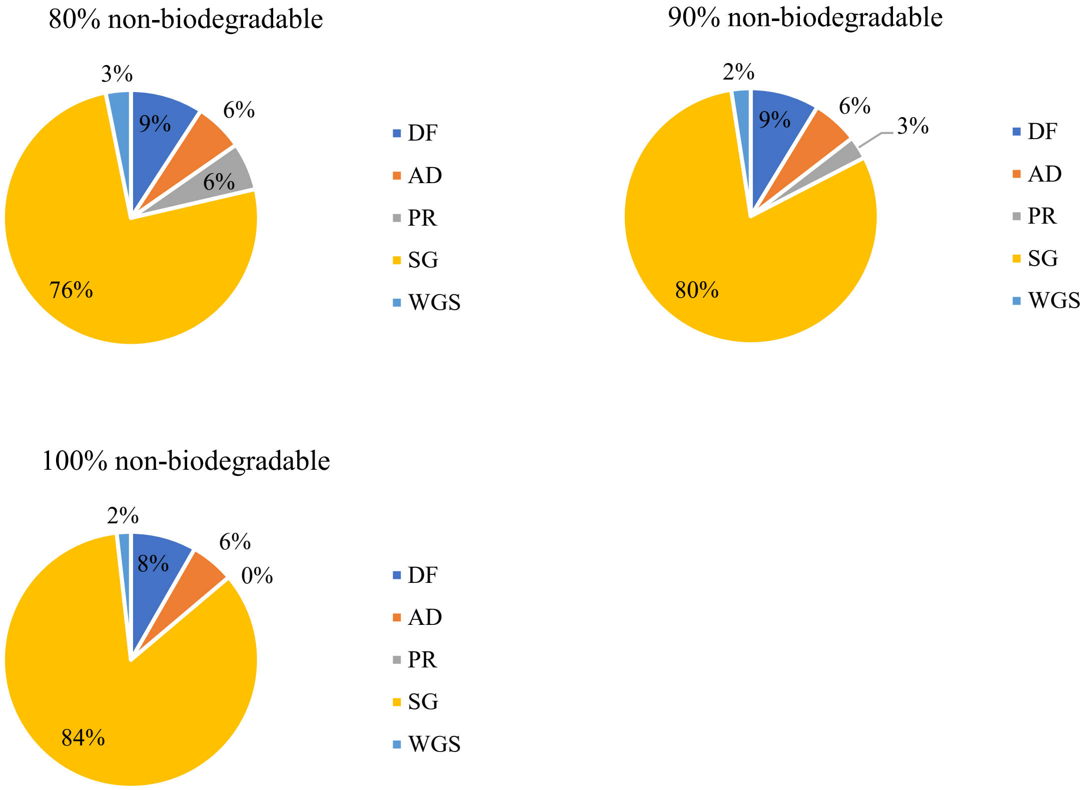
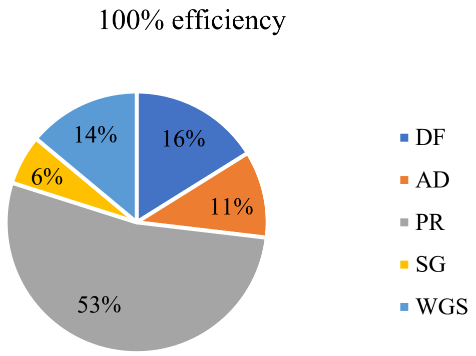
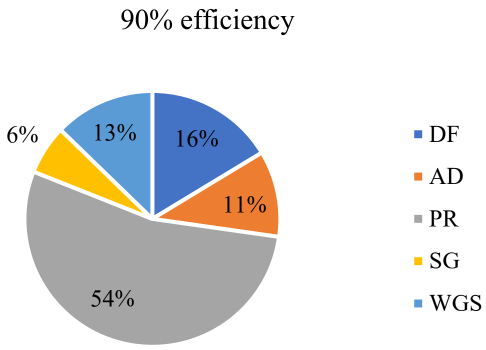


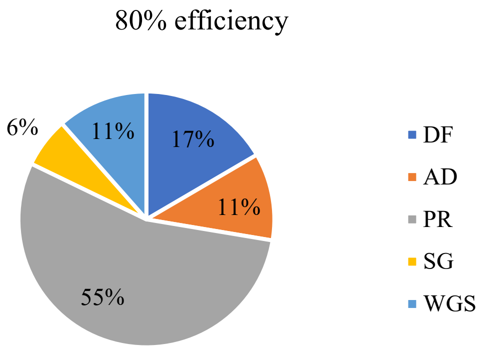
Figure A.89. Effect of the assumptions on the efficiency of the AD stage (non-biodegradable fraction in the feedstock) on the contribution of each stage to total energy consumption

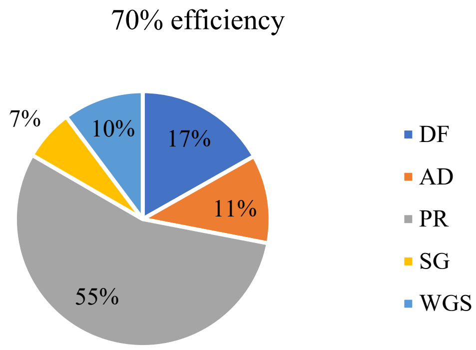
A.2.7.3 Plasma reforming

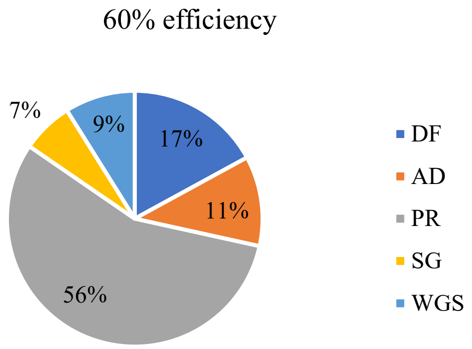
Figure A.90 shows the contribution of each stage to the total energy consumption of the process as a function of the efficiency of the PR stage. The figure shows an increase in the contribution of the PR stage to the total energy consumption. Indeed, with the assumptions used in these calculations, the energy consumption of the PR stage does not change as the stage efficiency is reduced, meaning that the role of PR in the total energy consumption increases because the total hydrogen production decreases (as shown in previous sections).

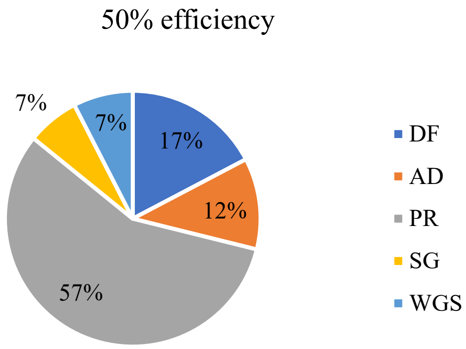

100% efficiency
16%
11%
53%
6%
14%
DF
AD
PR
SG
WGS

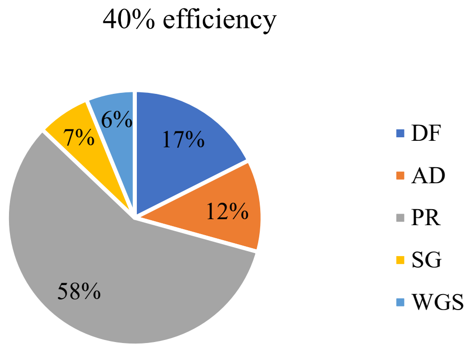

90% efficiency
16%
11%
54%
6%
13%
DF
AD
PR
SG
WGS

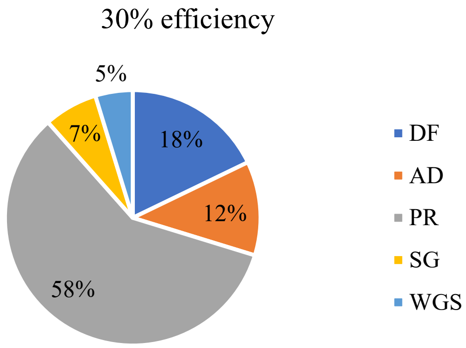

80% efficiency
17%
11%
55%
6%
11%
DF
AD
PR
SG
WGS


70% efficiency
17%
11%
55%
7%
10%
DF
AD
PR
SG
WGS


60% efficiency
17%
11%
56%
7%
9%
DF
AD
PR
SG
WGS


50% efficiency
17%
12%
57%
7%
7%
DF
AD
PR
SG
WGS


40% efficiency
17%
12%
58%
7%
6%
DF
AD
PR
SG
WGS


30% efficiency
18%
12%
58%
7%
5%
DF
AD
PR
SG
WGS

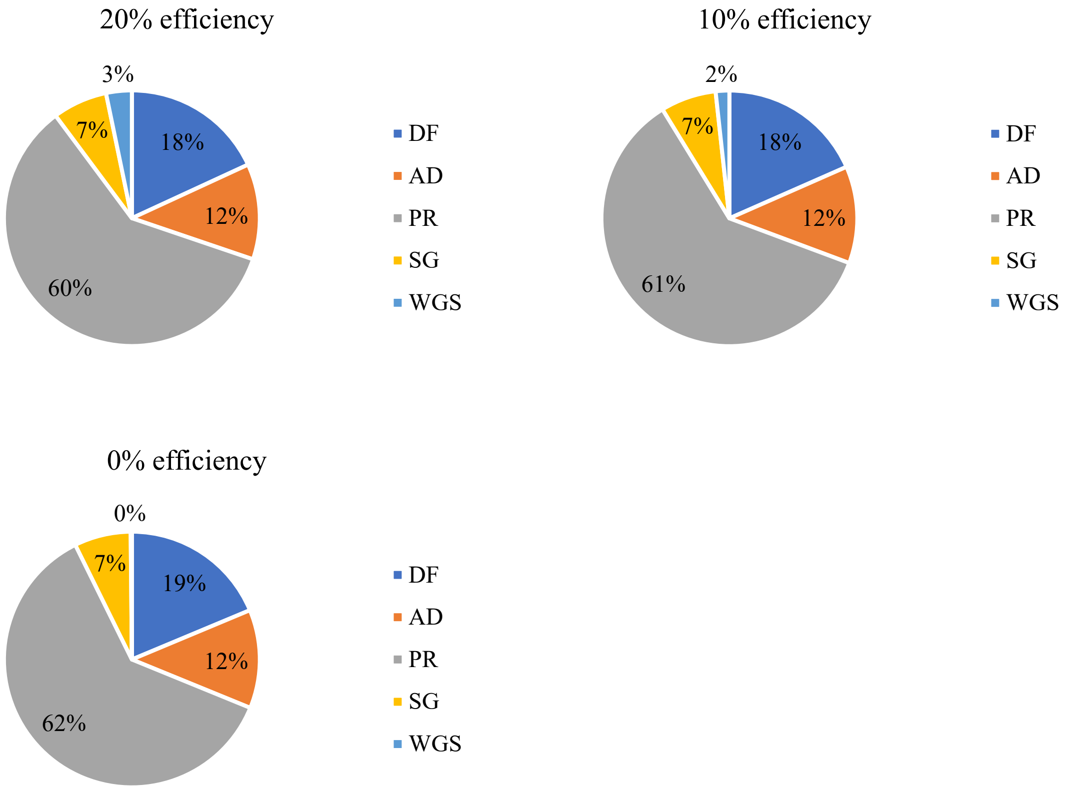
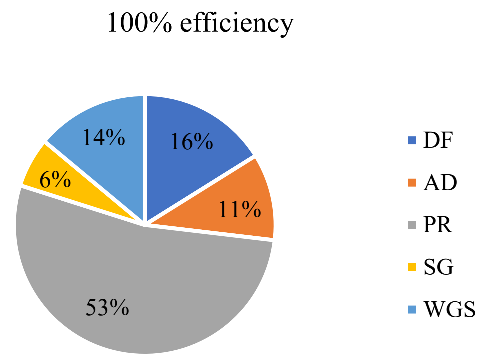
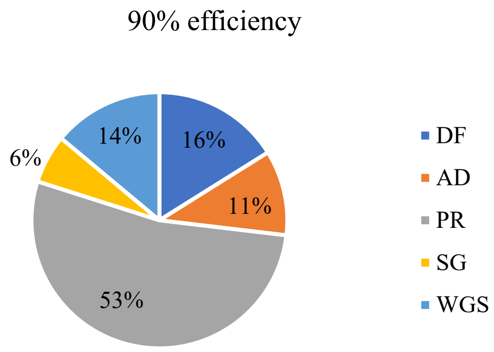


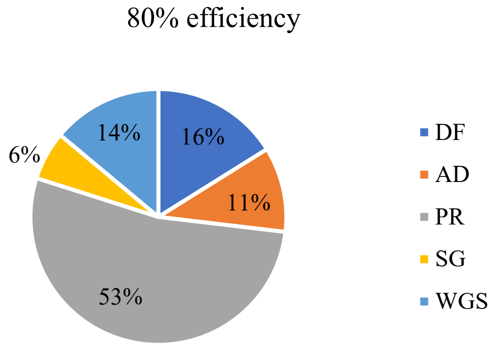
Figure A.90. Effect of the assumptions on the efficiency of the PR stage on the contribution of each stage to total energy consumption

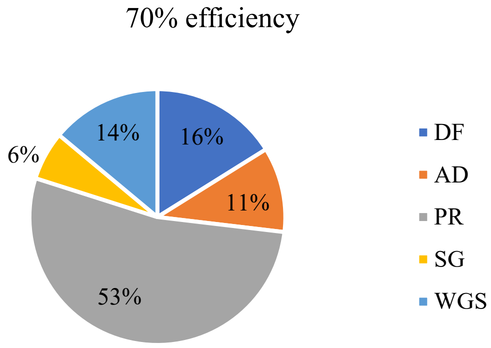
A.2.7.4 Steam gasification

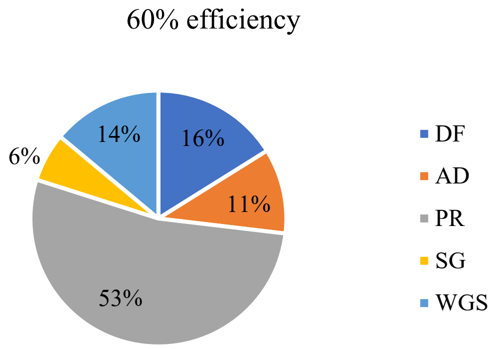
Figure A.91 shows the contribution of each stage to the total energy consumption of the process as a function of the efficiency of the SG stage. The figure shows almost no effect of the SG stage. This is due to the assumptions of the base case used here, for which all the organic matter is biodegraded in the AD stage and therefore the SG has little role in hydrogen production and energy consumption.

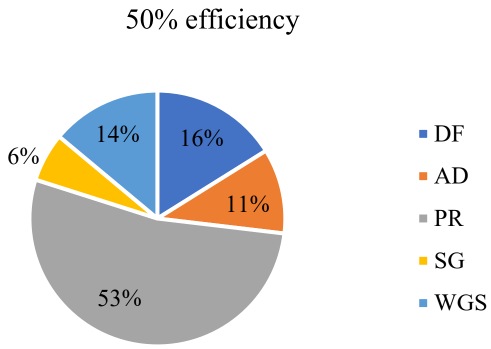

100% efficiency

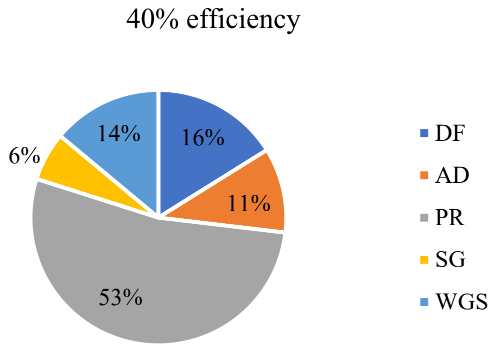

90% efficiency

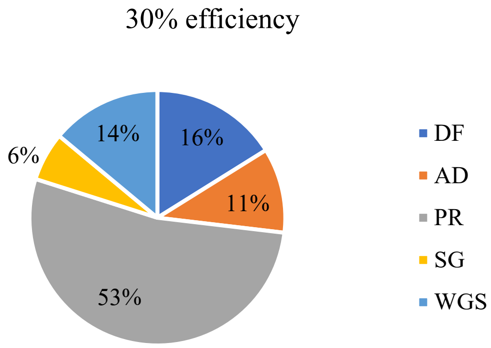

80% efficiency

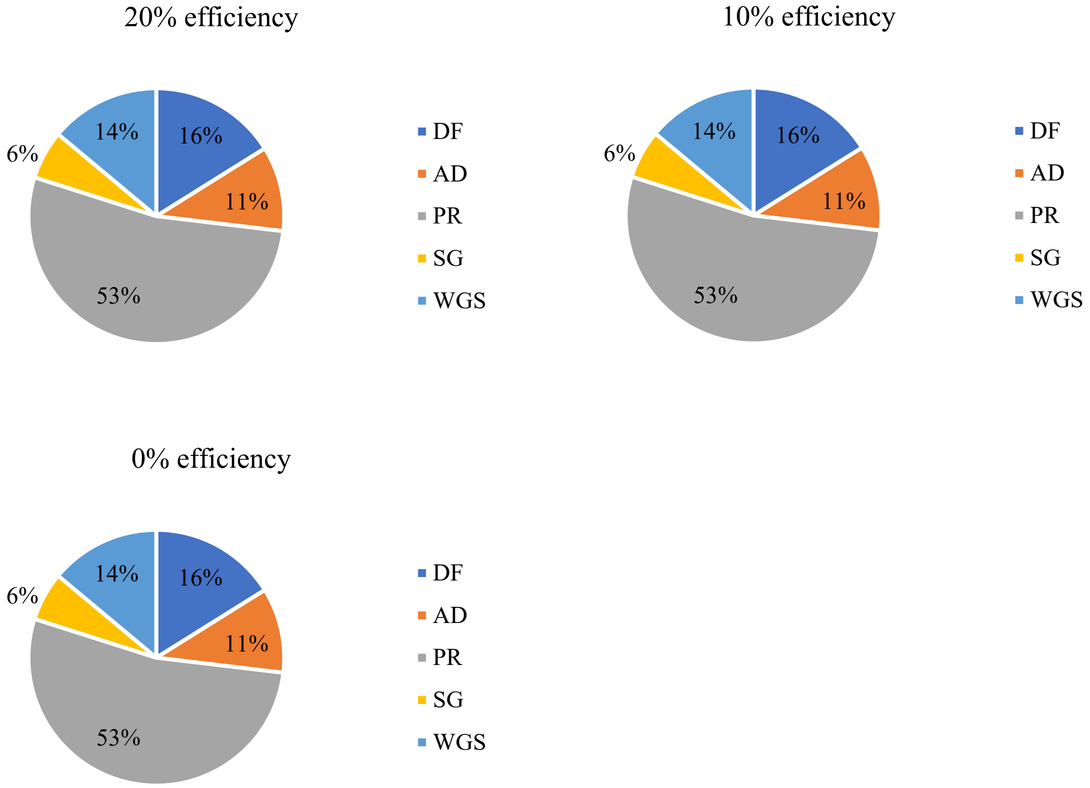

70% efficiency


60% efficiency


50% efficiency


40% efficiency


30% efficiency


20% efficiency

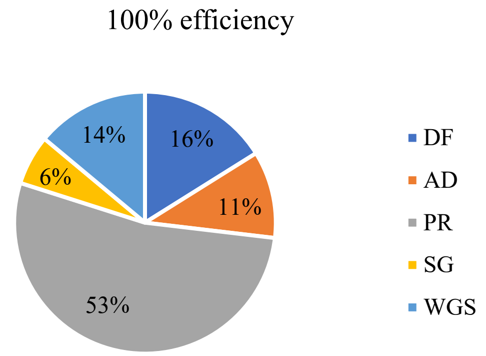
10% efficiency

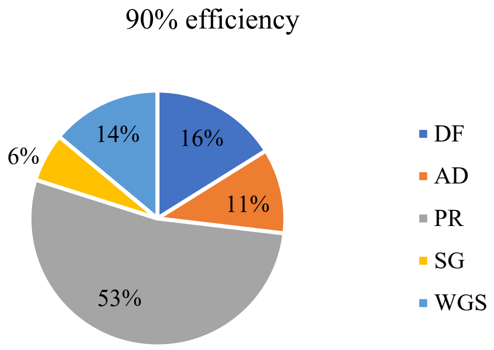
0% efficiency

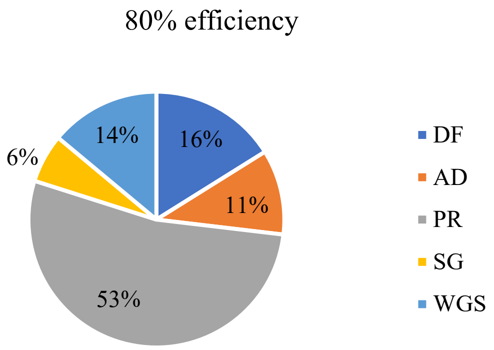
Figure A.91. Effect of the assumptions on the efficiency of the SG stage on the contribution of each stage to total energy consumption

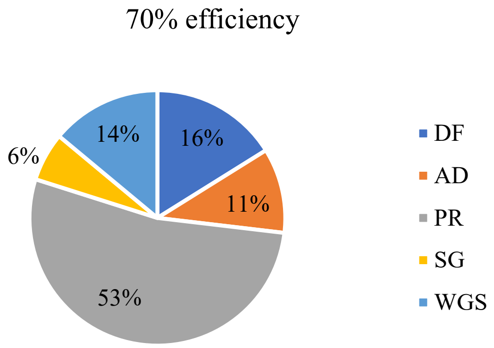
A.2.7.5 Water gas shift

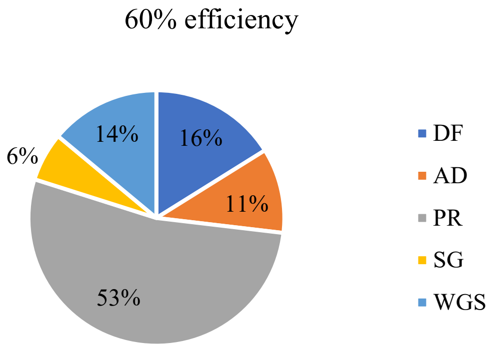
Figure A.92 shows the contribution of each stage to the total energy consumption of the process as a function of the efficiency of the WGS stage. The figure shows almost no effect of the WGS stage. This is due to the assumption of constant energy consumption in the WGS stage, regardless of its efficiency, therefore the role of each stage in the total energy consumption does not change.

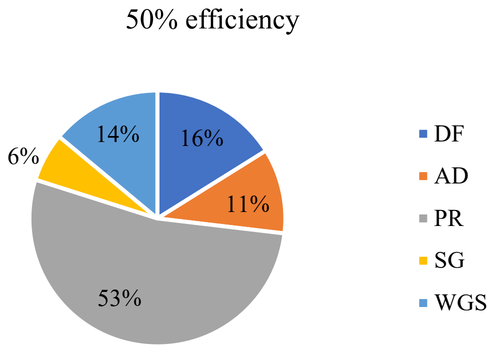

100% efficiency
16%
11%
53%
6%
14%
DF
AD
PR
SG
WGS

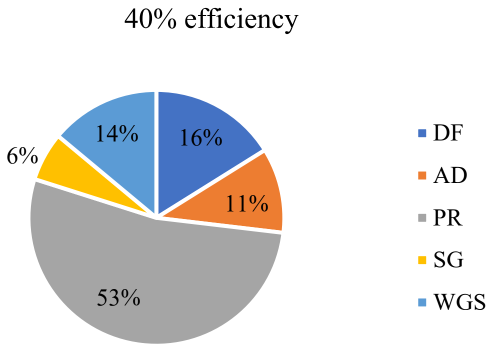

90% efficiency
16%
11%
53%
6%
14%
DF
AD
PR
SG
WGS

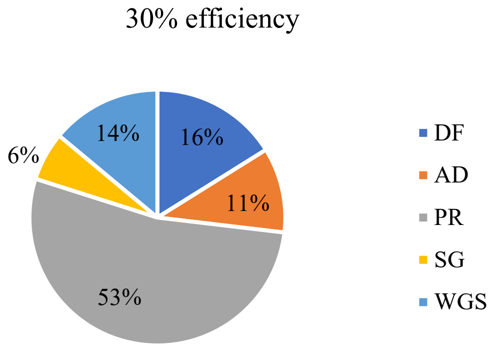

80% efficiency
16%
11%
53%
6%
14%
DF
AD
PR
SG
WGS


70% efficiency
16%
11%
53%
6%
14%
DF
AD
PR
SG
WGS


60% efficiency
16%
11%
53%
6%
14%
DF
AD
PR
SG
WGS


50% efficiency
16%
11%
53%
6%
14%
DF
AD
PR
SG
WGS


40% efficiency
16%
11%
53%
6%
14%
DF
AD
PR
SG
WGS


30% efficiency
16%
11%
53%
6%
14%
DF
AD
PR
SG
WGS

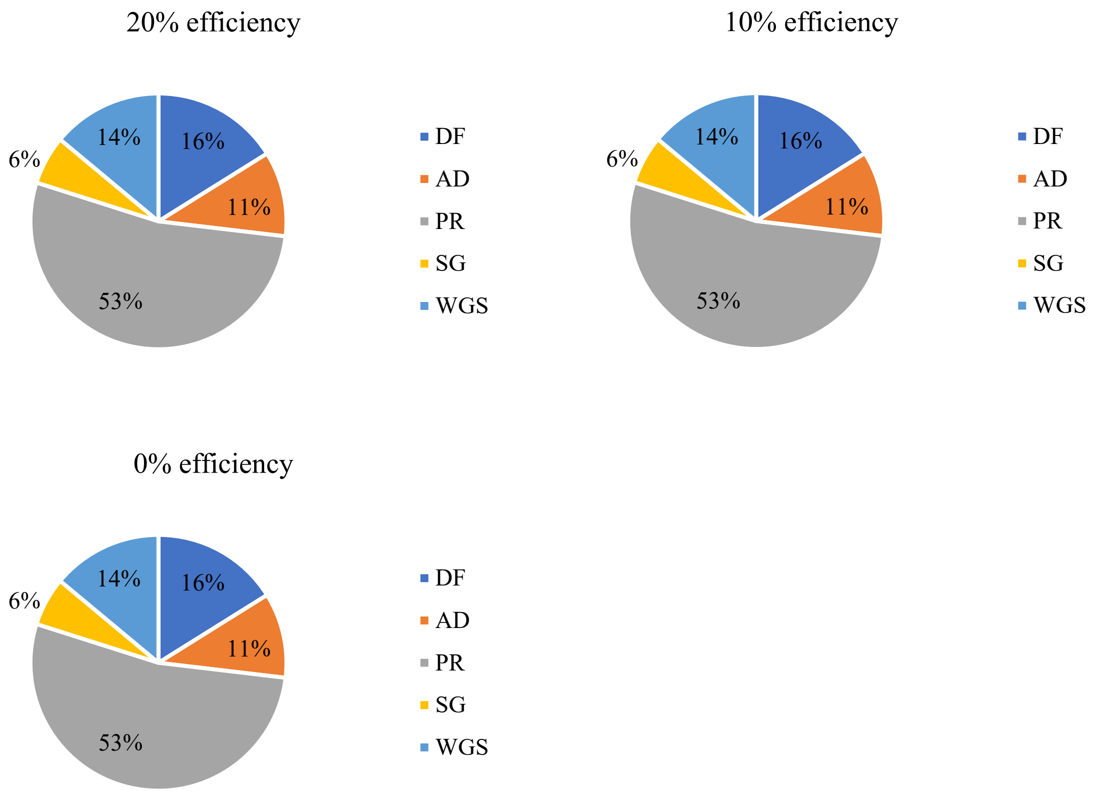


Figure A.92. Effect of the assumptions on the efficiency of the WGS stage on the contribution of each stage to total energy consumption

A.2.7.6 50% efficiency at all stages

Figure A.93 shows the contribution of each stage to the total energy consumption of the process when the conversion efficiency of each stage is 50 % than the value assumed for the base case. The figure shows that in this case the role of SG is much larger than for the base case. This is due to the larger fraction of organic matter which is not converted in AD and which is then converted in SG. SG has a higher energy consumption than other stages, due to the significant need for steam, therefore the more the organic matter converted in this stage the larger the role of SG in the total energy consumption.

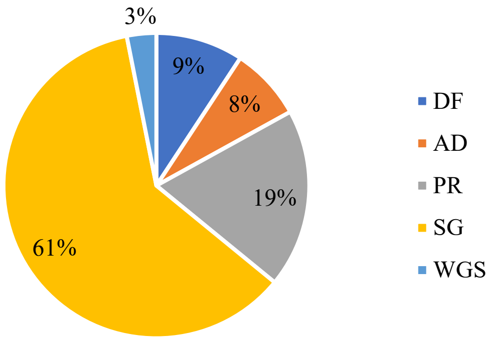


Figure A.93. Contribution of each stage to the total energy consumption when the efficiency of each stage is 50 % than the assumed efficiency for the base case

A.2.7.7 Double the energy consumption at each stage

Figure A.94 shows the contribution of each stage to the total energy consumption of the process when the unit energy consumption of each stage is twice the value assumed in Table A.2. The most important effect is the one of PR, as a higher energy consumption in this stage causes this stage to contribute to 69 % of the total energy consumption. The effect of increasing the unit consumption of the other stages has relatively little effect on their contribution to the total energy consumption. These results indicate the importance of optimising the energy efficiency of the PR stage.

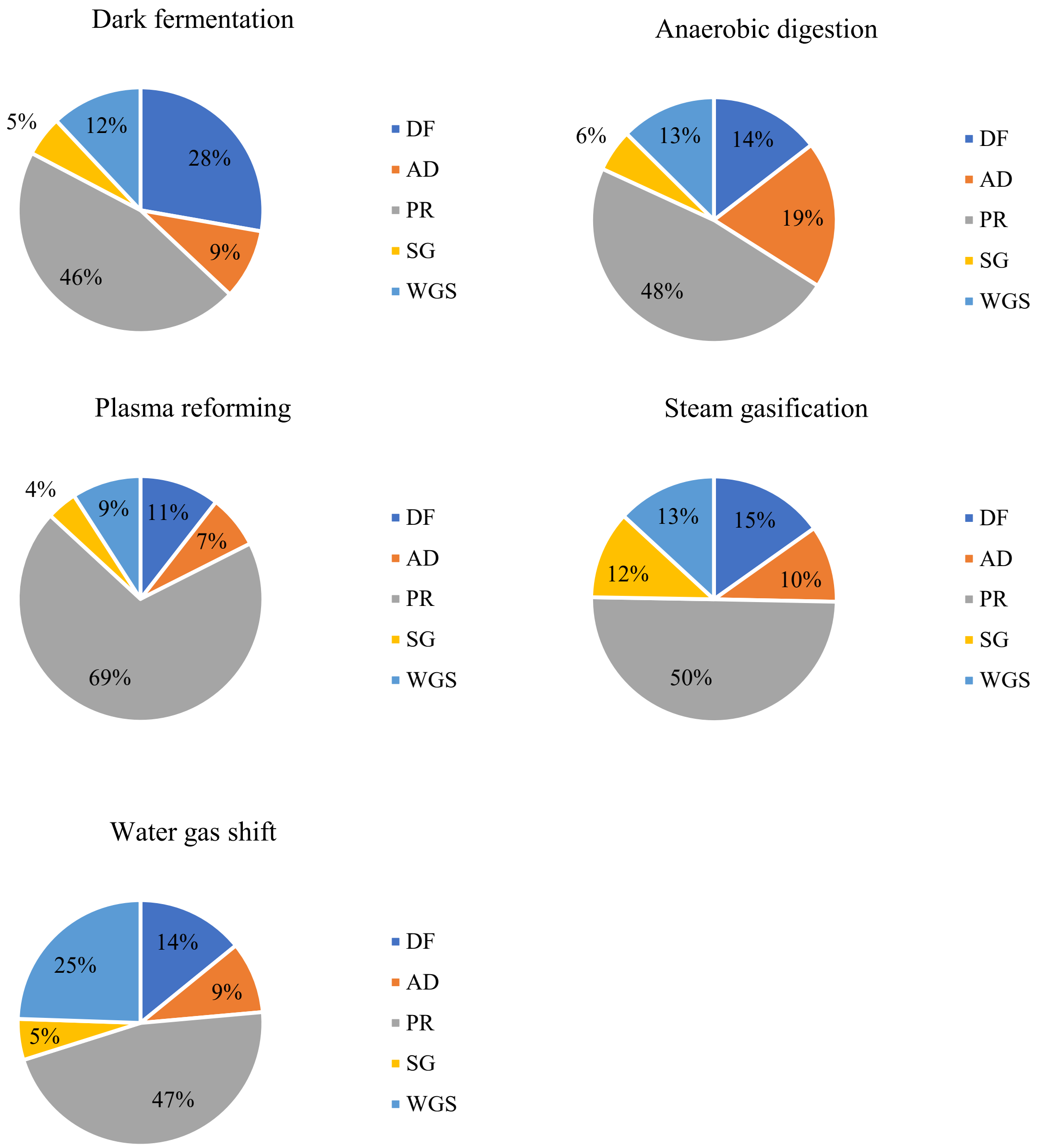
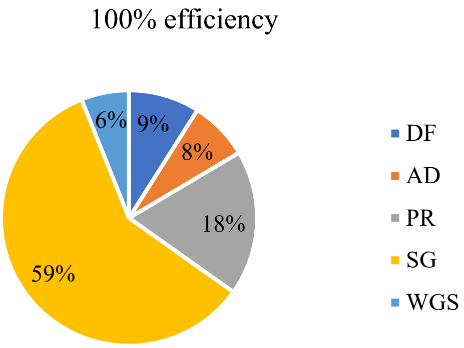
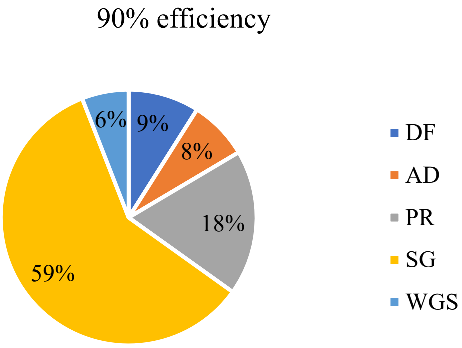


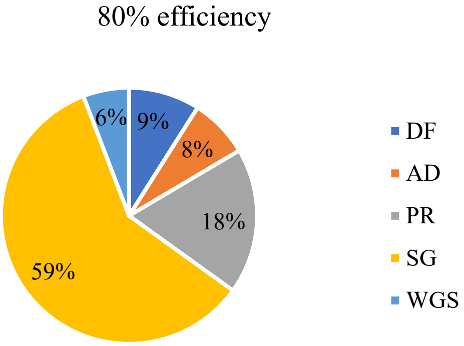
Figure A.94. Contribution of each stage to the total energy consumption when the energy consumption of each stage is double than the value assumed for the base case

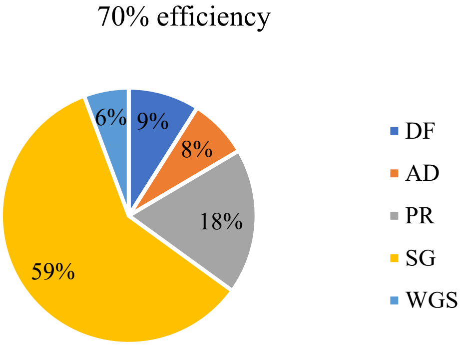
A.2.7.8 Steam gasification with 50% non-biodegradable organic matter in dark fermentation and anaerobic digestion

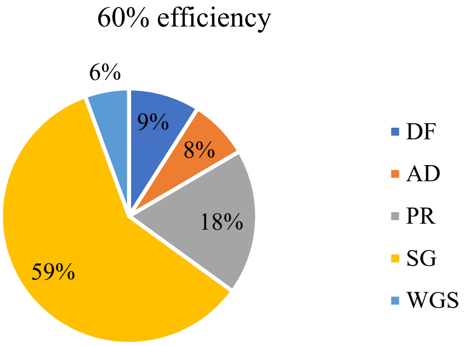
Figure A.95 shows the contribution of each stage to the total energy consumption of the process when the efficiency of SG reduces, for the assumption that only 50 % of the organic matter is biodegraded in the DF and AD stages. This assumption is different than for the base case when it was assumed complete biodegradation of the organic matter in the biological stages. Figure A.95 shows that in al cases the SG stage gives the highest contribution to the energy consumption, because of the energy consumption to vaporise the steam, as observed in previous sections.

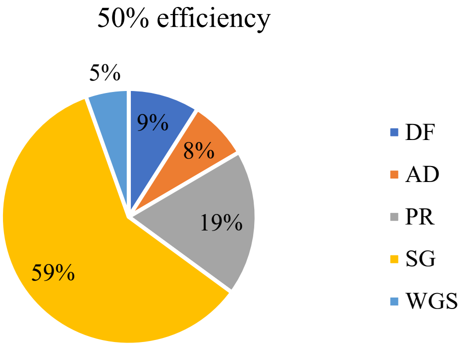

100% efficiency
6%
9%
8%
18%
59%
DF
AD
PR
SG
WGS

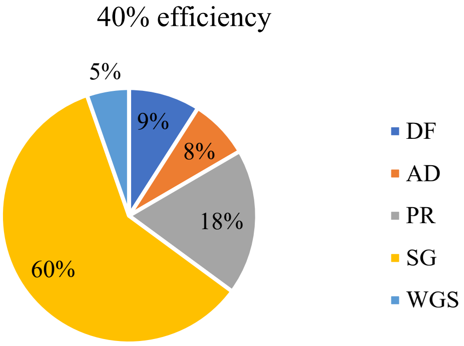

90% efficiency
6%
9%
8%
18%
59%
DF
AD
PR
SG
WGS

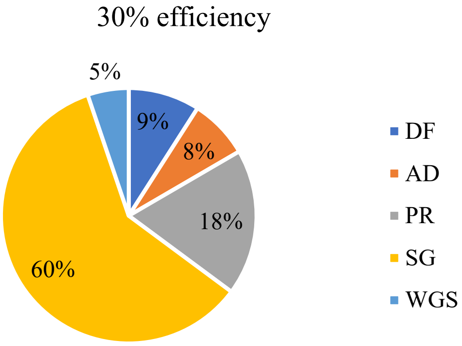

80% efficiency
6%
9%
8%
18%
59%
DF
AD
PR
SG
WGS


70% efficiency
6%
9%
8%
18%
59%
DF
AD
PR
SG
WGS


60% efficiency
6%
9%
8%
18%
59%
DF
AD
PR
SG
WGS


50% efficiency
5%
9%
8%
19%
59%
DF
AD
PR
SG
WGS


40% efficiency
5%
9%
8%
18%
60%
DF
AD
PR
SG
WGS


30% efficiency
5%
9%
8%
18%
60%
DF
AD
PR
SG
WGS

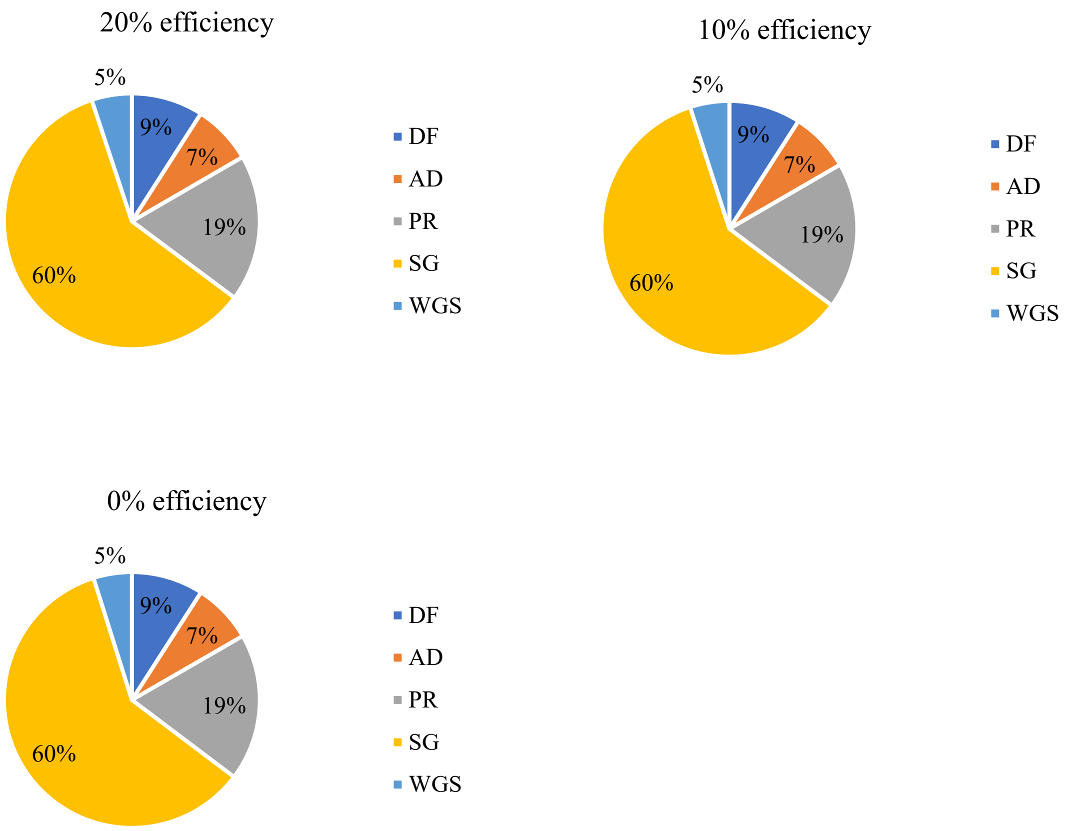


Figure A.95. Contribution of each stage to the total energy consumption as a function of the efficiency of the SG stage under the assumption that in the biological stages the non-biodegradable fraction of the organic matter is 50 %.

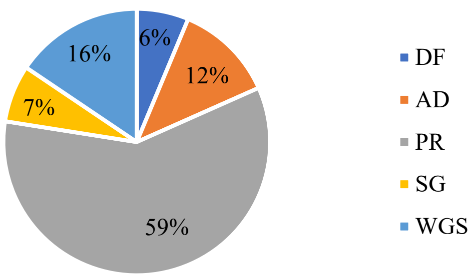
A.2.8 Energy consumption by process stage for food waste (lipids)

The following graphs illustrates the simulations for food waste assuming lipids composition (COD factor 2.894). Same assumptions as for Section A.2.7. The results shown here follow the same trends as for the assumption of carbohydrate composition (Section A.2.7) although with different numerical values.

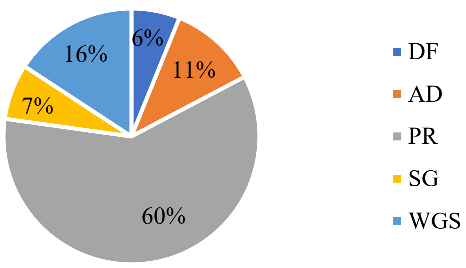
A.2.8.1 Dark fermentation

Figure A.96 shows the contribution of each stage to the total energy consumption of the process as a function of the non-biodegradable fraction of the organic matter in the DF stage. The figure shows the same trends observed in Section A.2.7.1 for the feedstock composed of carbohydrates, with however a larger role of PR due to the larger conversion of the organic matter into methane in the AD stage.

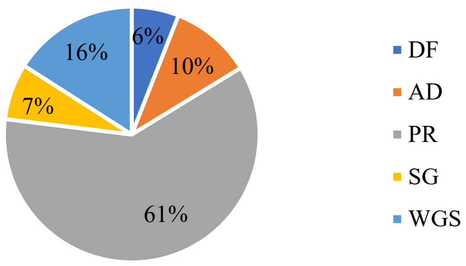
0% non-biodegradable



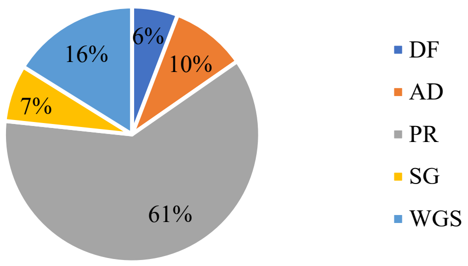
10% non-biodegradable



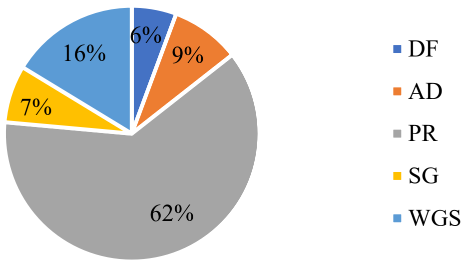
20% non-biodegradable



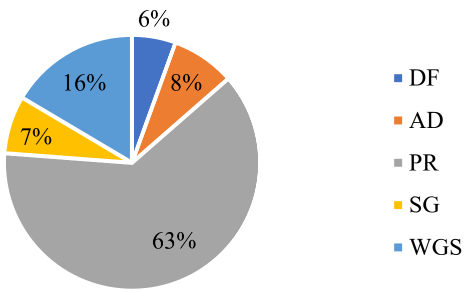
30% non-biodegradable



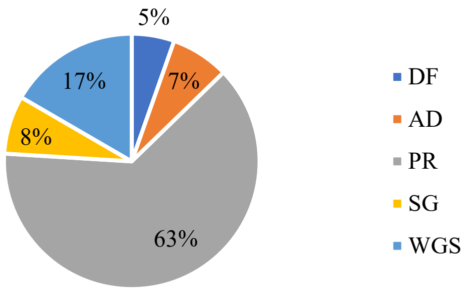
40% non-biodegradable



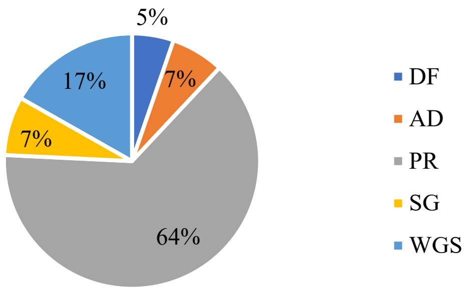
50% non-biodegradable

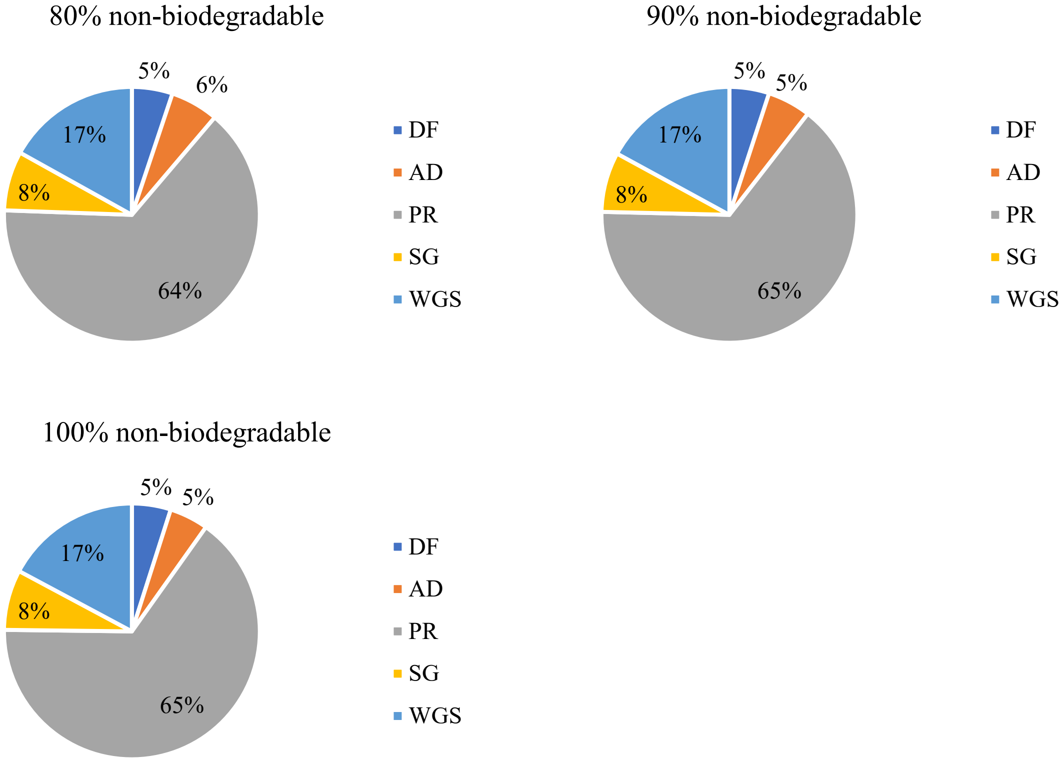


60% non-biodegradable



70% non-biodegradable




80% non-biodegradable

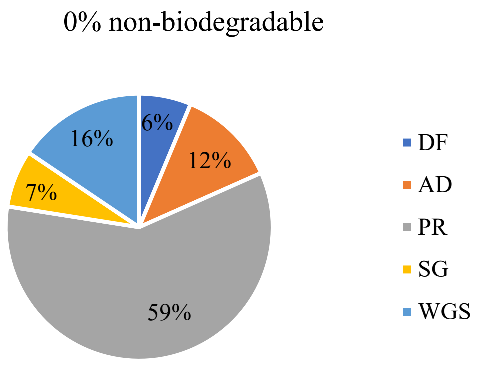
90% non-biodegradable

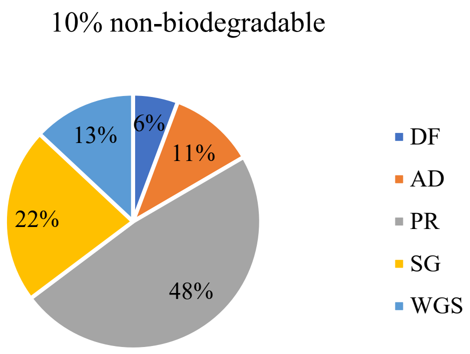
100% non-biodegradable

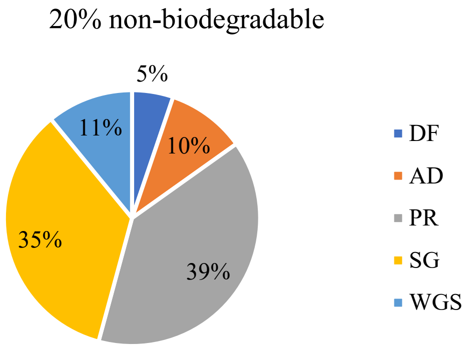
Figure A.96. Effect of the assumptions on the efficiency of the DF stage (non-biodegradable fraction in the feedstock) on the contribution of each stage to total energy consumption (lipid feedstock)

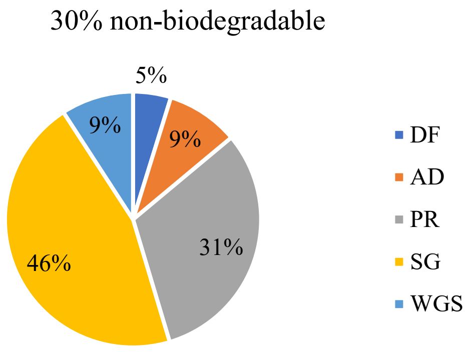
A.2.8.2 Anaerobic digestion

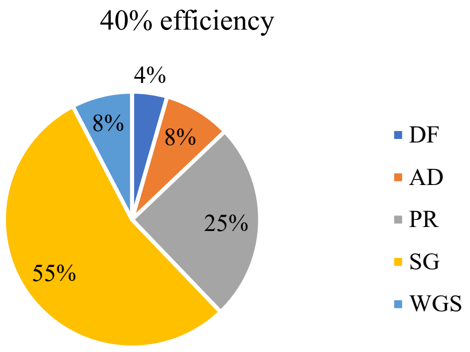
Figure A.97 shows the contribution of each stage to the total energy consumption of the process as a function of the non-biodegradable fraction of the organic matter in the AD stage. The figure shows the same trends observed in Section A.2.7.2 for the feedstock composed of carbohydrates. It is important to observe, as already observed in Section A.2.7.2, the higher role of the SG stage in the total energy consumption as the efficiency of the AD stage decreases.

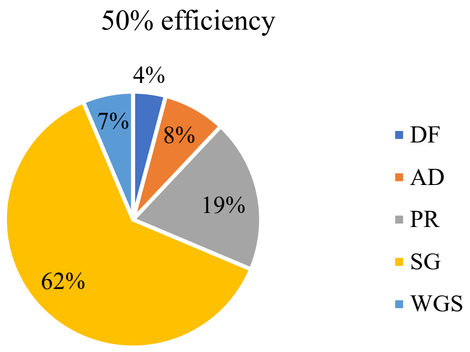

0% non-biodegradable

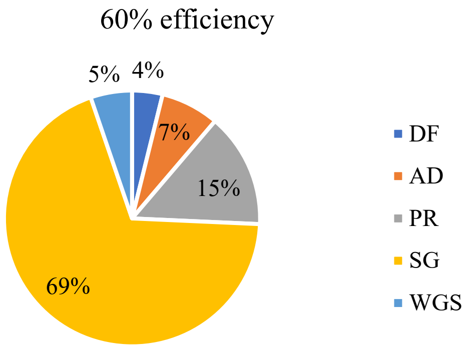

10% non-biodegradable

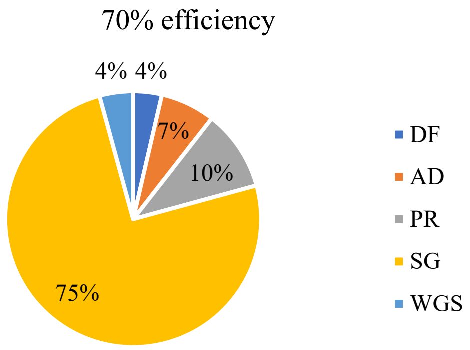

20% non-biodegradable


30% non-biodegradable


40% efficiency


50% efficiency


60% efficiency


70% efficiency

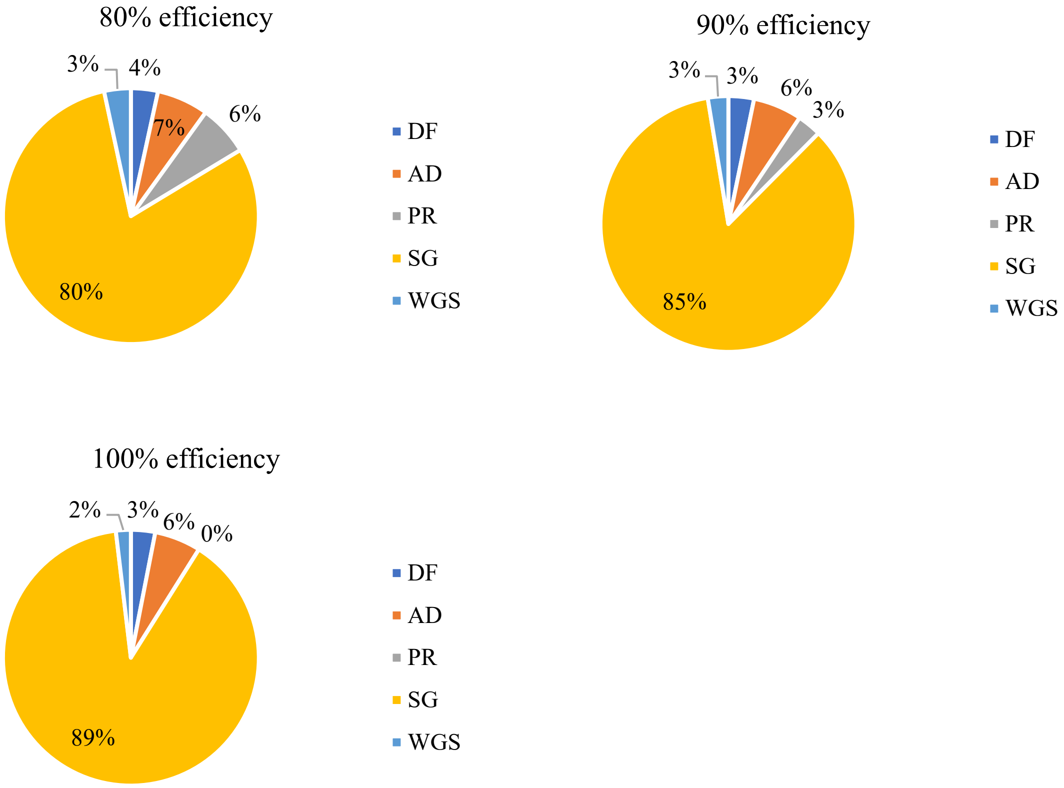
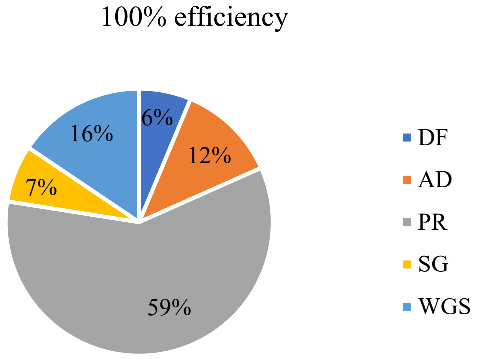
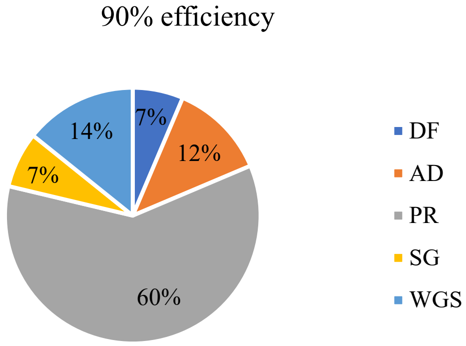


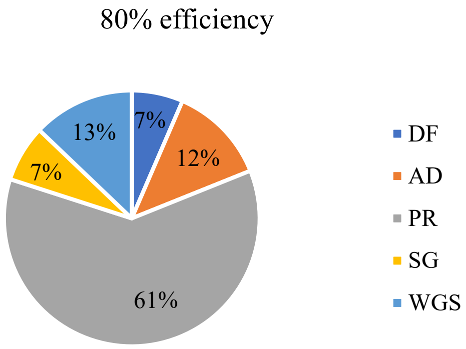
Figure A.97. Effect of the assumptions on the efficiency of the AD stage (non-biodegradable fraction in the feedstock) on the contribution of each stage to total energy consumption (lipid feedstock)

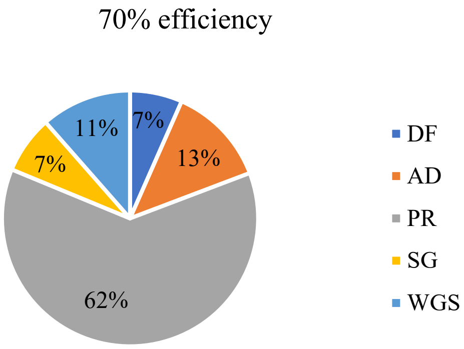
A.2.8.3 Plasma reforming

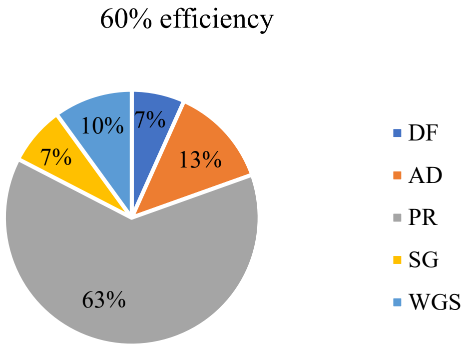
Figure A.98 shows the contribution of each stage to the total energy consumption of the process as a function of the efficiency of the PR stage. The figure shows the same trends, although with slightly different numerical values, observed in Section A.2.7.3 for the feedstock composed of carbohydrates.

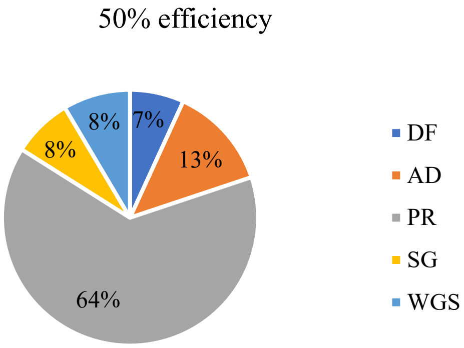

100% efficiency
6%
12%
59%
7%
16%
DF
AD
PR
SG
WGS

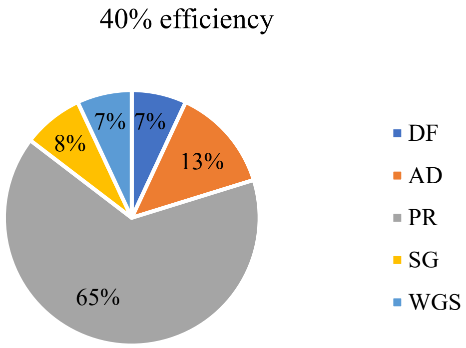

90% efficiency
7%
12%
60%
7%
14%
DF
AD
PR
SG
WGS

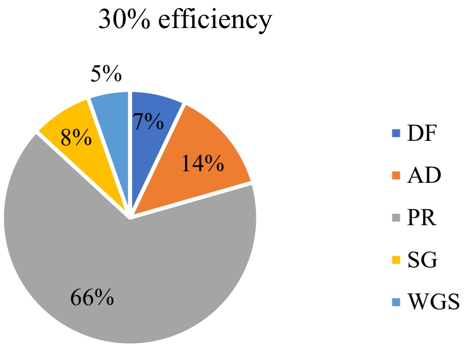

80% efficiency
7%
12%
61%
7%
13%
DF
AD
PR
SG
WGS


70% efficiency
7%
13%
62%
7%
11%
DF
AD
PR
SG
WGS


60% efficiency
7%
13%
63%
7%
10%
DF
AD
PR
SG
WGS


50% efficiency
7%
13%
64%
8%
8%
DF
AD
PR
SG
WGS


40% efficiency
7%
13%
65%
8%
7%
DF
AD
PR
SG
WGS


30% efficiency
7%
14%
66%
8%
5%
DF
AD
PR
SG
WGS

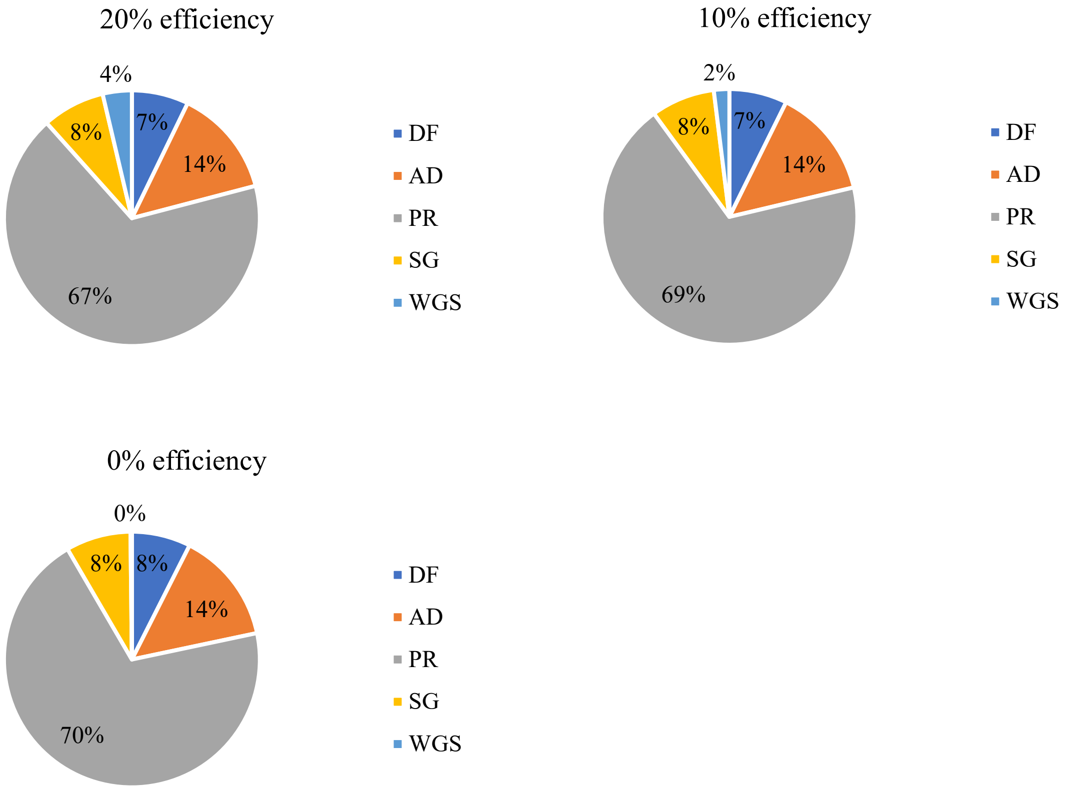
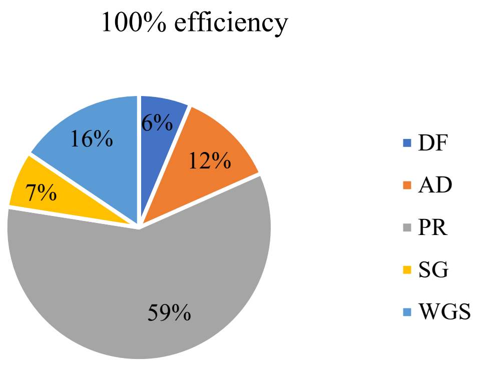
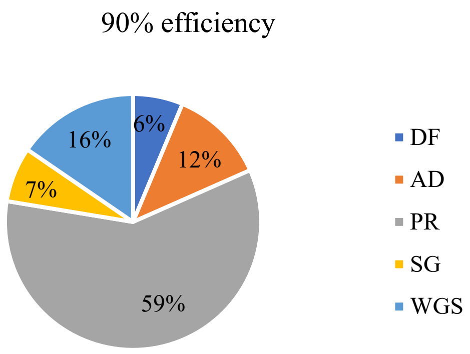


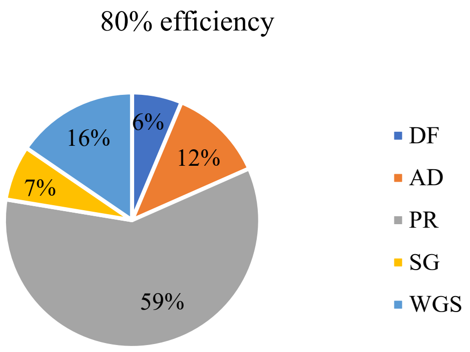
Figure A.98. Effect of the assumptions on the efficiency of the PR stage on the contribution of each stage to total energy consumption (lipid feedstock)

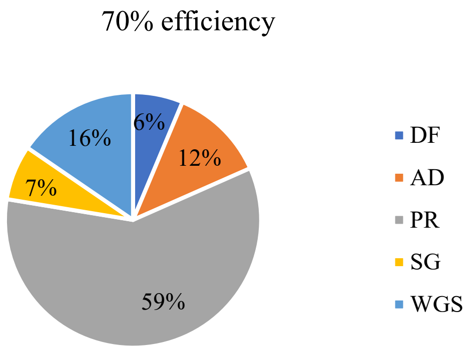
A.2.8.4 Steam gasification

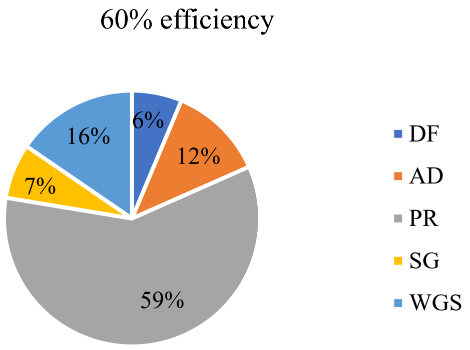
Figure A.99 shows the contribution of each stage to the total energy consumption of the process as a function of the efficiency of the SG stage. As observed in Section A.2.7.4 for the organic matter made of carbohydrates, the effect of the efficiency of the SG case is very low under the assumptions of the base case (complete biodegradation of the organic matter in the biological stages).

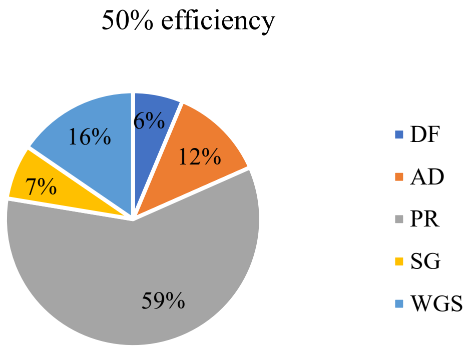

100% efficiency
6%
12%
59%
7%
16%
DF
AD
PR
SG
WGS

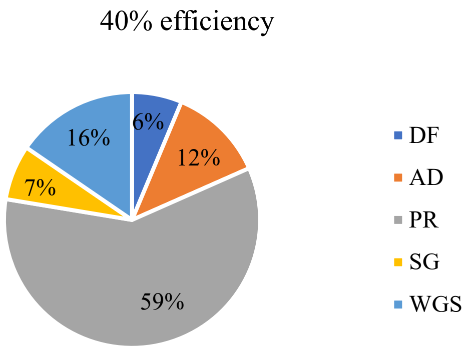

90% efficiency
6%
12%
59%
7%
16%
DF
AD
PR
SG
WGS

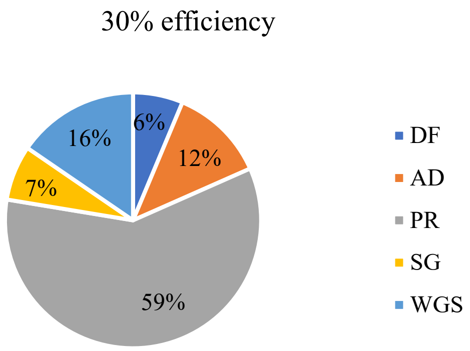

80% efficiency
6%
12%
59%
7%
16%
DF
AD
PR
SG
WGS


70% efficiency
6%
12%
59%
7%
16%
DF
AD
PR
SG
WGS


60% efficiency
6%
12%
59%
7%
16%
DF
AD
PR
SG
WGS


50% efficiency
6%
12%
59%
7%
16%
DF
AD
PR
SG
WGS


40% efficiency
6%
12%
59%
7%
16%
DF
AD
PR
SG
WGS


30% efficiency
6%
12%
59%
7%
16%
DF
AD
PR
SG
WGS

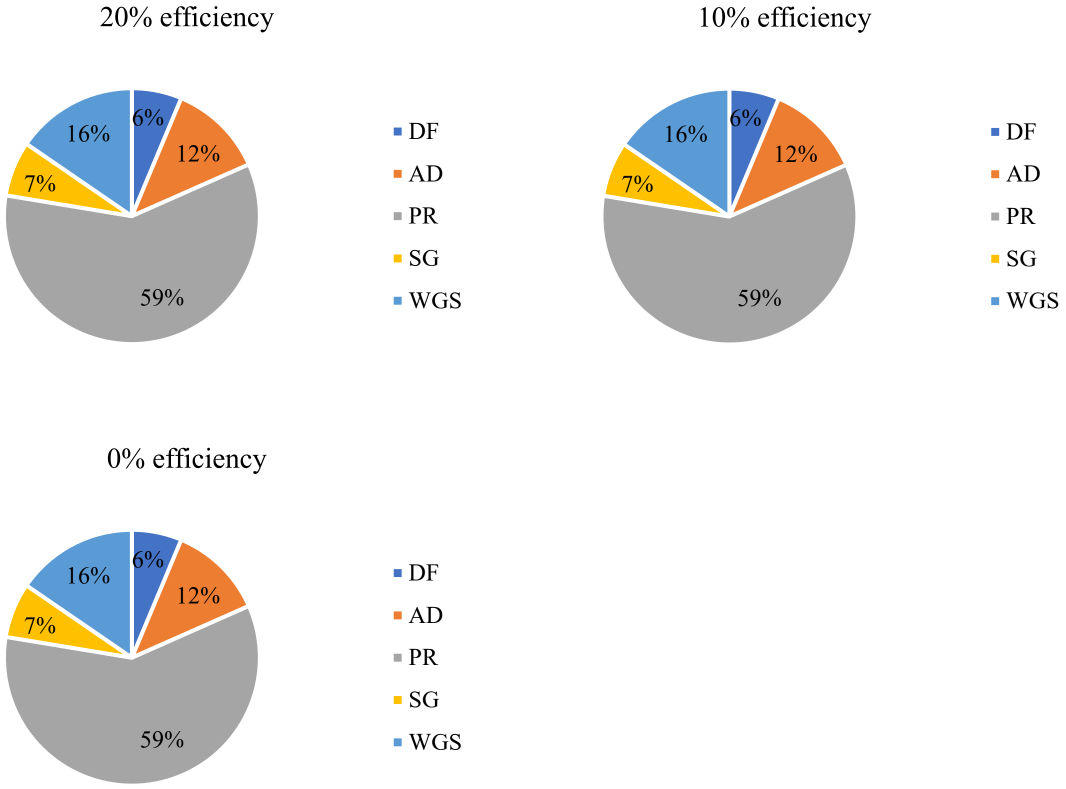
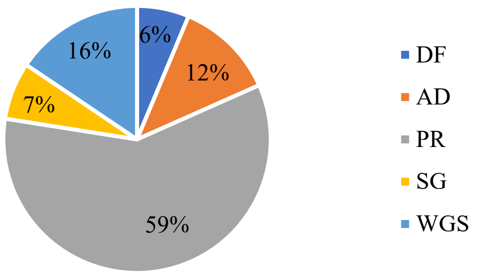


Figure A.99. Effect of the assumptions on the efficiency of the SG stage on the contribution of each stage to total energy consumption (lipid feedstock)

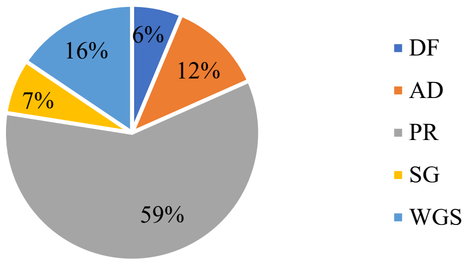
A.2.8.5 Water gas shift

Figure A.100 shows the contribution of each stage to the total energy consumption of the process as a function of the efficiency of the WGS stage. The results are analogous to what observed in section A.2.7.5 for the carbohydrate wastewater.

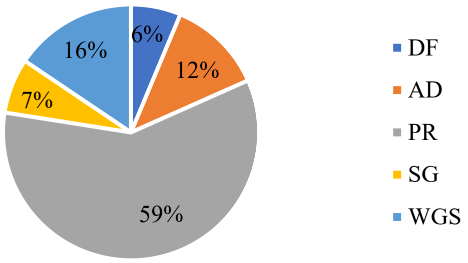
100% efficiency



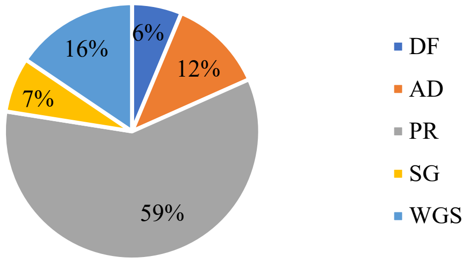
90% efficiency



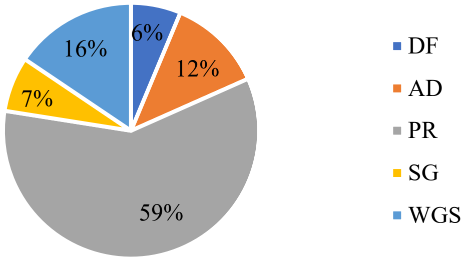
80% efficiency



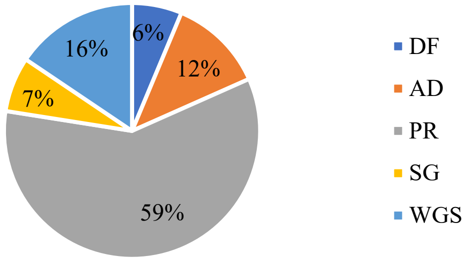
70% efficiency



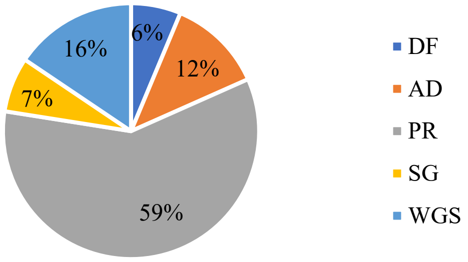
60% efficiency



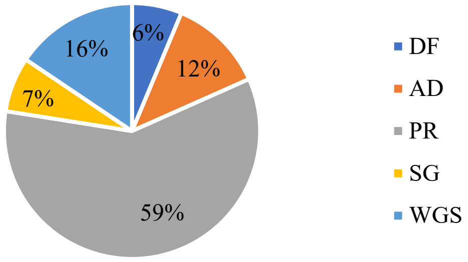
50% efficiency



40% efficiency



30% efficiency



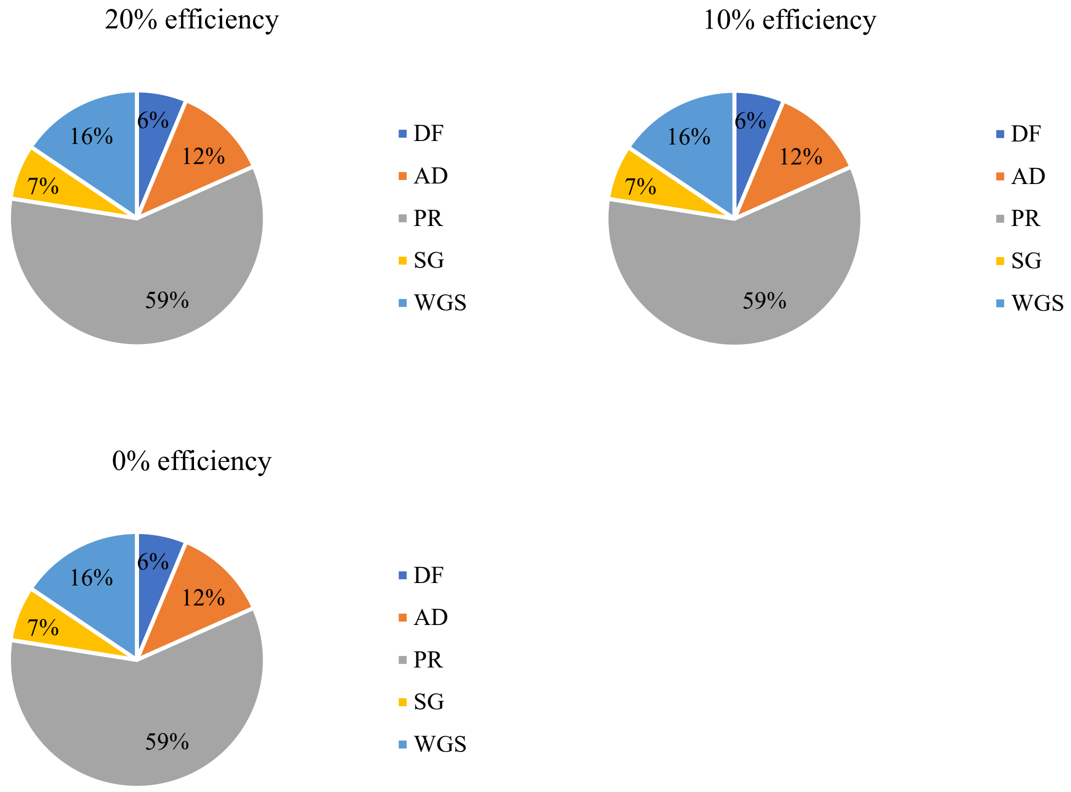


Figure A.100. Effect of the assumptions on the efficiency of the WGS stage on the contribution of each stage to total energy consumption (lipid feedstock)

A.2.8.6 50% efficiency at all stages

Figure A.101 shows the contribution of each stage to the total energy consumption of the process when the efficiency of each stage is 50 % of what assumed for the base case. As already observed in Section A.2.7.6 for the carbohydrate feedstock, the role of SG is much larger than for the base case because of the higher fraction of the organic matter in the feedstock that is processed in this stage, with a consequent higher energy consumption.

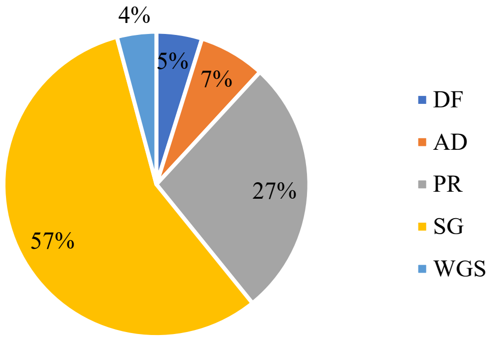


Figure A.101. Contribution of each stage to total energy consumption (lipid feedstock) when the efficiency of each stage is 50 % as for the base case

A.2.8.7 Double the energy consumption at each stage

Figure A.102 shows the contribution of each stage to the total energy consumption of the process when the unit energy consumption of each stage is doubled compared to the assumptions used so far (Table A.2). As observed in Section A.2.7.7, the most important contribution to the energy consumption is the one of the PR stage. This shows the importance of optimising the energy efficiency of this stage to minimise the energy consumption of the process.

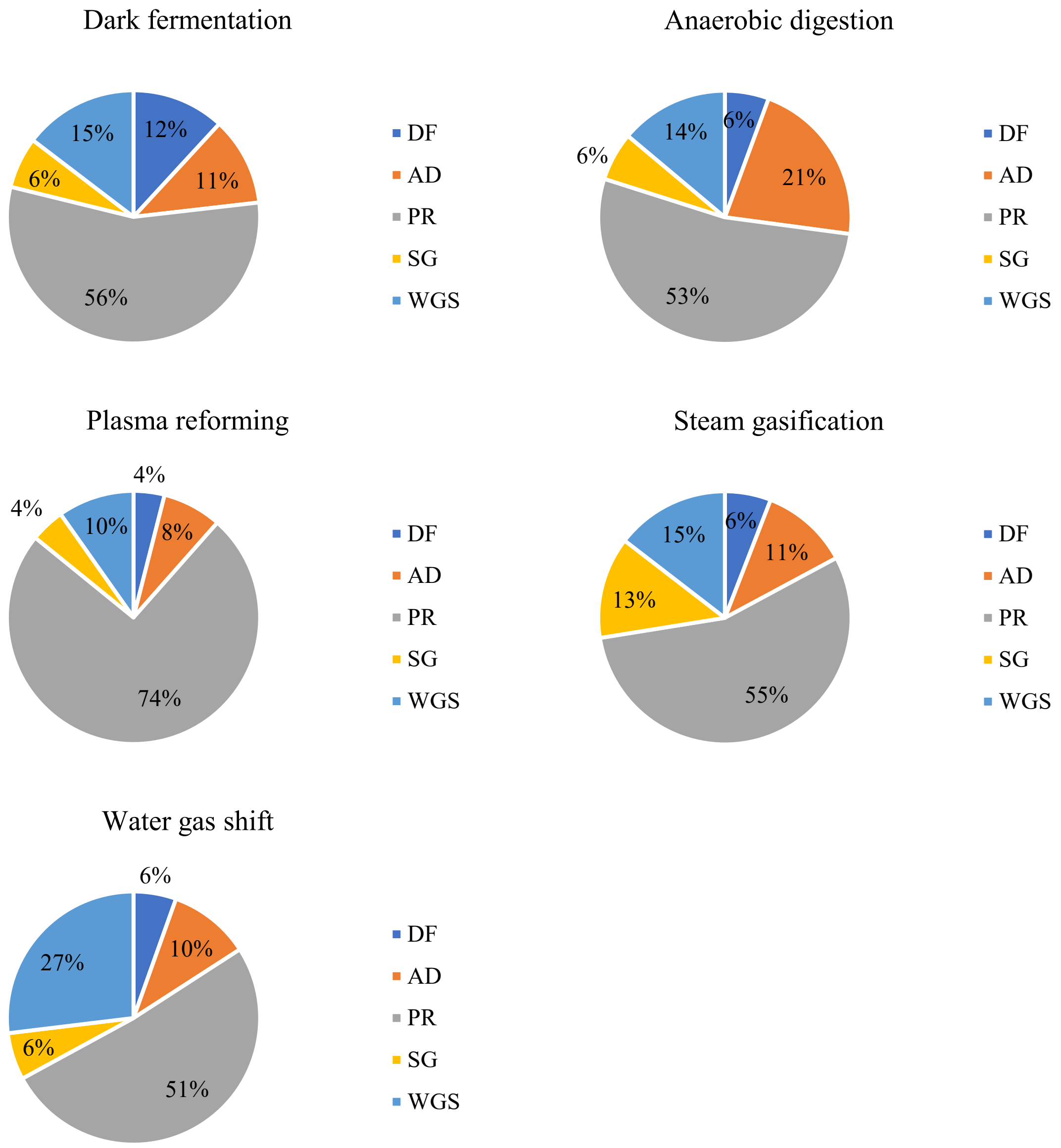
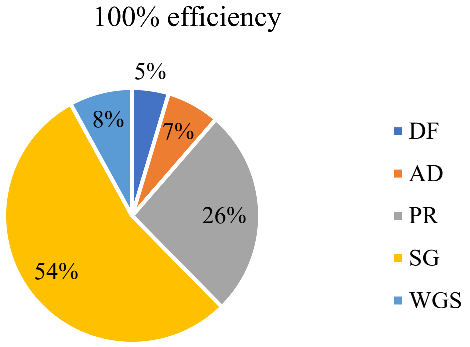
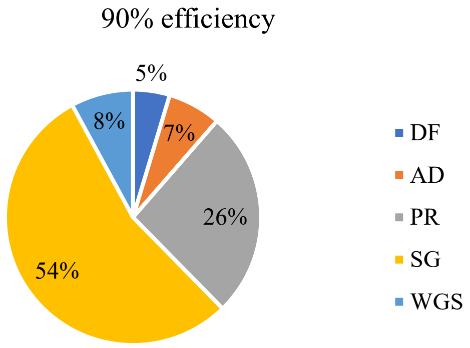


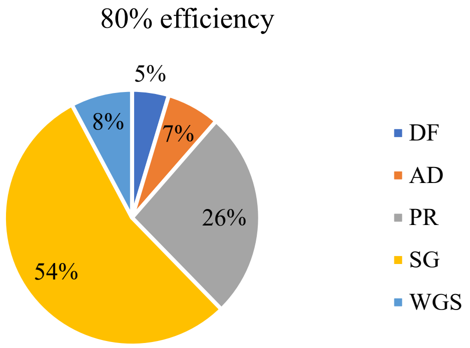
Figure A.102. Contribution of each stage to total energy consumption (lipid feedstock) when the energy consumption of each stage is double the values assumed for the base case

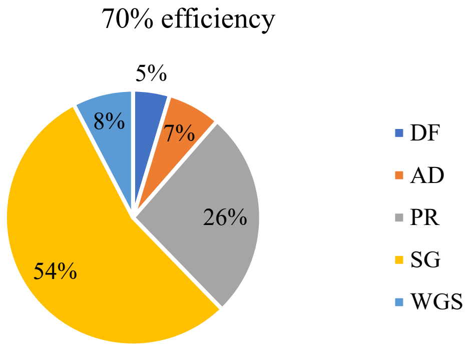
A.2.8.8 Steam gasification with 50% non-biodegradable organic matter in dark fermentation and anaerobic digestion

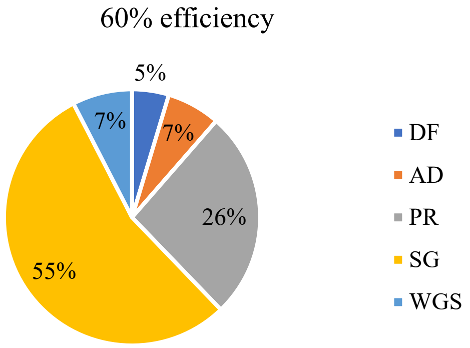
Figure A.103 shows the effect of the efficiency of the SG stage on the total energy consumption when the conversion of the organic matter in the biological stages is 50 % than what was assumed for the base case. As observed in Section A.2.7.8, in all cases the SG stages gives the main contribution to the energy consumption due to the higher fraction of the influent organic matter that is converted in this stage.

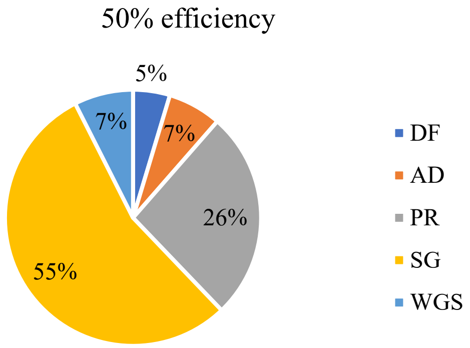

100% efficiency
5%
7%
26%
54%
8%
DF
AD
PR
SG
WGS

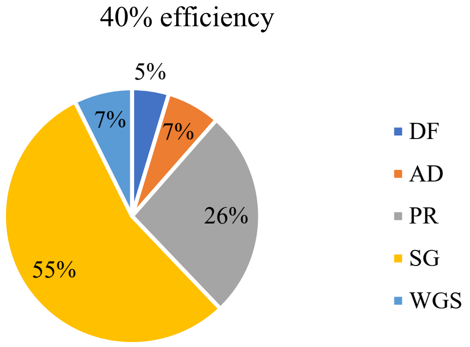

90% efficiency
5%
7%
26%
54%
8%
DF
AD
PR
SG
WGS

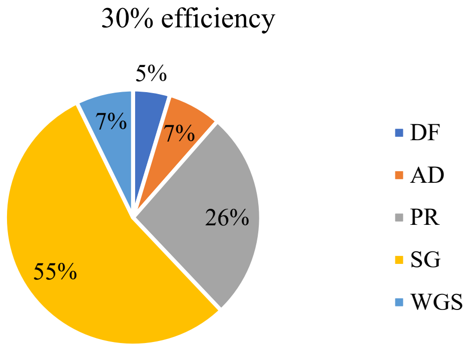

80% efficiency
5%
7%
26%
54%
8%
DF
AD
PR
SG
WGS


70% efficiency
5%
7%
26%
54%
8%
DF
AD
PR
SG
WGS


60% efficiency
5%
7%
26%
55%
7%
DF
AD
PR
SG
WGS


50% efficiency
5%
7%
26%
55%
7%
DF
AD
PR
SG
WGS


40% efficiency
5%
7%
26%
55%
7%
DF
AD
PR
SG
WGS


30% efficiency
5%
7%
26%
55%
7%
DF
AD
PR
SG
WGS

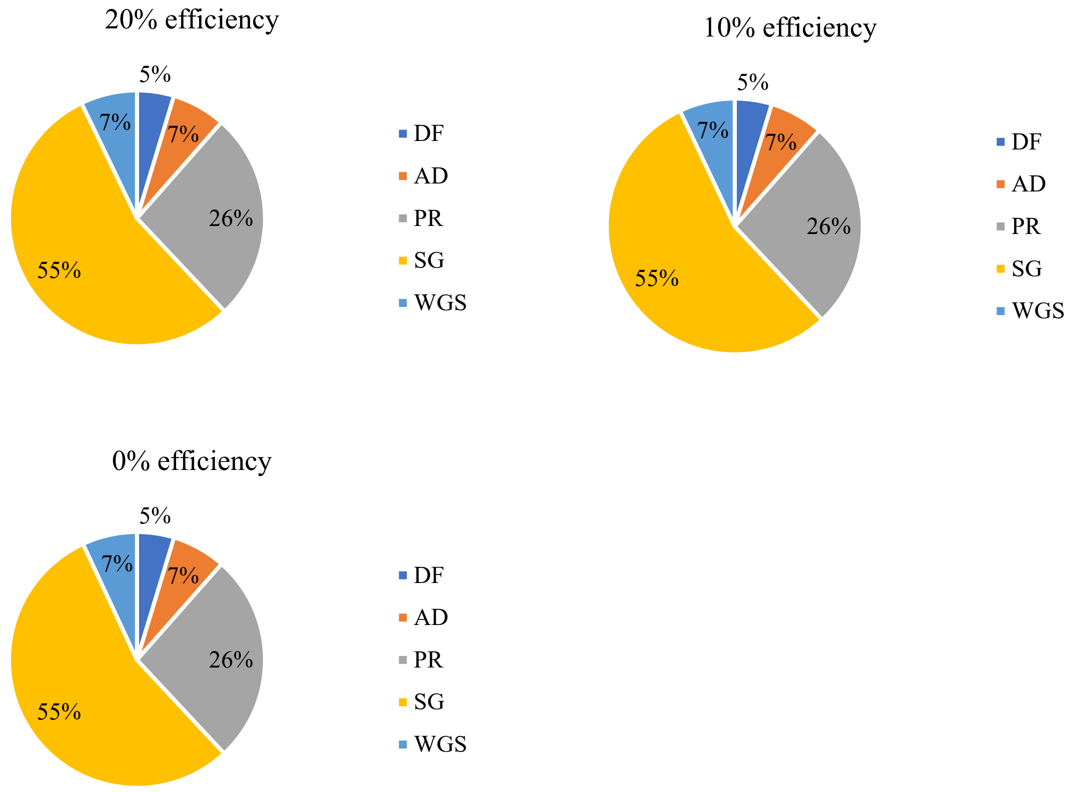


Figure A.103. Effect of the efficiency of the SG stage on the contribution of each stage to total energy consumption (lipid feedstock) when the non-biodegradable fraction in the biological stages is 50 %.

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[A.1] Dionisi, D., Bolaji, I., Nabbanda, D., & Silva, I. M. (2018). Calculation of the potential production of methane and chemicals using anaerobic digestion. Biofuels, Bioproducts and Biorefining, 12(5), 788-801.

[A.2] Pinto, Shawn, Aliakbar Jamshidi Far, and Davide Dionisi. Land and water requirements for the supply of renewable heating and transport energy using anaerobic digestion and water electrolysis. A case study for the UK. Sustainable Energy Technologies and Assessments 48 (2021): 101636.

[A.3] Dionisi, D. Biological wastewater treatment processes: mass and heat balances. CRC press, 2017.

[A.4] Abiev, R. S., Sladkovskiy, D. A., Semikin, K. V., Murzin, D. Y., & Rebrov, E. V. (2020). Non-thermal plasma for process and energy intensification in dry reforming of methane. Catalysts, 10(11), 1358.

[A.5] Zhang, Jingxin, Yuxuan Cui, Tengyu Zhang, Qiang Hu, Yen Wah Tong, Yiliang He, Yanjun Dai, Chi-Hwa Wang, and Yinghong Peng. Food waste treating by biochar-assisted high-solid anaerobic digestion coupled with steam gasification: Enhanced bioenergy generation and porous biochar production. Bioresource Technology 331 (2021): 125051.

Appendix B. WP2. Carbon life cycle assessment

B.1 Methodology

This study involves several stages: DF, AD, PR, SG and WGS. The simulations were carried out for food waste and municipal wastewater. The base case assumed the best performance at each stage, providing the maximum amount of H2 possible. It relies on several assumptions: the complete biodegradability of the organic matter in the DF and AD stages, and 100% efficiency of PR, SG and WGS. The total H2 yield, energy consumption and water consumption were obtained by varying the efficiency of the various stages from 0% to 100%. Simulations were carried out by varying the efficiency for one stage while leaving the rest of the stages at the highest efficiency. The total H2 yield, energy consumption for each stage and water consumption were used to obtain carbon emissions for food waste and water waste as the feedstock. The carbon emissions obtained were in terms of carbon emissions per kg of hydrogen produced and carbon emissions per kWh of hydrogen produced, calculated using the higher heating value of hydrogen (HHV=141.7 MJ/kg).
Life cycle assessment method was used to carry out the carbon emission calculations. A cradle to gate approach was used for scope limited to transportation of feedstock (food waste and wastewater) from source to the hydrogen production plant and hydrogen production process. A functional unit of 100 t/day of feedstock was used. The carbon emission calculations were performed based on the assumptions that HGV (Heavy Goods Vehicle) was used for the transportation of food waste to the hydrogen production facility with an average transportation of 20 km. However, when the feedstock is municipal wastewater the hydrogen production plant would replace existing sewage treatment plants and the municipal wastewater would be transferred using existing sewage lines to the hydrogen production facility. Natural gas was used for heating in SG and WGS stages. The emissions due to the energy consumed by the process were calculated from the energy consumption calculated in WP1 (Section 1 and Appendix A), with a 50% increase to take into account energy consumption due to pumping, compression and hydrogen purification which was not accounted for in WP1. Energy was assumed to be provided by electricity for the DF, AD and PR units, and by natural gas for the SG and WGS units. Each of the two cases (food waste and wastewater) were simulated by comparing electricity source from UK grid (Approx. 52% Nuclear and Renewable, 7% Thermal Renewables, 38% Gas, 2% Coal and Rest other sources) and other source of energy as Renewables (OVO energy, 14.4 % Solar, 1.4% Hydro and 84.2 % Wind). The carbon emissions calculations for each of the cases were carried using conversion factors of kg CO2 eq. / associated units are obtained from Greenhouse gas reporting: conversion factors 2022 and Agri-footprint version 2.0 and Eco-invent 3.3 database integrated with Simapro 8.3.0. Since there is no use of any crops from agricultural land for the production of hydrogen from food waste we have assumed that carbon emissions from direct and indirect land usage is zero.

B.2 Results

B.2.1 Base case

Tables B.1 and B.2 summarized the inventory data from mass and energy balance and carbon emissions (kg CO_2 eq.) for food waste using UK grid and Renewables as the electricity source for the base case, which assumes 100% efficiency for all stages. Tables B.3 and B.4 summarized the Inventory data from mass and energy balance and carbon emissions (kg CO_2 eq.) for wastewater using UK grid and Renewables as the electricity source for the base case.

Table B.1 Inventory data and total carbon emissions (kg CO_2 eq.) for food waste considering electricity supply from UK grid (Approx. 52% Nuclear and Renewable, 7% Thermal Renewables, 38% Gas, 2% Coal and Rest other sources).

		kg CO_2 eq./unit	kg CO_2 eq.
Transportation	2000 tkm	0.2135	426.90
Electricity (UK grid)	41323.32 kWh	0.1934	7991.10
Natural gas (heating)	10394.64 kWh	0.2000	2078.93
Water	8694.96 kg	2.5E-05	0.22
Overall CO_2 emissions			10497.15

Table B.2 Inventory data and total carbon emissions (kg CO_2 eq.) for food waste considering electricity supply from Renewable energy source (14.4 % Solar, 1.4% Hydro and 84.2 % Wind).

		kg CO_2 eq./unit	kg CO_2 eq.
Transportation	2000 tkm	0.2135	426.90
Electricity (Renewable energy)	41323.32 kWh	0.0297	1227.30
Natural gas (heating)	10394.64 kWh	0.2000	2078.93
Water	8694.96 kg	2.5E-05	0.22
Overall CO_2 emissions			3733.35

Table B.3 Inventory data and total carbon emissions (kg CO_2 eq.) for wastewater considering electricity supply from UK grid (Approx. 52% Nuclear and Renewable, 7% Thermal Renewables, 38% Gas, 2% Coal and Rest other sources).

		kg CO_2 eq./unit	kg CO_2 eq.
Transportation	0 tkm	0.2135	0.00
Electricity (UK grid)	96.90 kWh	0.1934	18.74
Natural gas (heating)	24.38 kWh	0.2000	4.88
Water	20.39 kg	2.5E-05	0.00
Overall CO_2 emissions			23.61

Table B.4 Inventory data and total carbon emissions (kg CO2 eq.) for wastewater considering electricity supply from Renewable energy source (14.4 % Solar, 1.4% Hydro and 84.2 % Wind).

		kg CO_2 eq./unit	kg CO_2 eq.
Transportation	0 tkm	0.2135	0.00
Electricity (Renewable energy)	96.90 kWh	0.0297	2.88
Natural gas (heating)	24.38 kWh	0.2000	4.88
Water	20.39 kg	2.5E-05	0.00
Overall CO_2 emissions			7.75

B.2.2 Effect of the main assumptions on CO_2 eq. emitted per kg of H_2 produced

B.2.2.1 Effect of non-biodegradable organic matter in the dark fermentation stage

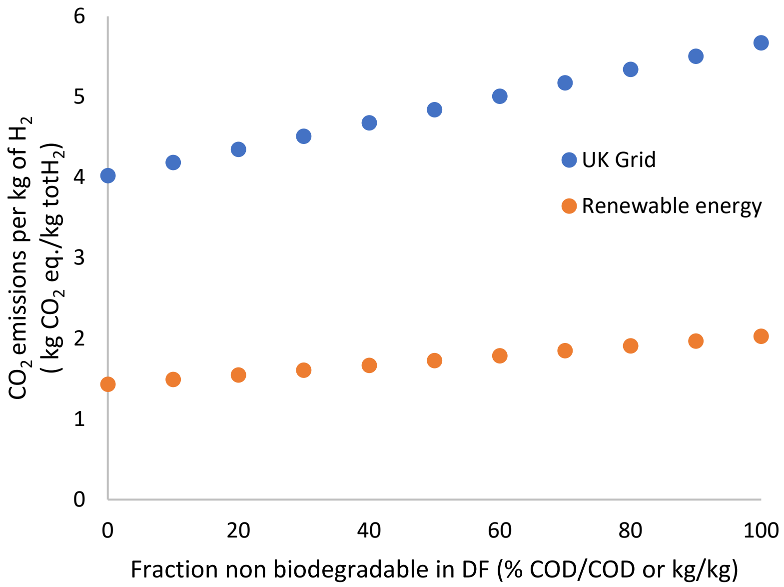


Figure B.1 Comparison of total carbon emissions per kg of hydrogen produced (kg CO_2 eq./kg totH_2) for food waste using electricity from Renewable and UK grid.

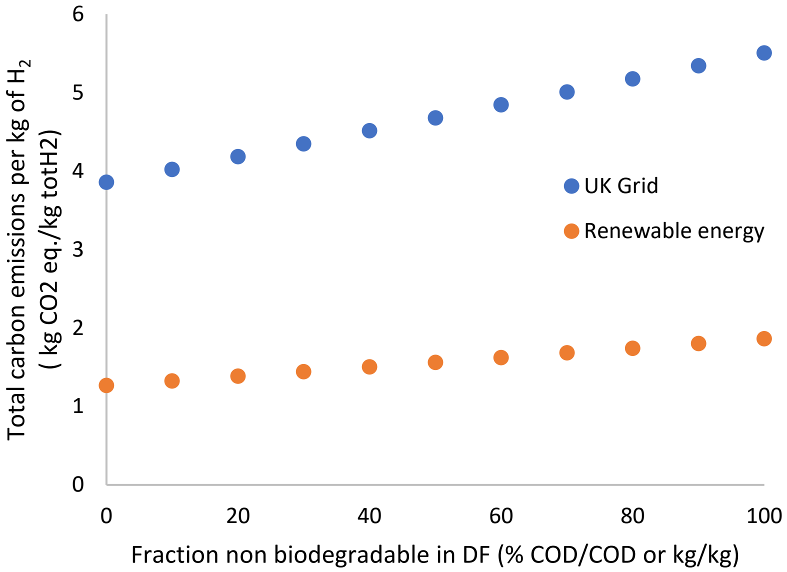


Figure B.2 Comparison of total carbon emissions per kg of Hydrogen produced (kg CO_2 eq./kg totH_2) for wastewater using electricity from Renewable and UK grid.

The above figures illustrate the total carbon emissions in terms of CO_2 equivalents for food waste and wastewater as feedstock. Also, both the figures compare the carbon emissions using UK grid and Renewables as the source of electricity for hydrogen production using each of the two feedstocks. As seen in the figures, the total carbon emissions vary differently depending on the source of electricity as the non-biodegradable fraction changes from 0-100% for both cases. The carbon emissions from wastewater are almost similar to food waste. The carbon emissions using UK grid as the energy source shows a steeper variation when compared to carbon emissions using Renewables as the electricity source. The carbon emissions are not significantly affected in DF stage when compared with the other stages as the hydrogen yield is not significantly affected in this stage.

B.2.2.2 Effect of non-biodegradable organic matter in the anaerobic digestion stage

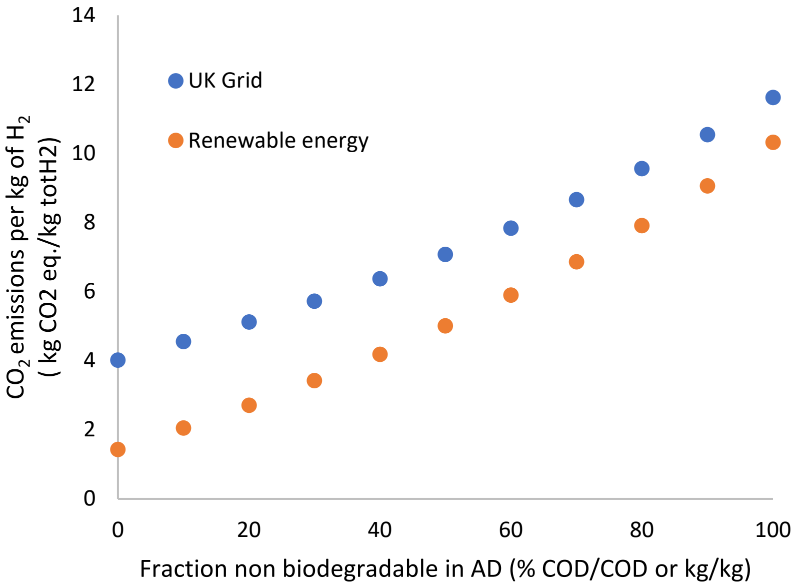


Figure B.3 Comparison of total carbon emissions per kg of hydrogen produced (kg CO_2 eq./kg totH_2) for food waste using electricity from Renewable and UK grid.

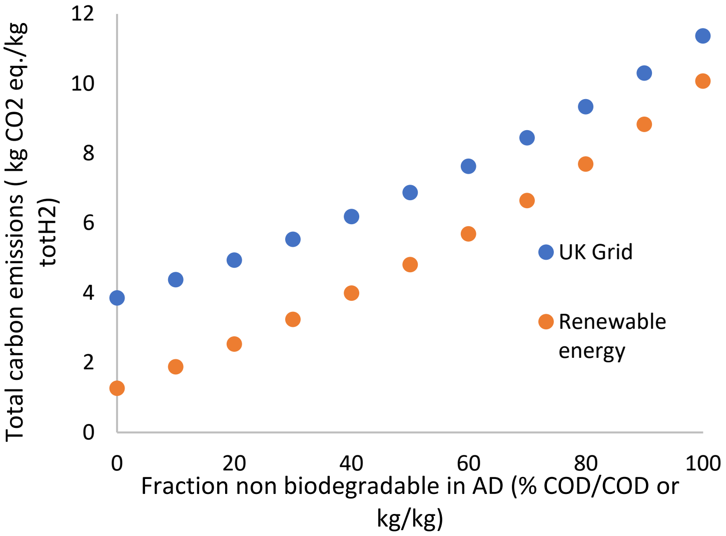


Figure B.4 Comparison of total carbon emissions per kg of Hydrogen produced (kg CO_2 eq./kg totH_2) for wastewater using electricity from Renewable and UK grid.

The above figures illustrate the total carbon emissions in terms of CO_2 equivalents for food waste and wastewater as feedstock. Also, both the figures compare the carbon emissions using UK grid and Renewables as the source of electricity for hydrogen production using each of the two feedstocks. As the non-biodegradable fraction increases in AD, CO_2 emissions increases steadily in both the cases for both sources of energy. This is the expected result because as the non-biodegradable fraction increases, more heating is required in SG stage and therefore more natural gas requirement which is a major contributor to carbon emission. In case of wastewater conversion, the carbon emissions per kg of Hydrogen produced shows a similar trend to food waste even when the source of electricity is changed from UK grid to Renewables.

B.2.2.3 Effect of the efficiency of the plasma reforming stage

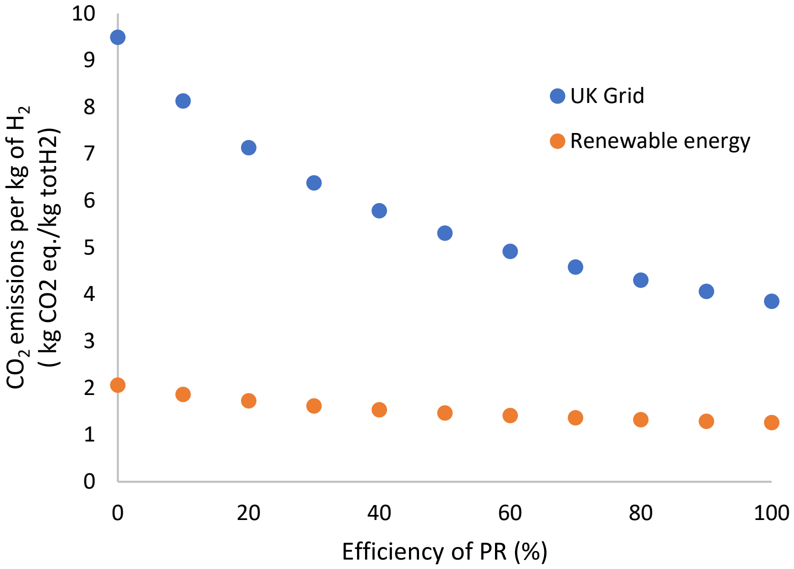


Figure B.5 Comparison of total carbon emissions per kg of hydrogen produced (kg CO_2 eq./kg totH_2) for food waste using electricity from Renewable and UK grid.

The above figures illustrate the total carbon emissions in terms of CO_2 equivalents per kg of hydrogen produced for food waste and wastewater as feedstock. As the efficiency of PR stage increases to 100%, the total carbon emissions decreases. This is expected as more methane is converted to H_2 there is less load on the downstream SG and WGS stages. In case of food waste, the variation in carbon emissions is higher when UK grid is used as a source of electricity as compared to Renewables. For wastewater conversion carbon emissions produced give similar results to with slightly lower value than food waste.

B.2.2.4 Effect of the efficiency of the steam gasification stage

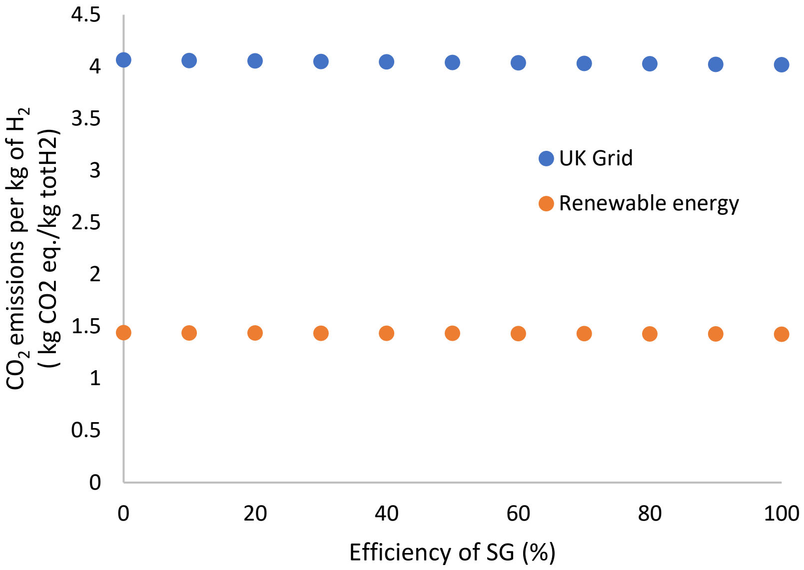


Figure B.6 Comparison of total carbon emissions per kg of hydrogen produced (kg CO_2 eq./kg totH_2) for food waste using electricity from Renewable and UK grid.

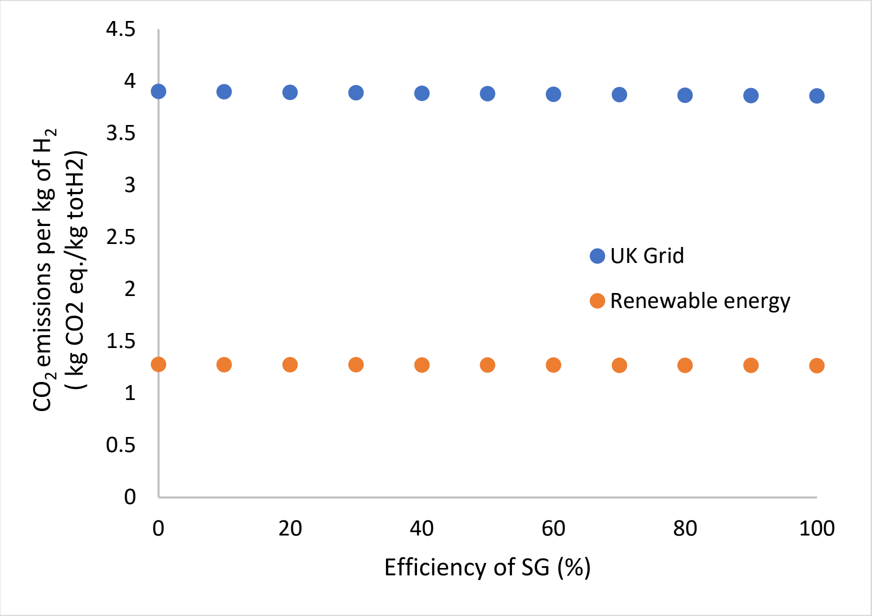


Figure B.7 Comparison of total carbon emissions per kg of Hydrogen produced (kg CO_2 eq./kg totH_2) for wastewater using electricity from Renewable and UK grid.

The above figures illustrate the total carbon emissions in terms of CO_2 equivalents per kg of hydrogen produced for SG when food waste and wastewater is used as feedstock. SG efficiency is varied from 0-100% for both the cases. As seen in the figures, the total carbon emissions do not vary much throughout. This is because the simulations assume 100% efficiency of all the stages while varying the efficiency of the SG stage. This means that with 100% efficiency of the DF and AD stage, all the organic matter is biodegraded and converted into H_2.

B.2.2.5 Effect of the efficiency of the water gas shift stage

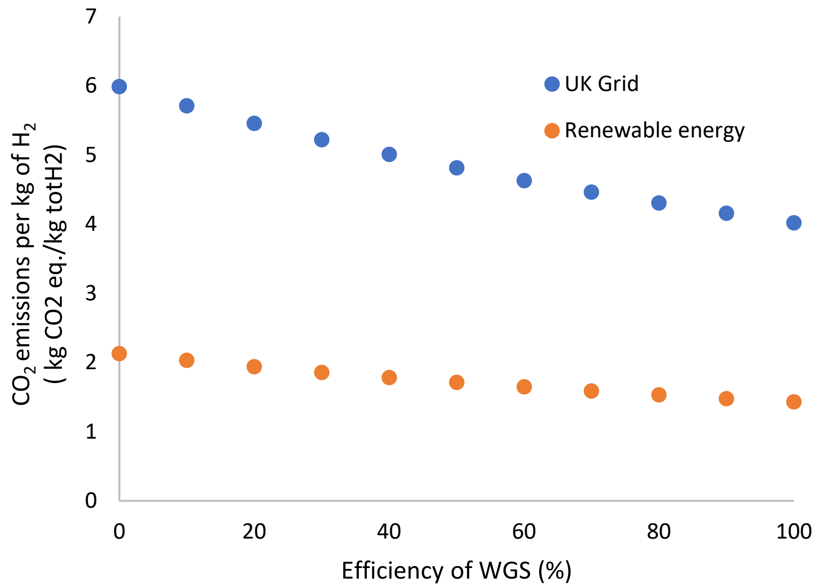


Figure B.8 Comparison of total carbon emissions per kg of hydrogen produced (kg CO_2 eq./kg totH_2) for food waste using electricity from Renewable and UK grid.

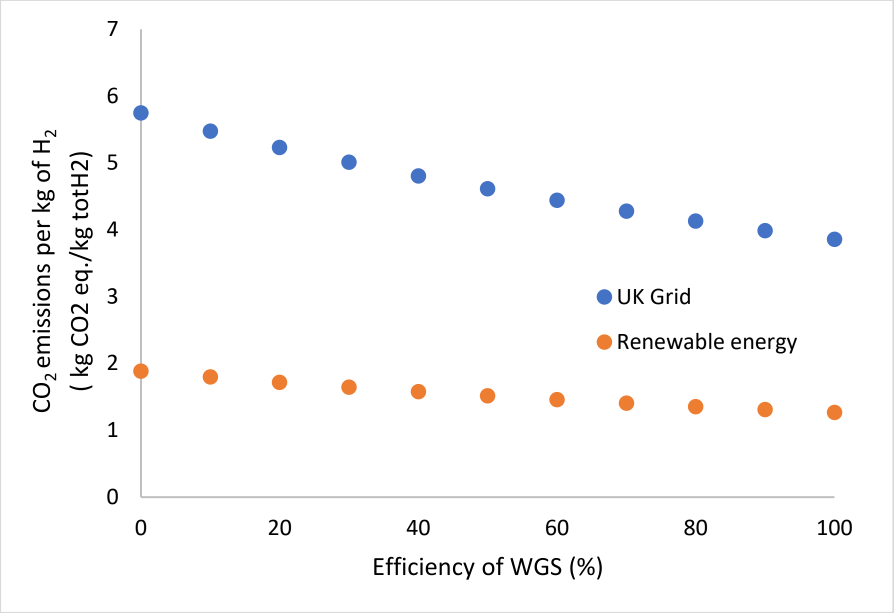


Figure B.9 Comparison of total carbon emissions per kg of Hydrogen produced (kg CO_2 eq./kg totH_2) for wastewater using electricity from Renewable and UK grid.

The figures above show the varying total carbon emissions yields for the WGS stage. With increasing efficiency in WGS, the total carbon emissions decreases. This is because more of energy is consumed as efficiency decreases. For wastewater conversion carbon emissions produced give similar results to food waste.

B.2.2.6 50% efficiency at all stages

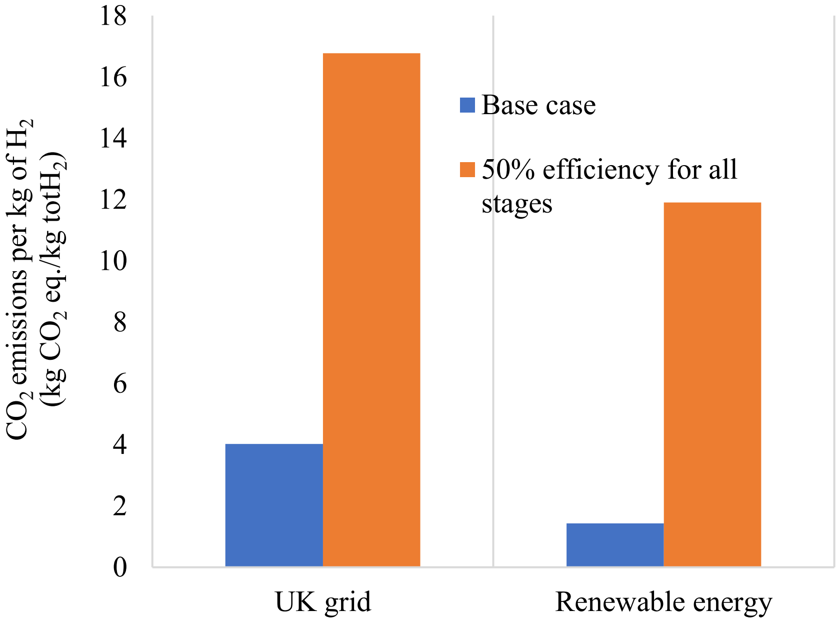


Figure B.10 Comparison of total carbon emissions per kg of hydrogen produced (kg CO_2 eq./kg totH_2) for food waste using electricity from Renewable and UK grid.

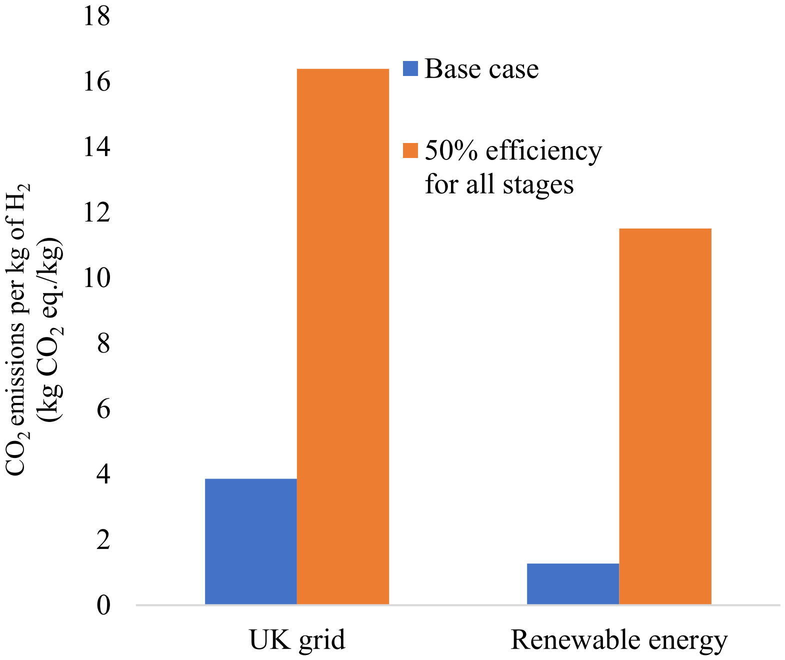


Figure B.11 Comparison of total (kg CO_2 eq./kg totH_2) for wastewater using electricity from Renewable and UK grid.

Above figures give the total carbon emissions per kg of Hydrogen produced when all stages are operating at 50% efficiency. Food waste shows the biggest drop in H_2 yield per kg of dry organic matter when compared to base case therefore, the carbon emissions per kg of hydrogen produced are almost 4 times higher as compared to the base cases. Similarly, in case of wastewater the carbon emissions are higher when all the stages are operated at 50% efficiency due to the drop in hydrogen yield.

B.2.2.7 Double the energy consumption at each stage

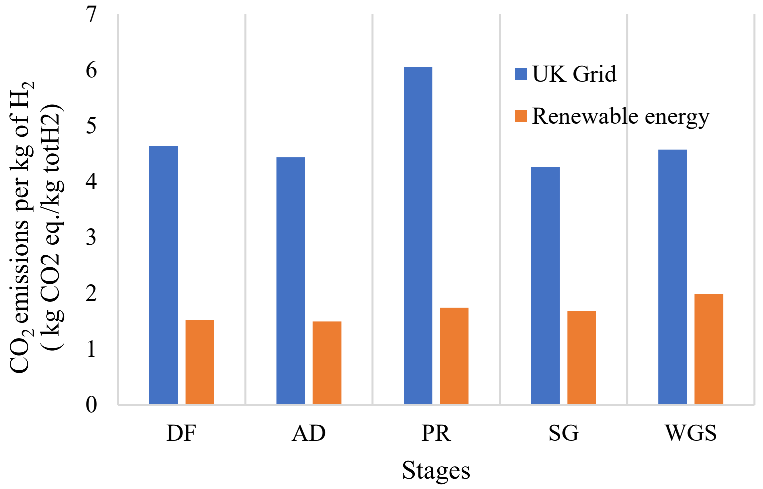


Figure B.12 Double the energy consumption for food waste.

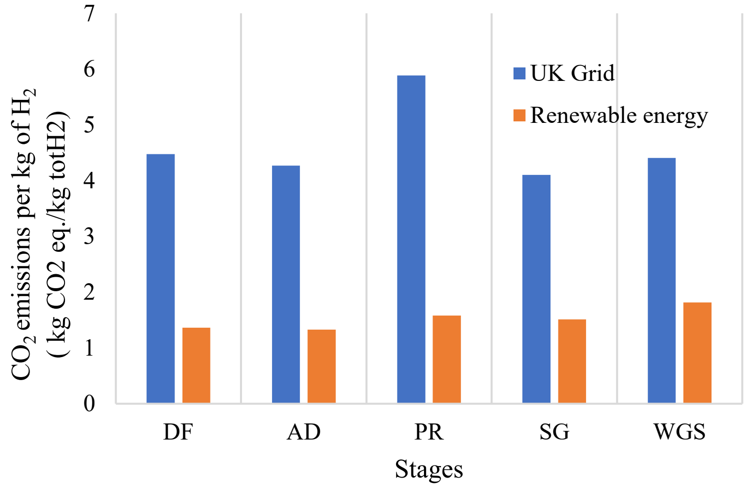


Figure B.13 Double the energy consumption for wastewater.

The effect of doubling the energy consumption of each stage on the total carbon emissions was investigated. The above bar graphs illustrate this for each of the two cases. As evident from the graphs, doubling the energy consumption at the PR stage gives the highest carbon emissions than the rest of the stages (for both the cases). This is because PR is an energy intensive stage and requires much more energy than the other stages. Doubling the energy consumption of the SG stage gives the lowest total energy consumption therefore, a comparatively lowest carbon emission.

B.2.2.8 Steam gasification with 50% non-biodegradable organic matter in dark fermentation and anaerobic digestion

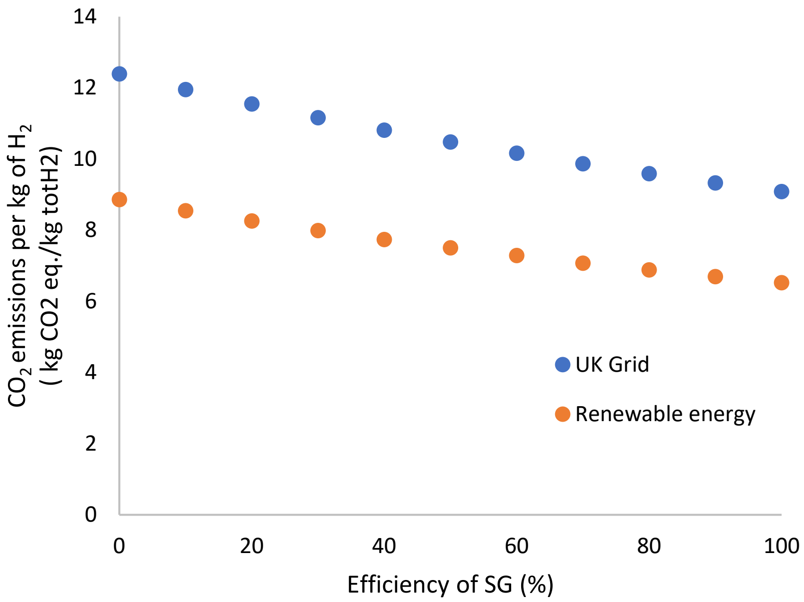


Figure B.14 Comparison of total carbon emissions per kg of hydrogen produced (kg CO_2 eq./kg totH_2) for food waste using electricity from Renewable and UK grid**.**

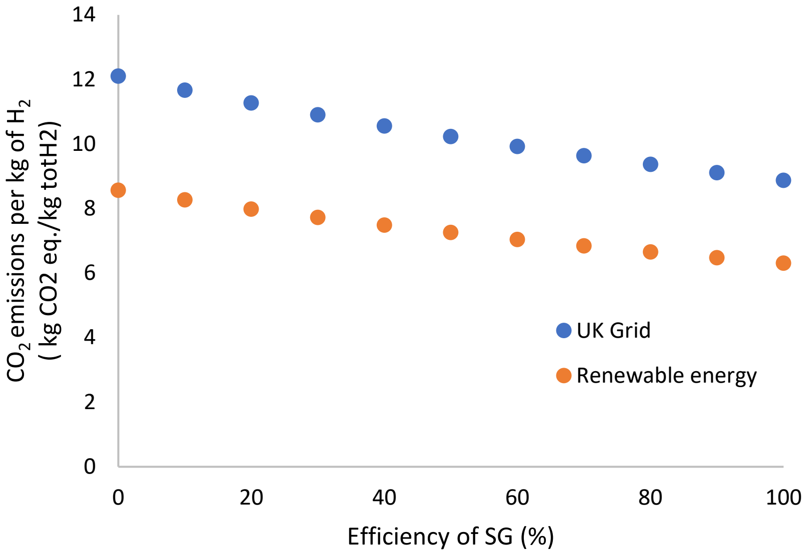


Figure B.15 Comparison of total carbon emissions per kg of hydrogen produced (kg CO_2 eq./kg totH_2) for wastewater using electricity from Renewable and UK grid.

The above figures illustrate the total carbon emissions per kg of hydrogen produced when the efficiency of the SG stage is varied from 0-100% while maintaining the efficiency of the DF and AD stages at 50%. This was investigated because just varying the SG stage does not produce a noticeable change in the total H_2 yield as all the organic matter is biodegraded in the DF and AD stages. All the above figures show that, there is a noticeable decrease in the total carbon emissions as the efficiency of the SG stage increases; this is because the total H_2 yield increases with increase in the efficiency of DF and AD stages (50%).

B.2.3 Effect of the main assumptions on CO_2 eq. emitted per kWh of H_2 produced

B.2.3.1 Effect of non-biodegradable organic matter in the dark fermentation stage

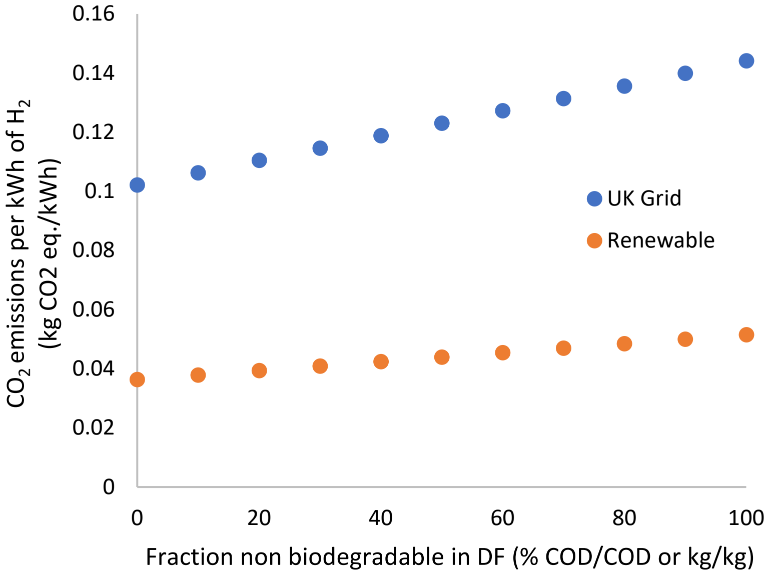


Figure B.16 Comparison of total carbon emissions per kWh of hydrogen produced (kg CO_2 eq./kWh) for food waste using electricity from Renewable and UK grid.

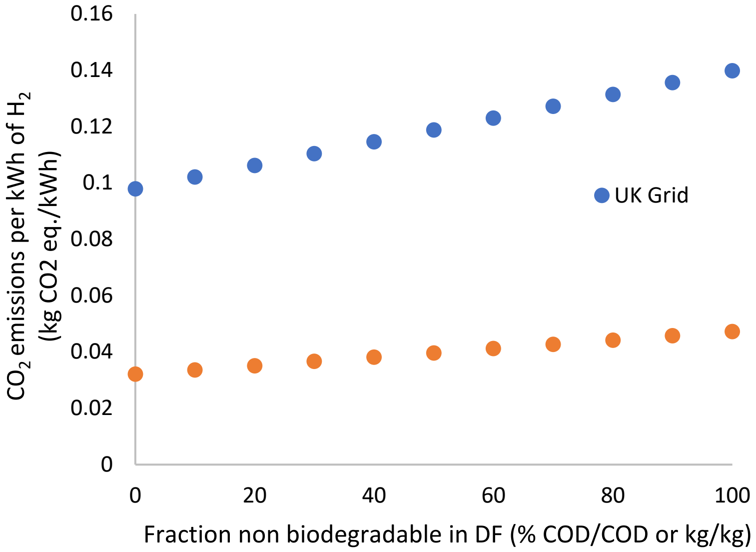


Figure B.17 Comparison of total carbon emissions per kWh of hydrogen produced (kg CO_2 eq./kWh) for wastewater using electricity from Renewable and UK grid.

The above figures illustrate the total carbon emissions in terms of CO_2 equivalents for food waste and wastewater as feedstock. Also, both the figures compare the carbon emissions using UK grid and Renewables as the source of electricity for hydrogen production using each of the two feedstocks. As seen in the figures, the total carbon emissions vary differently depending on the source of electricity as the non-biodegradable fraction changes from 0-100% for both cases. The carbon emissions from wastewater are much higher than from food waste due to the lower yield of hydrogen in case of wastewater. The carbon emissions using UK grid as the energy source shows a steeper variation when compared to carbon emissions using Renewables as the electricity source. The carbon emissions per kWh of hydrogen produced shows an increasing trend as the efficiency of DF stage increases.

B.2.3.2 Effect of non-biodegradable organic matter in the anaerobic digestion stage

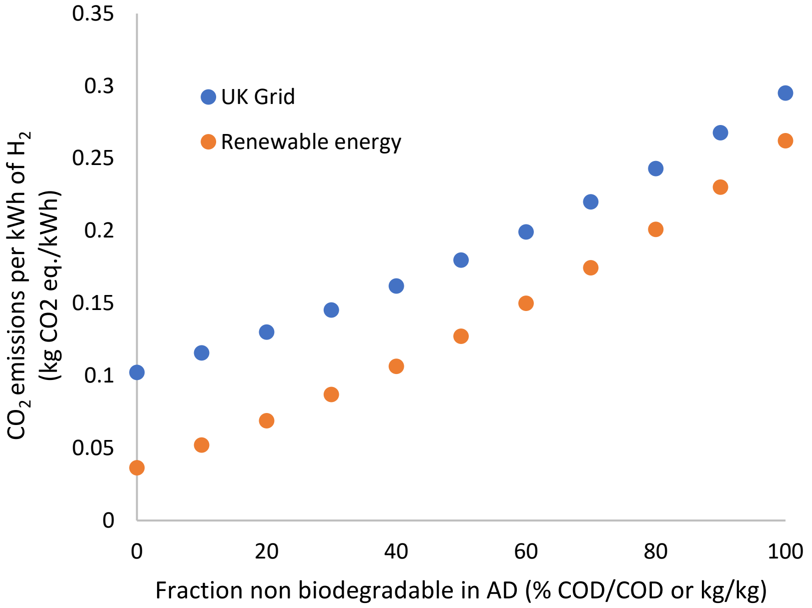


Figure B.18 Comparison of total carbon emissions per kWh of hydrogen produced (kg CO_2 eq./kWh) for food waste using electricity from Renewable and UK grid.

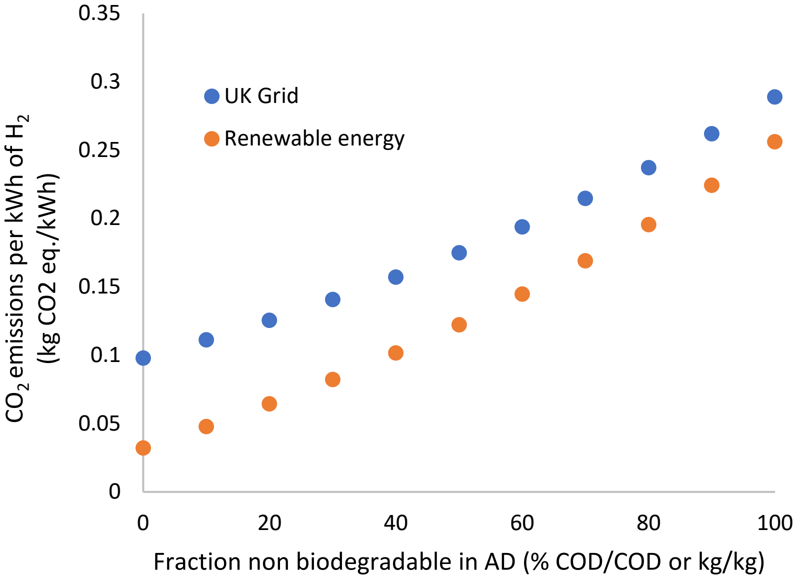


Figure B.19 Comparison of total carbon emissions per kWh of hydrogen produced (kg CO_2 eq./kWh) for wastewater using electricity from Renewable and UK grid.

The above figures illustrate the total carbon emissions in terms of CO_2 equivalents for food waste and wastewater as feedstock. Also, both the figures compare the carbon emissions using UK grid and Renewables as the source of electricity for hydrogen production using each of the two feedstocks. As the non-biodegradable fraction increases in AD, CO_2 emissions increases steadily in both the cases for both sources of energy. The increase in the total carbon emissions with increase in the non-biodegradable fraction is because the organic matter that is not biodegraded in this stage would react in the SG stage to produce H_2 and CO. The CO is then further converted to H_2 using the WGS stage which is energy intensive.

B.2.3.3 Effect of the efficiency of the plasma reforming stage

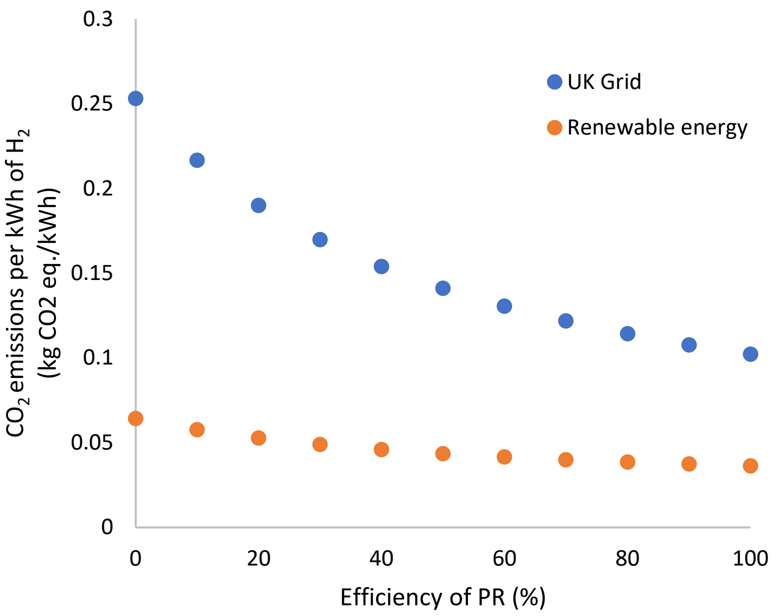


Figure B.20 Comparison of total carbon emissions per kWh of hydrogen produced (kg CO_2 eq./kWh) for food waste using electricity from Renewable and UK grid.

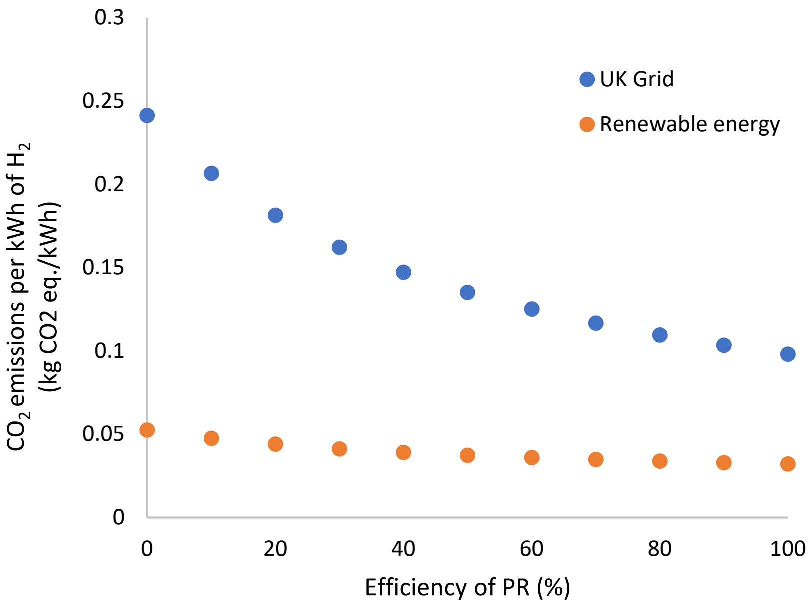


Figure B.21 Comparison of total carbon emissions per kWh of hydrogen produced (kg CO_2 eq./kWh) for wastewater using electricity from Renewable and UK grid.

The above figures illustrate the total carbon emissions in terms of CO_2 equivalents per kWh of hydrogen produced for SG when food waste and wastewater is used as feedstock. SG efficiency is varied from 0-100% for both the cases. The above figures show how the total carbon emissions varies with the efficiency of the PR stage. Unlike the previous stages, the total carbon emissions in terms of CO_2 equivalents per kWh of hydrogen produced decreases with increasing efficiency of PR. This is because the PR stage is energy intensive, hence with increasing efficiency, the total CO_2 emissions per kWh of hydrogen produced is reduced.

B.2.3.4 Effect of the efficiency of the steam gasification stage

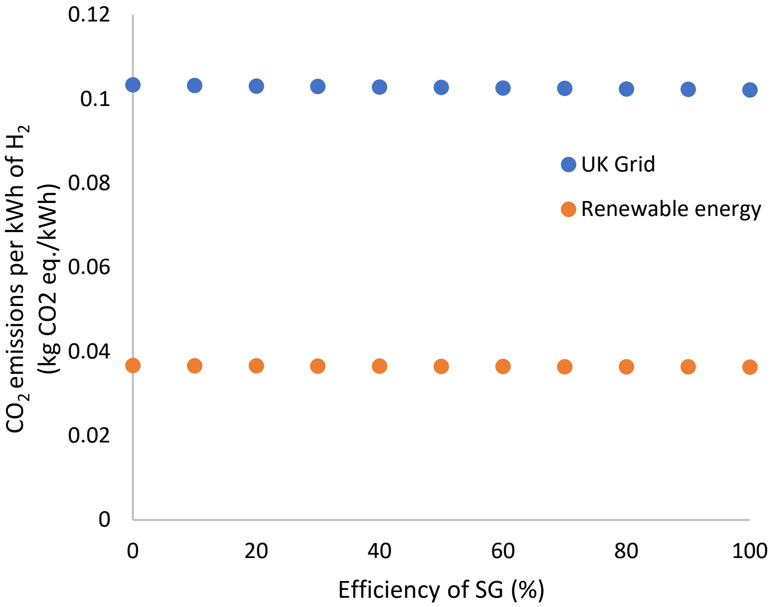


Figure B.22 Comparison of total carbon emissions per kWh of hydrogen produced (kg CO_2 eq./kWh) for food waste using electricity from Renewable and UK grid.

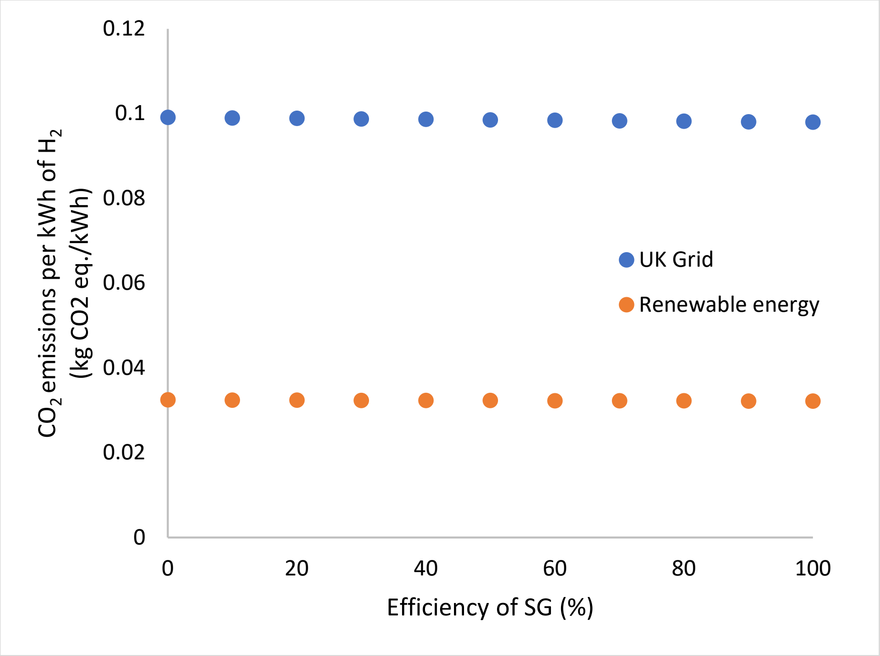


Figure B.23 Comparison of total carbon emissions per kWh of hydrogen produced (kg CO_2 eq./kWh) for wastewater using electricity from Renewable and UK grid.

The above figures illustrate the total carbon emissions in terms of CO_2 equivalents per kWh of hydrogen produced for SG when food waste and wastewater is used as feedstock. As seen in the figures, the total carbon emissions do not vary noticeably as the efficiency of the SG changes from 0-100%. This is because the simulations assume 100% efficiency of all the stages while varying the efficiency of the SG stage. This means that with 100% efficiency of the DF and AD stage, all the organic matter is biodegraded and converted into H_2. Therefore, the SG stage would not have any organic matter to react to produce H_2, hence, the carbon emissions do not change much.

B.2.3.5 Effect of the efficiency of the water gas shift stage

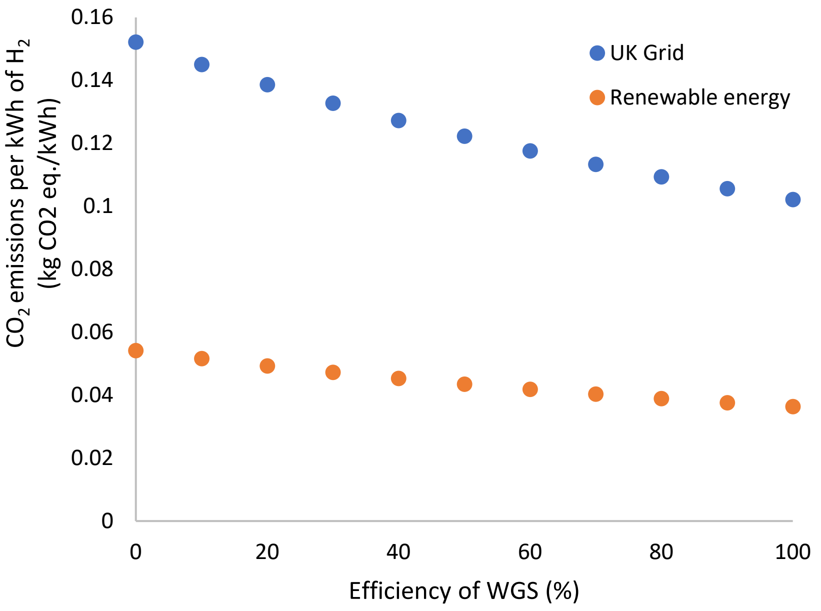


Figure B.24 Comparison of total carbon emissions per kWh of hydrogen produced (kg CO_2 eq./kWh) for food waste using electricity from Renewable and UK grid.

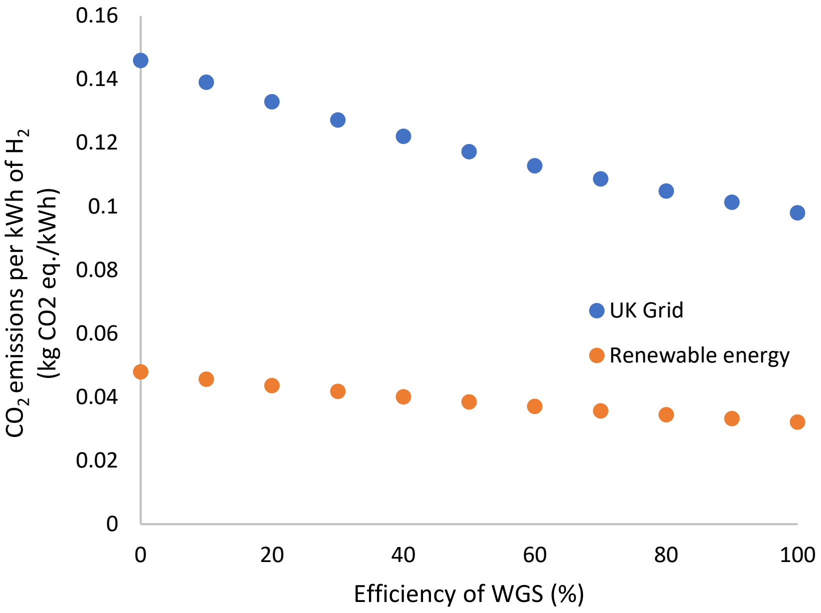


Figure B.25 Comparison of total carbon emissions per kWh of hydrogen produced (kg CO_2 eq./kWh) for wastewater using electricity from Renewable and UK grid.

The figures above show the varying total carbon emissions yields for the WGS stage. With increasing efficiency in WGS, the total carbon emissions per kWh of hydrogen produced decreases. This is because more of energy is consumed as efficiency decreases. For wastewater conversion carbon emissions produced give similar results irrespective of the source of electricity used.

B.2.3.6 50% efficiency at all stages

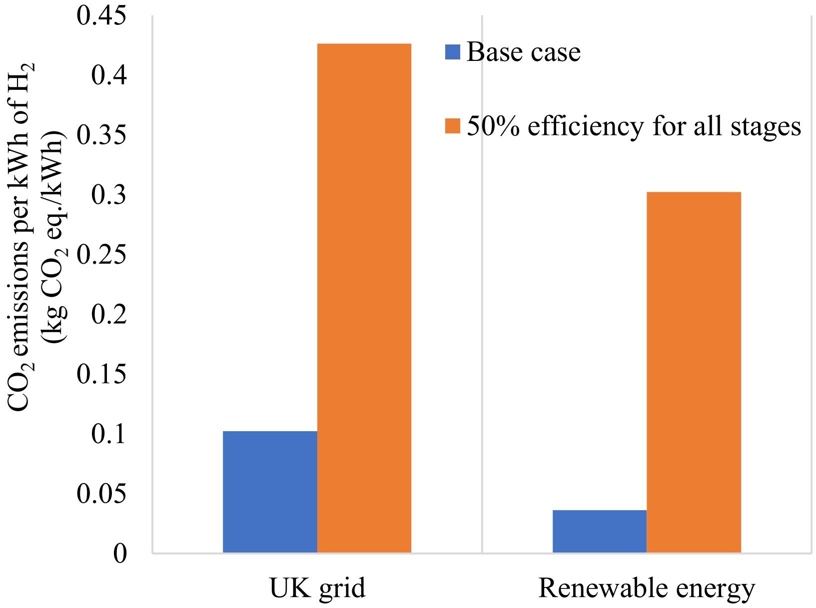


Figure B.26 Comparison of total carbon emissions per kWh of hydrogen produced (kg CO_2 eq./kWh) for food waste using electricity from Renewable and UK grid.

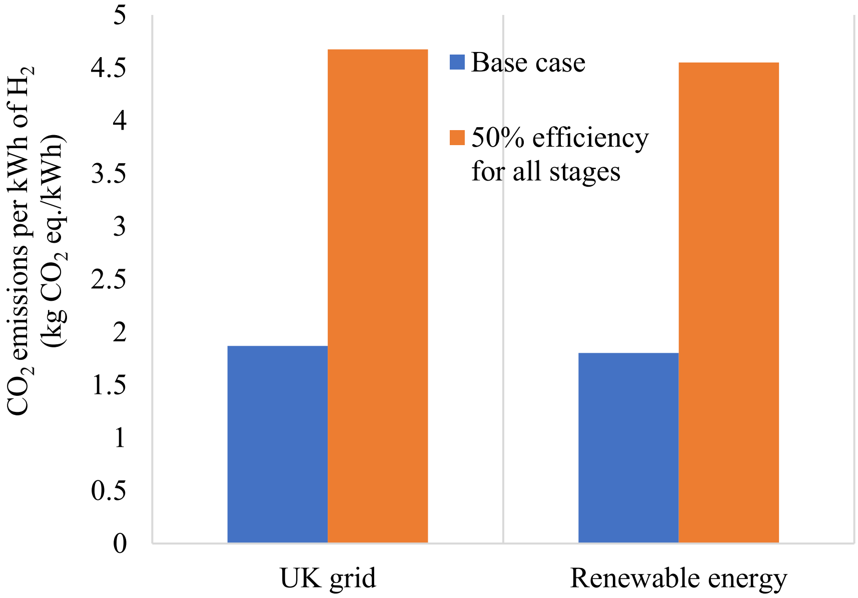


Figure B.27 Comparison of total carbon emissions per kWh of hydrogen produced (kg CO_2 eq./kWh) for wastewater using electricity from Renewable and UK grid.

Above figures gives the total carbon emissions per kWh of Hydrogen produced when all stages are operating at 50% efficiency. Food waste shows the biggest drop in H_2 yield per kg of dry organic matter when compared to base case therefore, the carbon emissions per kWh of hydrogen produced are much higher than the base cases. Similarly, in case of wastewater the carbon emissions are higher when all the stages are operated at 50% efficiency due to the drop in hydrogen yield. In reality, the stages would not operate at 100% efficiency.

B.2.3.7 Double the energy consumption at each stage

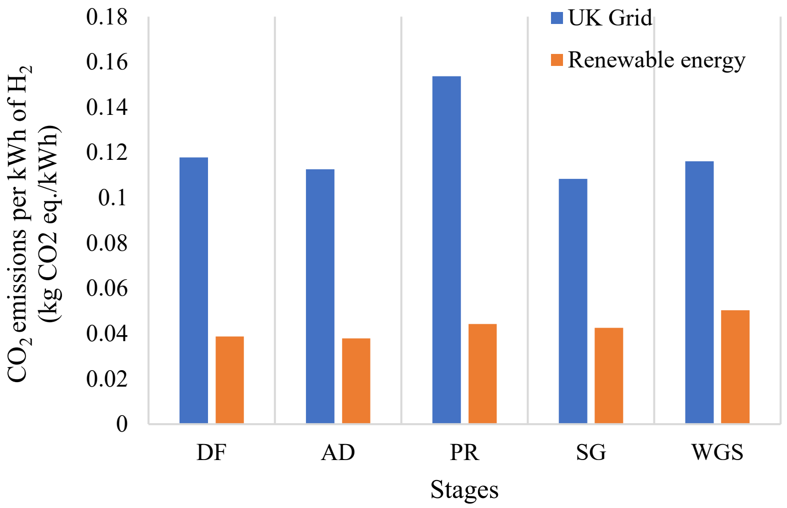


Figure B.28 Double the energy consumption for food waste.

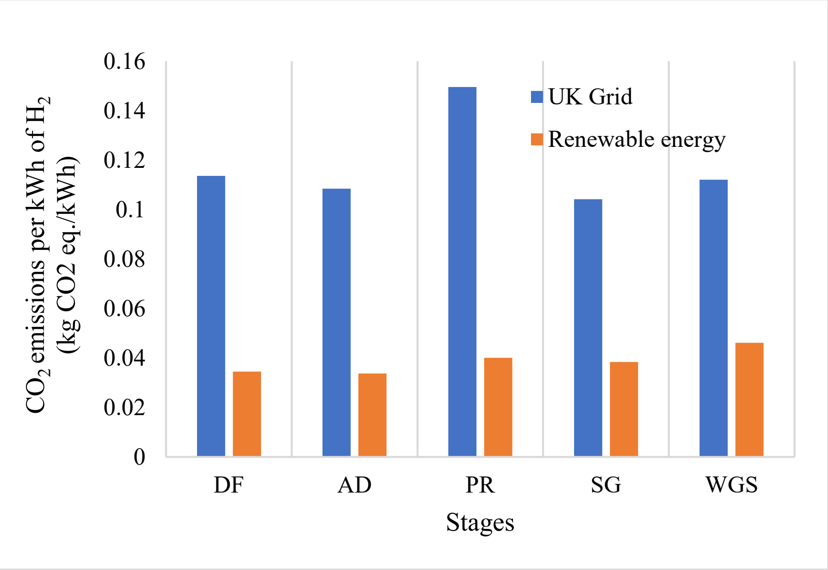


Figure B.29 Double the energy consumption for wastewater.

The effect of doubling the energy consumption of each stage on the total energy consumption was investigated. The above bar graphs illustrate this for each of the two cases. As evident from the graphs, doubling the energy consumption at the PR stage gives the highest total carbon emissions than the rest of the stages (for all three cases). This is because PR is an energy intensive stage and requires much more energy than the other stages. Doubling the energy consumption of the SG stage gives the lowest total carbon emissions per kWh of hydrogen produced.

B.2.3.8 Steam gasification with 50% non-biodegradable organic matter in dark fermentation and anaerobic digestion

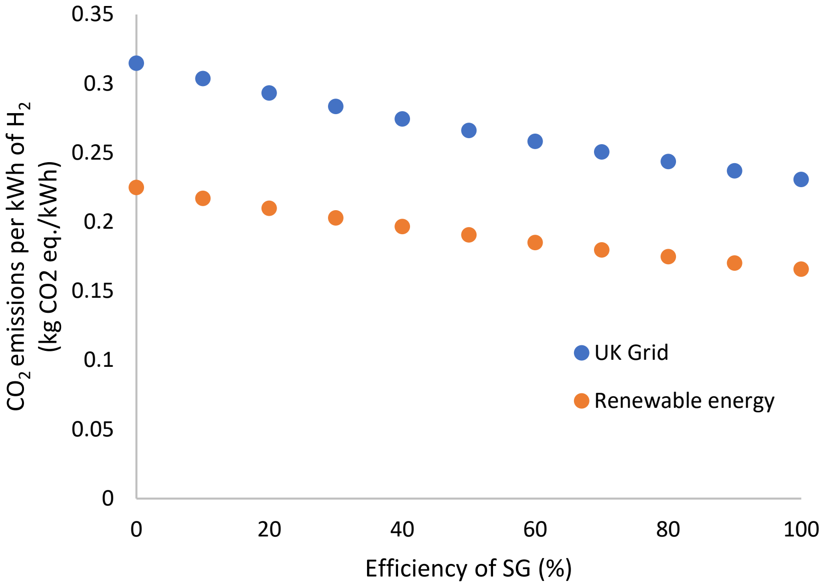


Figure B.30 Comparison of total carbon emissions per kWh of hydrogen produced (kg CO_2 eq./kWh) for food waste using electricity from Renewable and UK grid.

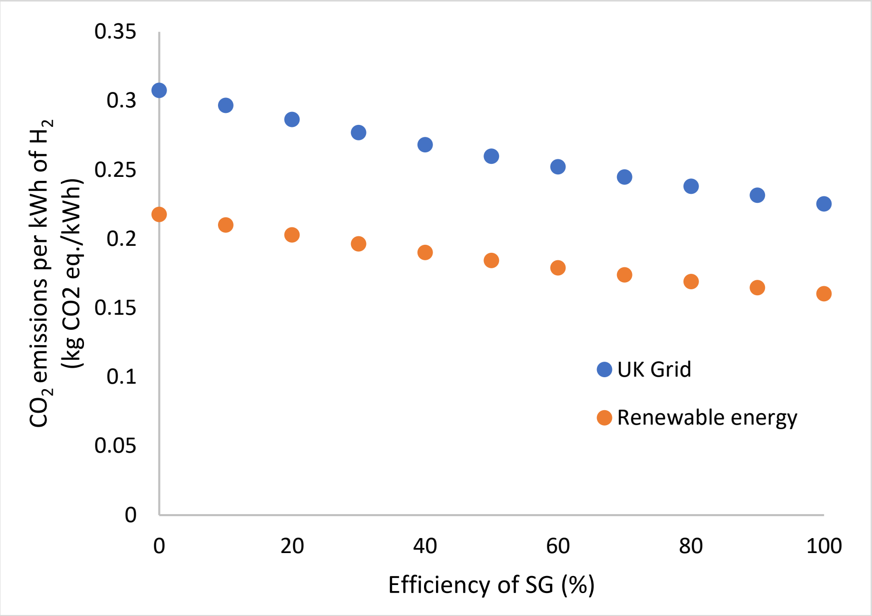


Figure B.31 Comparison of total carbon emissions per kWh of hydrogen produced (kg CO_2 eq./kWh) for wastewater using electricity from Renewable and UK grid.

The above figures illustrate the total carbon emissions per kWh of hydrogen produced when the efficiency of the SG stage is varied from 0-100% while maintaining the efficiency of the DF and AD stages at 50%. This was investigated because just varying the SG stage does not produce a noticeable change in the total H_2 yield as all the organic matter is biodegraded in the DF and AD stages. All the above figures show that, there is a noticeable decrease in the total carbon emissions as the efficiency of the SG stage increases; this is because the total H_2 yield increases with increase in the efficiency of DF and AD stages (50%).

Appendix C. WP3. Lab-scale prototype

C.1 Design and assembly of the lab prototype

C.1.1 Biological stages (DF and AD)

Lab scale batch and sequencing batch reactors have been designed and purchased to run the biological stages. The system (Figure C.1) consists of glass bottles and jacketed vessels for the reaction stages (DF and AD), and of vessels for feed and effluent collection. All the vessels are made of glass, with a volume of 1-3.5 L. The vessels are closed with lids with various ports for sampling, feeding and effluent collection. The gas phase leaves from one of the ports and passes through a gas sampling tube, from which samples are taken to analyse the gas composition via GC (gas chromatography). After the sampling tube, the gas passes through a gas counter (Milligascounter, Ritter) to measure the volumetric gas production.

The effluent vessels are sampled regularly to measure the biodegradation of the organic matter.

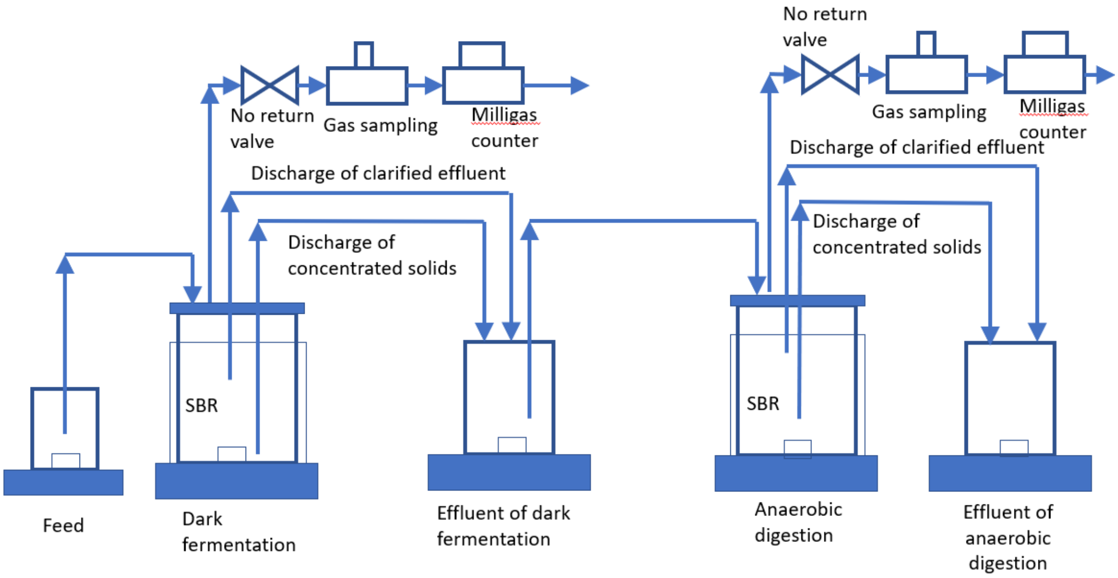
The batch reactor set-up consists of 250 mL glass bottles, closed with lids and septa. The bottles are sampled at regular time intervals to measure the production of acids and the biodegradation of the organic matter.

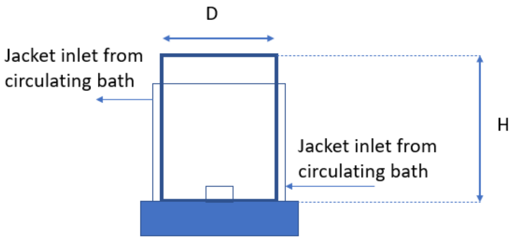
Table C.1. summarises the experimental conditions of the DF and AD batch experiments ran in Phase 1.

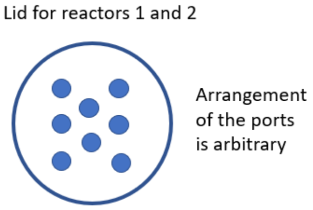
For the SBR experiments (results shown in Figure 3.3 in the main report), the feed was composed of glucose 2 g/L until day 7, then it was composed of a mixture of glucose (6.2 g/L), yeast extract (1.8 g/L) and oleic acid (2.0 g/L) (total 10 g/L), modelled based on the composition of food waste used in our earlier study [C.1].

Table C.1. Experimental conditions for DF and AD batch experiments in Phase 1.

Experiment no.	Inoculum	Substrate	Pre-treatment	Length (d)	pH controlled
1	Digestate from AD plant treating food and farm waste	Glucose 2 g/L	No	7	No
2		Glucose 2 g/L	Inoculum pre-heated at 97 ^{O}C for 20 min	7	No
3		Glucose 2 g/L	No	7	No
4		Glucose 10 g/L	No	7	Buffered vs unbuffered
5		Glucose 2 g/L	No	7	No
6		Yeast extract 2 g/L	No	7	No







For reactor 1 (Dark Fermentation): Volume=1.5 L; D=11 cm; H=16 cm

For reactor 2 (Anaerobic Digestion): Volume=3.5 L; D=16 cm; H=18 cm

Lids for reactors 1 and 2 with 8 ports each for: Feed; Effluent discharge; Sludge discharge; Sampling; Gas outlet; pH probe; Base addition; Acid addition.
The lid and the ports should be able to be securely fitted with gas tight connections avoiding gas leaks.
The ports should be able to be closed if not in use.

Example of gas sampling port

Tubes for gas outlet and collection should be in Tygon

Figure C.1 DF and AD stages: Experimental set-up for the lab-prototype.

C.1.2 Steam Gasification (SG) stage

The lab-scale assembly of the SG stage (Figure C.2) consists of a furnace able to reach temperatures of up to 1,000 ^{O}C, a tube and holder for the biomass sample, a syringe pump for the feeding of the reaction water (turned into steam in the furnace), a thermocouple for temperature measurement and a tube for nitrogen purging.

In the operation of the equipment, the sample of organic matter is placed inside the furnace which is then heated to the desired temperature (typically in the range 750-850 ^{O}C). The product gases are collected in a gas bag and then analysed in a GC. The experiments of the SG stage were carried out in the temperature range 750-850 ^{O}C with 0.5 g of digestate and with a steam/organic matter ratio of 3 g/g.

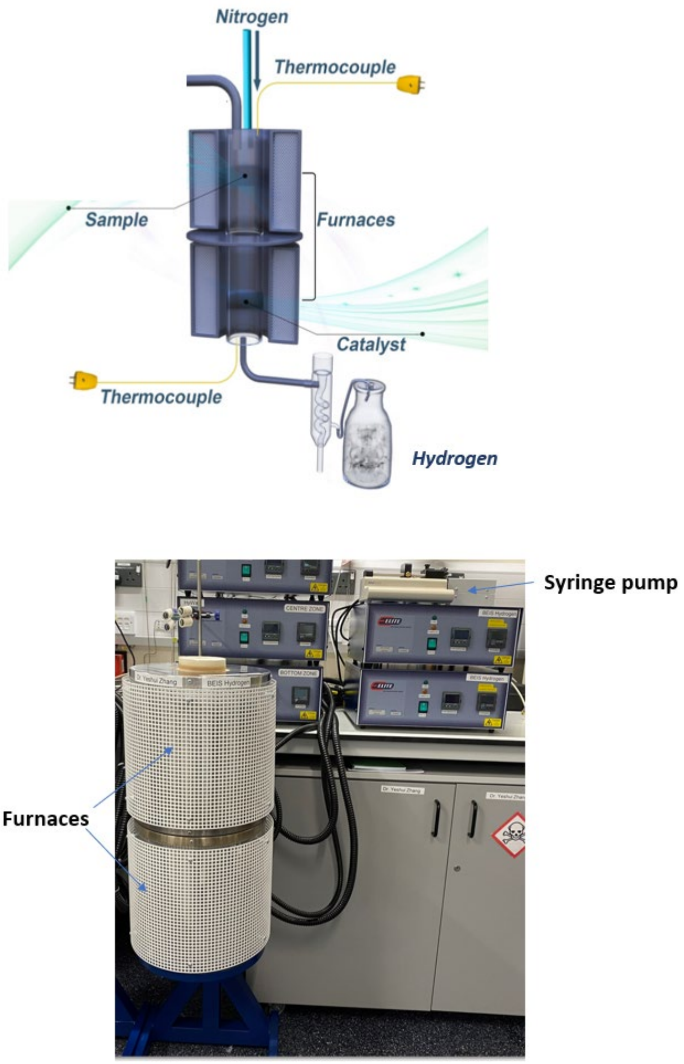


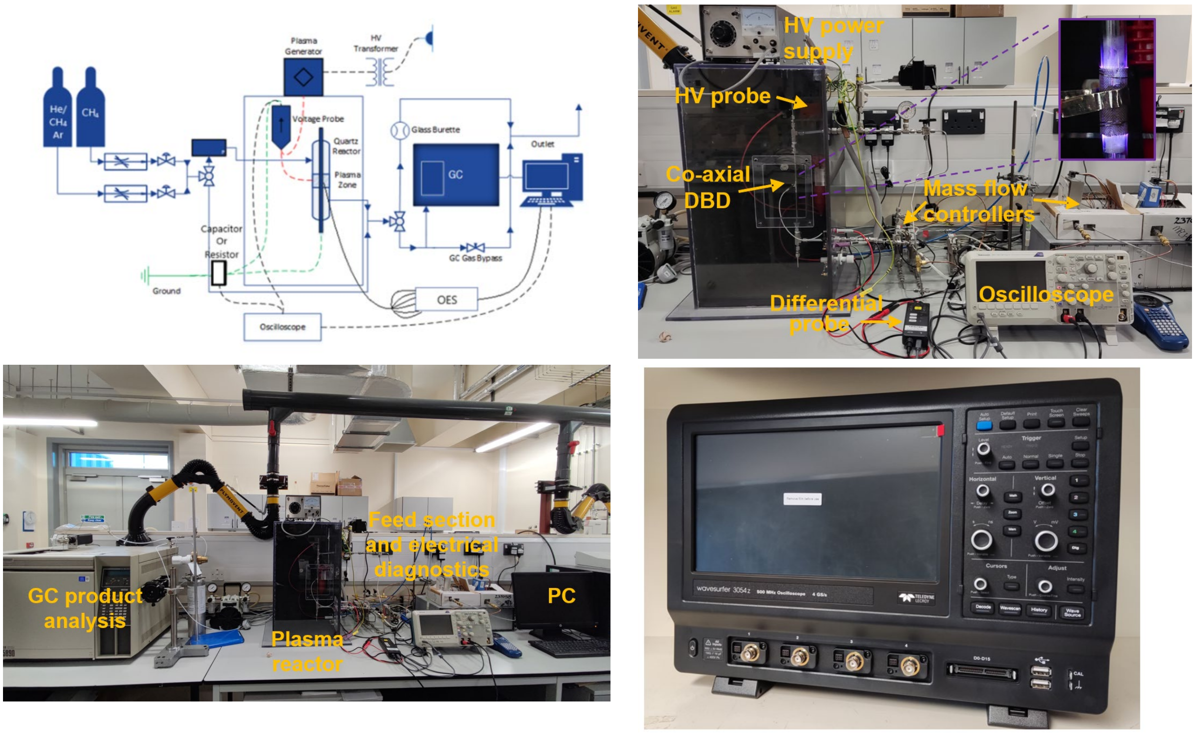
Figure C.2. SG stage: Experimental set-up of the lab prototype

C.1.3 Plasma Reforming (PR) stage

The lab-scale plasma assembly of the PR stage consists of the following equipment (Figure C.3):

- HVP-15P Nanosecond High Voltage Pulse generator: Power supply able to deliver high voltage pulses of up to +15 kV of nanosecond duration at KHz repetition frequencies;
- Teledyne LeCroy WaveSurfer 3054z Oscilloscope: 500MHz 4 Channel Mixed Signal Oscilloscope for electrical diagnostics of the plasma;
- Tektronix P6015A High Voltage probe: Oscilloscope probe for the measurement of the applied high voltage potential (up to 20kV and 75MHz) for the generation of the plasma;
- Testec TT-SI 8052 Differential Probe: Oscilloscope probe for the measurement of differential voltage (up to 1.5kV and 200MHz) used to quantify the deposited power in the plasma.

The gas mixture, controlled to the desired composition, is fed to the plasma reactor via mass flow controllers. The outlet gases pass through a GC for the measurement of the gas composition.



Teledyne LeCroy WaveSurfer 3054z Oscilloscope

Tektronix P6015A High Voltage probe

Testec TT-SI 8052 Differential Probe

Figure C.3. PR stage: Experimental set-up of the lab prototype

C.2 Experimental results

C.2.1 Biological stages

In Experiment 1 (Figure C.4), the pH dropped in the first three days of the experiment from an initial value of 8.0 to approximately 6.0, due to the production of organic acids. Organic acids were formed during the experiment, with predominance of butyric and acetic acids. The formation of butyric and acetic acids is consistent with the production of hydrogen, according to the respective fermentation reactions of glucose under anaerobic conditions. The COD balance at the end of Experiment 1 indicated that 24 % of the COD fed with the initial glucose was converted into gas. This gas formation can be attributed to hydrogen due to the low pH, which is known to inhibit methanogenic activity, and to the formation of organic acids which are typically associated with hydrogen production.

In Experiment 2 (Figure C.5), the pre-treatment of the inoculum at high temperature seemed to favour methanogenic (anaerobic digestion) rather than dark fermentation conditions. This can be observed from the higher pH than in Experiment 1 (7.0 vs 6.0), from the higher COD removal (COD removal higher than 30 % is typically associated to methane rather than hydrogen formation) and from the absence among the acids formed of acetic and butyric acid, which are usually associated with hydrogen production.

In Experiment 3 (Figure C.6), the pH dropped in a few days to the value of approximately 4, indicating high production of organic acids. A high hydrogen production started at day 4, with pressure up to 300 mbar and hydrogen content in the biogas of up to 14 % in volume. No methane was detected in the biogas. At the end of the experiment, the decrease in COD of the liquid phase was 28% compared to the start of the test, which indicate high hydrogen yield. By comparison, the hydrogen yield calculated for the base case in WP1 was 33 % on a COD basis (Equation A.5 in Appendix A), which is only slightly higher than the experimental yield measured in Experiment 3.

In Experiment 4 (Figure C.7), as expected, the pH in the buffered experiment decreased only slightly, with a final pH of 7.0. On the contrary, in the unbuffered experiment the pH decreased very significantly to a final value of below 4.0, due to acidification. The COD removal at the end of the experiment was higher in the buffered experiment. This is consistent with the occurrence of methanogenesis in the buffered experiment and with hydrogen production in the unbuffered experiment.

Experiment 5 was essentially a replicate of Experiment 3, with more frequent sampling for pressure and biogas composition. The results were similar to Experiment 3, with a final pH of 4 a removal of COD of 16 % and the pressure and hydrogen content in the biogas shown in Figure C.8. No methane was detected in the biogas.

Experiment 6 was done in the same way as Experiment 3 and Experiment 5, but with yeast extract as a substrate. At the end of the 7-day experiment, a final pH of 4 and a 29% COD removal was measured, which is particularly high and indication of high hydrogen yield.

Considerations on the hydrogen yield from these experiments have been done in Section 3 of the main report (Figure 3.1). The hydrogen content in the biogas was, during hydrogen production, up to 10-15 % v/v, the remaining mostly being CO_2. The relatively low hydrogen content in the biogas from DF is consistent with the low pH observed in the DF experiment, as at low pH a larger fraction of the produced CO_2 will be in the biogas due to the chemical equilibria of carbonic acid. This hydrogen content in the biogas from DF is not expected to be a problem for the pilot and commercial process as the membranes used in the purification stage are selectively permeable only to hydrogen and are still expected to give hydrogen of the required purity.

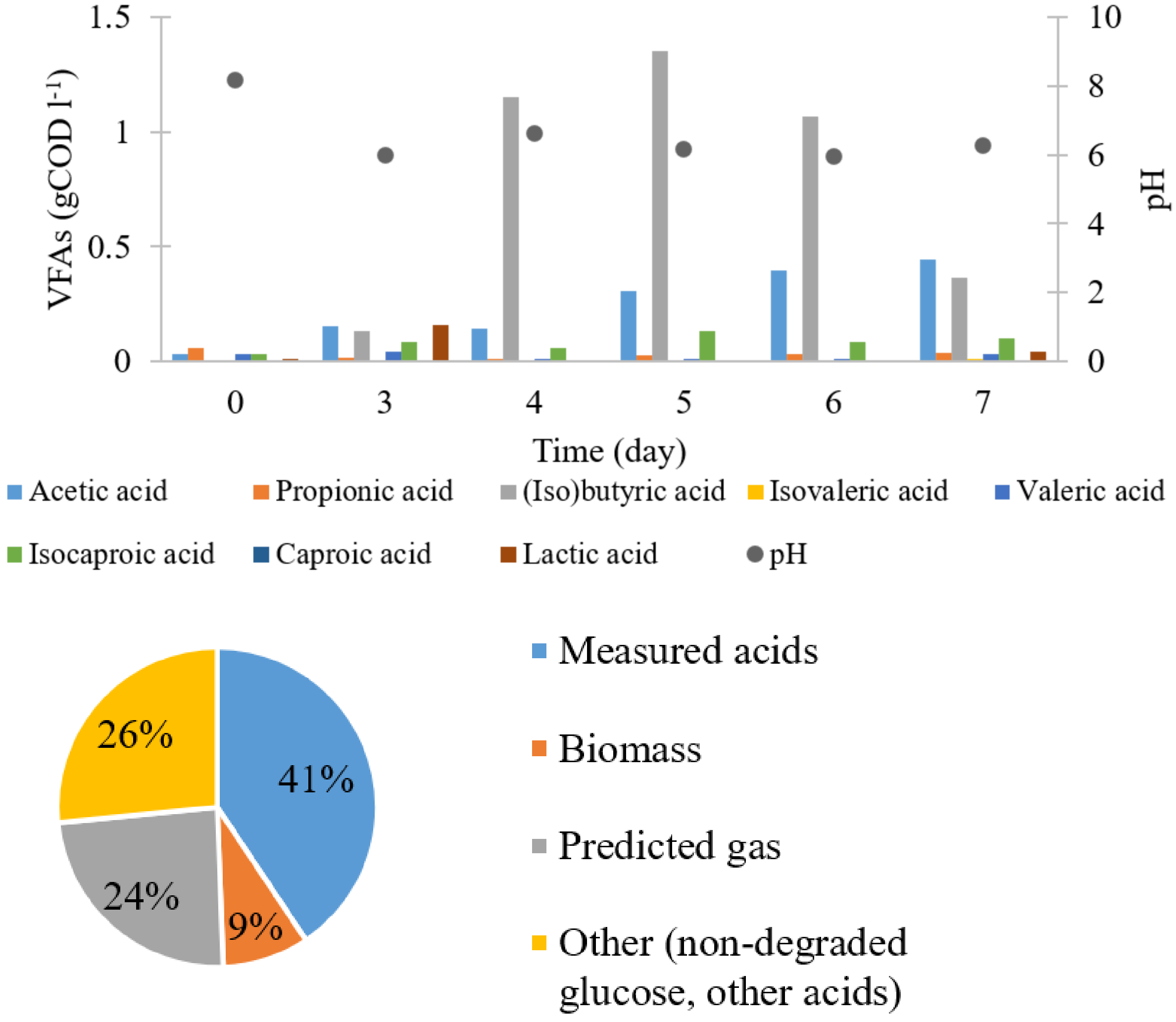


Figure C.4. Biological stages. Results of Experiment 1

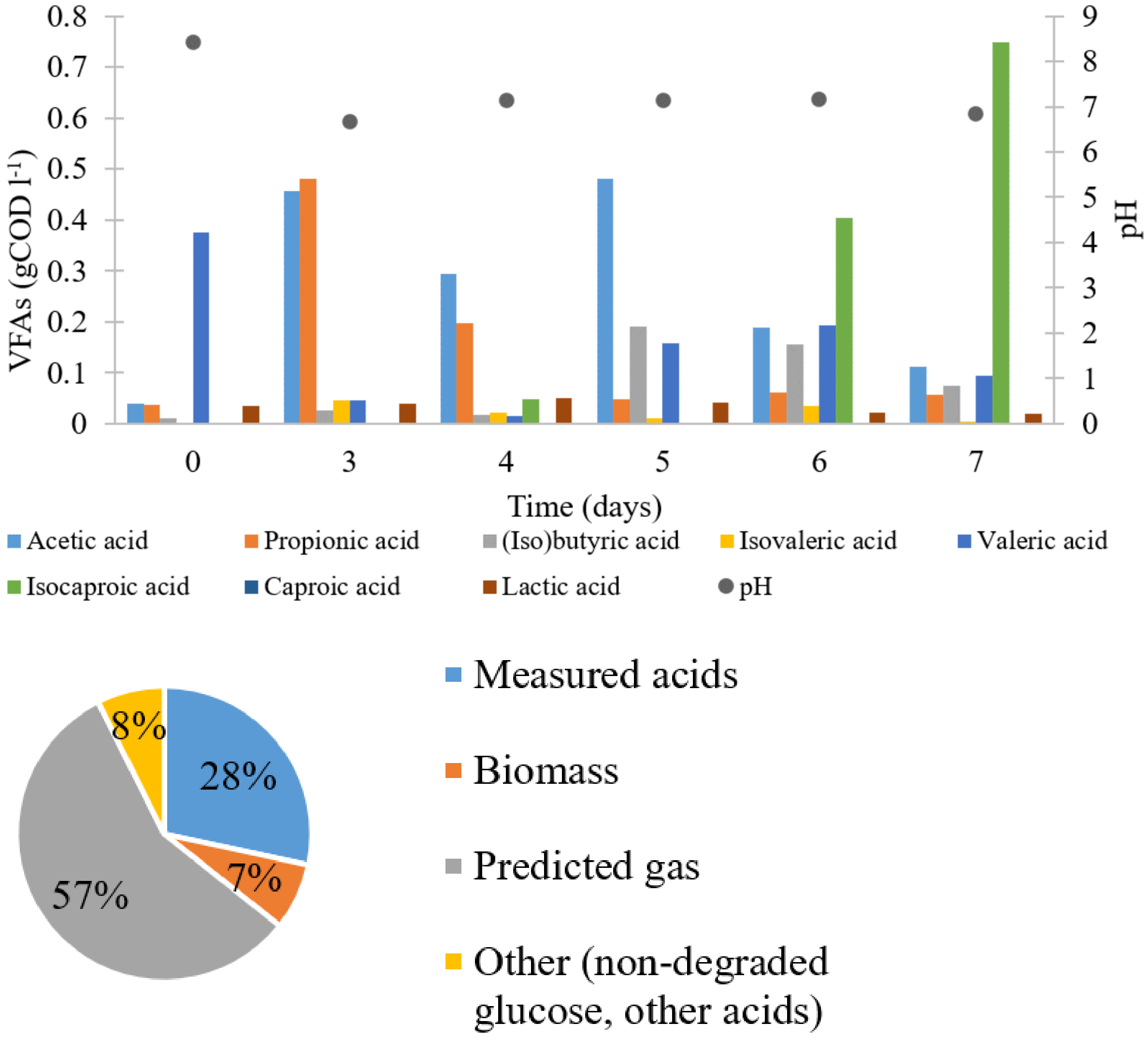


Figure C.5. Biological stages. Results of Experiment 2

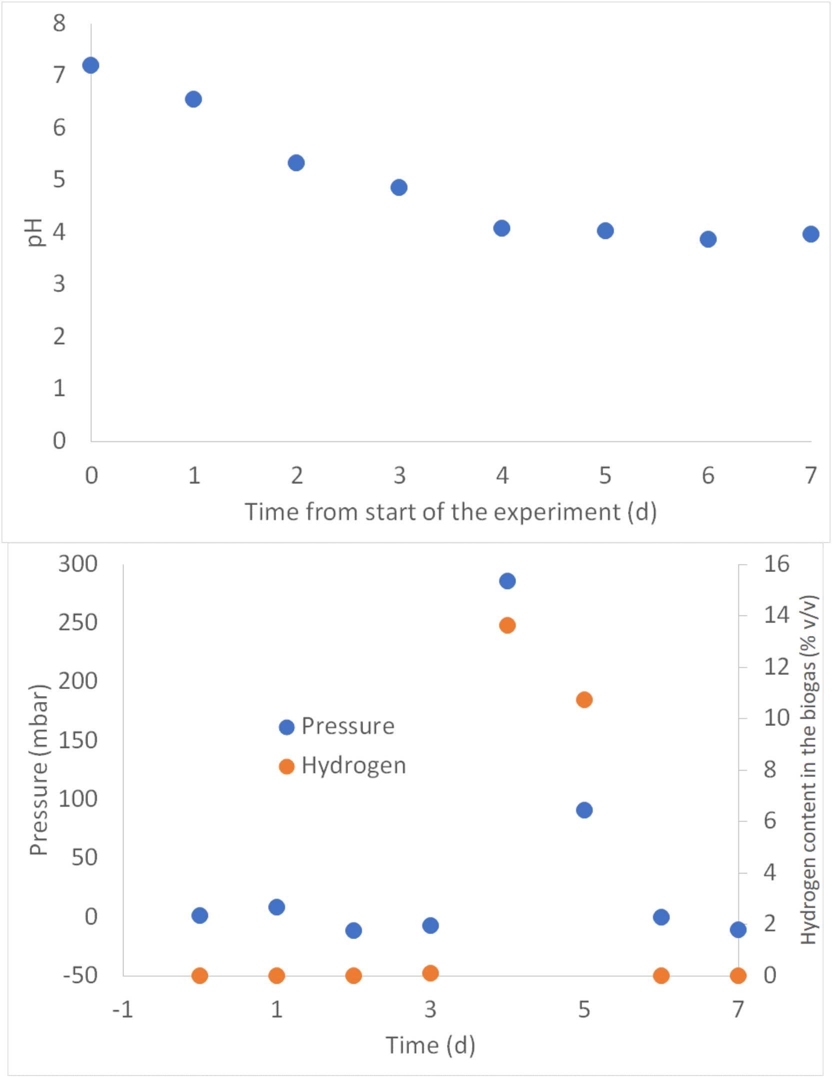


Figure C.6. Biological stages. Results of Experiment 3

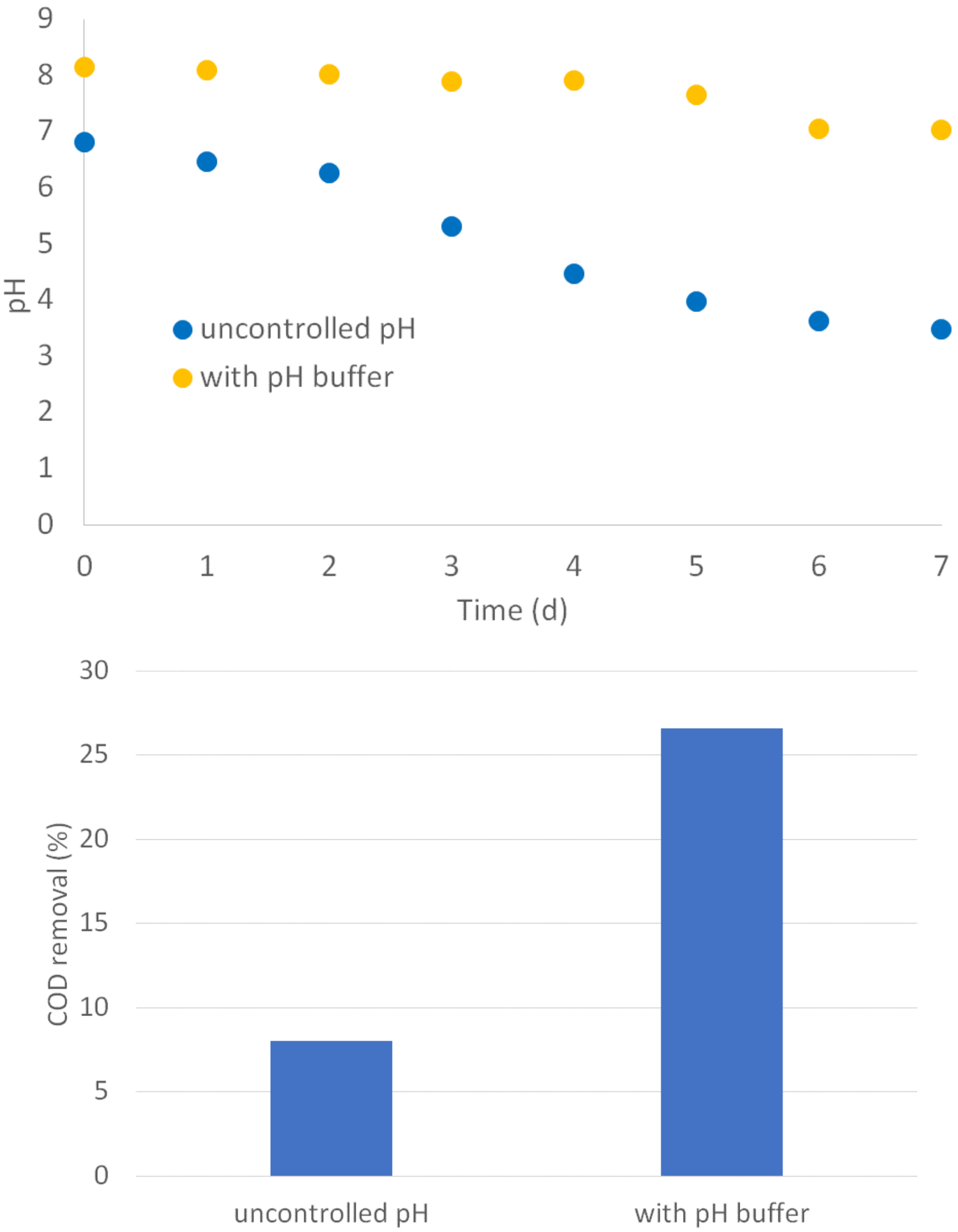


Figure C.7. Biological stages. Results of Experiment 4.

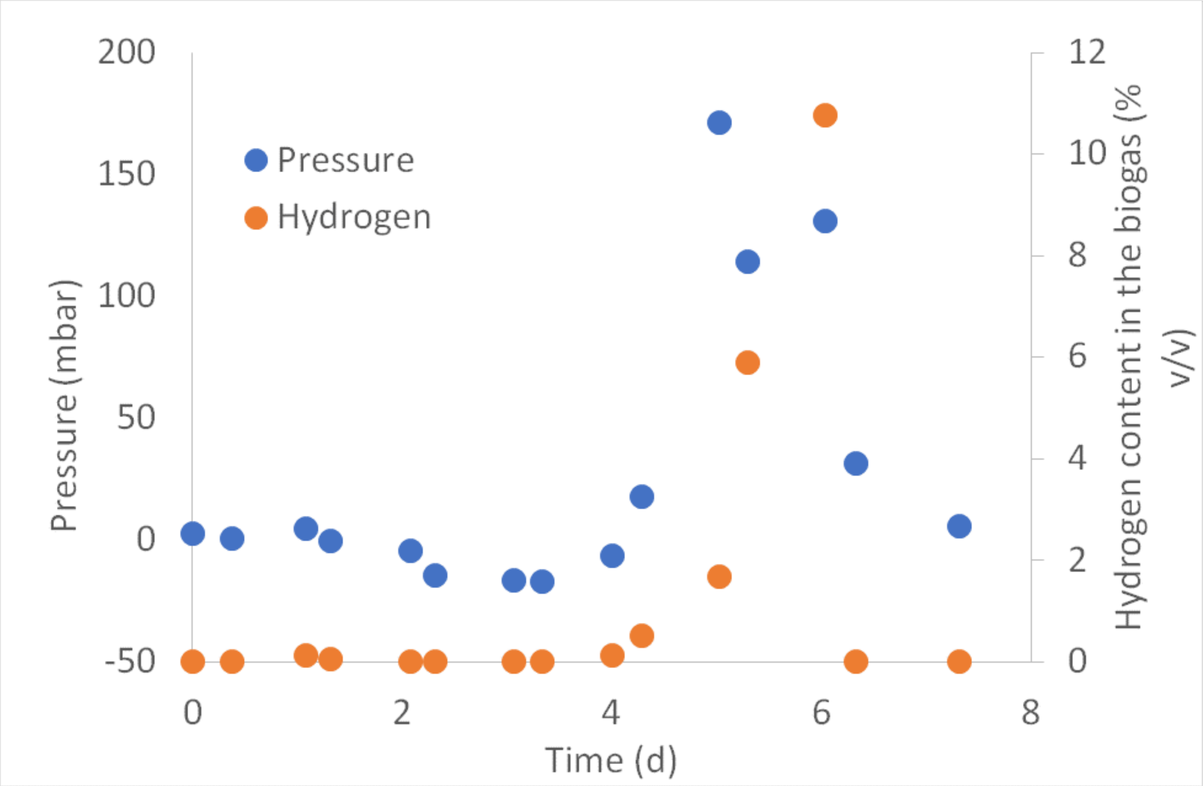


Figure C.8. Biological stages. Results of Experiment 5.

C.2.2 Plasma reforming

C.2.2.1 Effect of metal catalyst

To investigate the effect of catalysts on biogas plasma activation, a range of active metal phases supported on alumina were tested. 500 mg of the catalysts were loaded into the reaction zone, diluted with 500 mg of Al_2O_3. In-situ reduction using a 5% H_2 in He flow at 17 W and was used prior testing. Results are shown in Figure C.8, where the introduction of catalysts is seen to have had a significant effect on conversion and product distribution. In terms of hydrogen production, the best results were obtained with rhodium catalyst supported on alumina (Al_2O_3) as evident from the highest selectivity towards CO which is associated with hydrogen production. There is a clear improvement in the conversion of CO_2 with the introduction of packing, even with the pure Al_2O_3. For alumina this is due to improved electron density and temperature along with a stronger reduced field strength. The presence of metal catalysts improves CO_2 conversion significantly, with the best conversions achieved with the rhodium, ruthenium, and platinum catalysts. Again, the improved reduced field strength and electron temperatures due to packing enhance electron dissociation, in parallel with catalytic effects driven by the different metals tested. The lack of change in the CH_4 conversion suggests that catalysts are selectively able to drive the dry reforming reaction towards syngas, while non-catalytically the dissociation and secondary reactions of the two reactants were progressing largely in parallel and with minimal interaction.

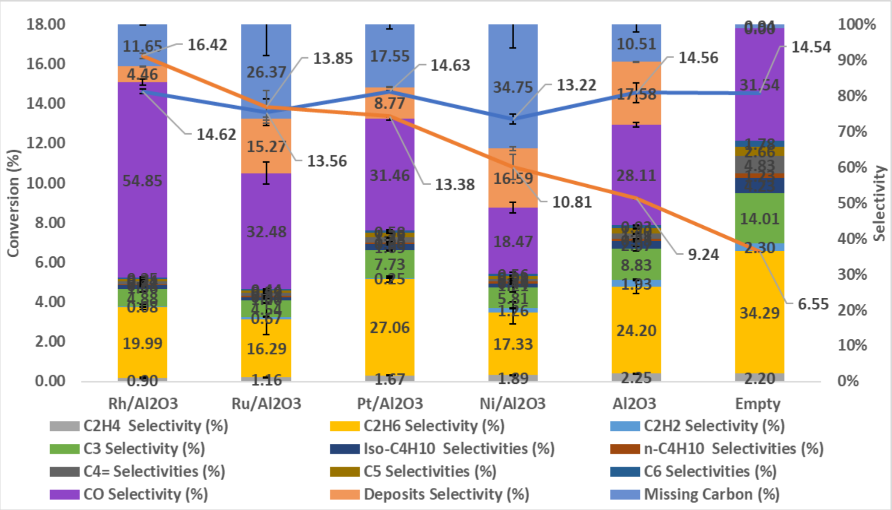


Figure C.8. Effect of metal phase on the plasma-catalytic conversion of biogas at a constant flowrate of 50 ml min-1 with a gas composition of 60% CH_4/40% CO_2.

The above is evident in the stark differences in selectivity for the different metal catalysts despite having similar electrical properties between them (indicated by electrical diagnostics not shown here). The nickel catalyst presents poor selectivity towards both hydrocarbon and CO products with a low carbon balance, suggesting the formation of carbon deposits or unidentified long chain or oxygenated hydrocarbons. The platinum and ruthenium catalysts perform better with higher CO_2 conversion and higher selectivities of products along with a higher carbon balance. The rhodium presents the best results of the catalysts tested in terms of CO_2 conversion and CO production, evidencing the efficient catalytic activation of dry reforming reactions as the CH_4 conversion is one of the highest of the catalysts tested. Rhodium is an excellent catalyst for dry reforming with high activity, good resistance to coke formation and high production of syngas in thermal dry reforming reactions. This has clearly translated to the plasma activation and the large amount of CO produced to CO_2 converted is testament to that, leading to the highest yield of H_2 and the lowest energy cost of conversion.

C.2.2.2 Effect of catalyst support

The structure of the catalyst can have a significant effect on the plasma upgrading of biogas. The metal loading, and support structure are investigated to assess their impact of performance, using rhodium as metal phase due to its optimal performance in biogas conversion. Experiments are carried out as above, besides using Argon dilution of 75%. The effect of catalyst thermal reduction is also tested using a 5% H_2/He flow at 600°C. The results of these experiments are shown in Figure C.9. Interestingly, using a lower metal loading is not detrimental to the conversion of CO_2 compared to the 5% catalyst, due to enhanced electrical properties with the 1% catalyst, reduced carbon deposition, and higher metal dispersion. Switching to the ceria support significantly improves CO_2 conversion for both the plasma *in situ* and thermally reduced catalysts. In both cases, a clear and large increase in syngas yield is evident compared to alumina. The high coke resistance of the ceria-zirconia complex is clearly evidenced with lower selectivity to carbon deposition present with both ceria catalysts. Interestingly the CH_4 conversion is not significantly affected by the changes in the catalyst structure which suggests that the CH_4 reactions occur more in the gas phase whilst CO_2 reactions occur more on the catalytic surface. Argon dilution is further seen to lead to an overall enhancement of reactants conversion, as it facilitates ionization leading to higher electron density and overall activity, leading to the highest conversions achieved in these runs of 50% or higher.

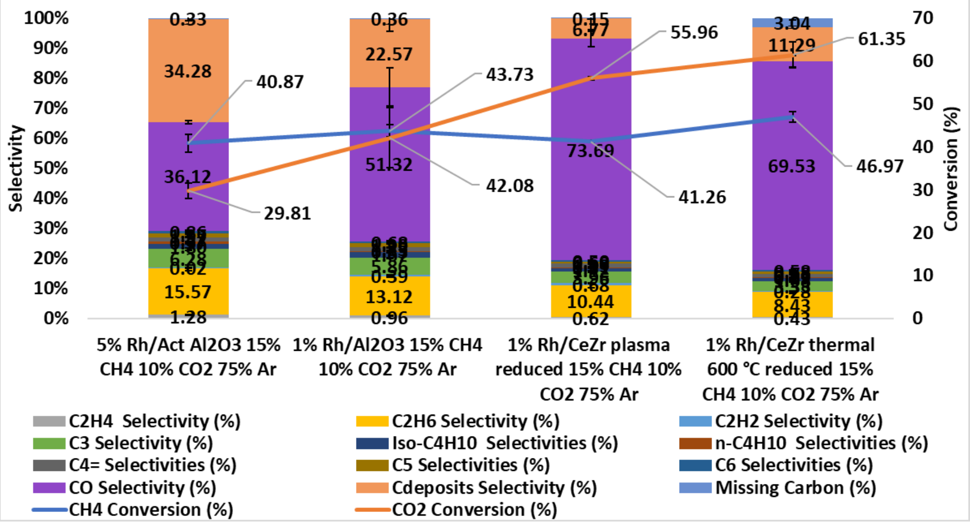


Figure C.9. Effect of catalyst support on the plasma-catalytic conversion of biogas at a constant flowrate of 50 ml min^{-1} with a gas composition of 60% CH_4/40% CO_2.

References

[C.1] Dionisi, D., Bolaji, I., Nabbanda, D., & Silva, I. M. (2018). Calculation of the potential production of methane and chemicals using anaerobic digestion. Biofuels, Bioproducts and Biorefining, 12(5), 788-801.

Appendix D. WP4. Engineering design of the pilot plant

D.1 Process flow diagram and equipment list

Figures D.1 and D.2 report the process flow diagram (PFD) and equipment list for the pilot plant. These were developed together by the project team and by the company Zeton, hired as sub-contractor for this task.
The description of the PFD is summarised below:
- The process converts organic waste into hydrogen. Main process steps are the anaerobic digestion (AD) in V-130, dark fermentation (DF) in V-150, steam gasification (SG) in R-330 and the plasma reformer (PR) R-210. Water gas shift (WGS) reactor R-410 converts the water from the SG and the CO from the PR to additional hydrogen.
- More details about all relevant equipment are summarised in Figure D.2 (Equipment List).
- Solid organic waste as main feed materials received from the lab and fed manually into the mixing tank V-120. The agitator in the mixing tank will be an anchor type and have no grinding function. Water will be dosed from an IBC via pump P-110.
- The DF and AD will run continuously as a Sequencing Batch Reactor (SBR), with cycles of feeding, mixing, settling and transfer to the next phase. Current assumption is 12 cycles per day. The feeds are transferred V-130 and V-150 via pumps. After feeding, there is a stirring phase/reaction phase, followed by a settling phase. After the settling phase, a specific amount of effluent (light phase) and solids (heavy phase) will be transferred into the AD. This because both phases have different residence times in the AD. During al the phases, the organic matter is converted into hydrogen. In the AD, the organic matter is converted into methane with similar operation.
- Both reactor can be regulated on pH by dosing caustic or acidic solution from two standard dosing systems.
- Both DF and AD will operate at slight overpressure (2÷4 barg), with continuous removal of products to the hydrogen compressor and Plasma reactor/Water gas shift reactor, respectively. With the selected operating conditions, pressure in V-130 and V-150 is higher than subsequent buffer tanks. This may provide the option for transfer via overpressure to the subsequent vessels and dispose of the pumps.
- The methane from the AD will be fed directly to the PR. The plasma reformer will be a free issue item. The H2 and CO will be subsequently fed into the WGS reactor.
- From the AD, the settled material (digestate) will go to a centrifugation step via a buffer tank. This step will be loaded batchwise from the intermediate tank and the solids are manually transferred. It will not be run continuously. The solids will be fed into the SG.
- The WGS will be fed either from the PR or the SG. The plasma reactor R-210's outlet flow will be present continuously, with outlet gas from R-330 only fed during the batches. The WGS will have a radiation or contact furnace for temperature control.
- The steam gasification step will operate at high temperature. A simple setup is foreseen, with manual filling and a small volume, mainly for proof of concept. Heating will be provided by an electrical preheater and a radiation furnace.
- The steam to the SG and WGS reactor will be provided by an electrical steam boiler package. The package includes a softener cartridge.

- To purify the H_2 coming from the system, a two-stage diaphragm compressor is available to feed a membrane purification step
- The process contains several small heat exchangers. For these applications, electrical tracing, small block heaters, finned tubes and small air coolers will be applied.
- Sampling points for gas are shown on the PFD as AT instruments. Two biogas analysers (installed in a dedicated sample container) are included, enabling switching between the 7 seven sampling points. This will give the composition of all samples every 2 hours, measuring concentration of H_2, CO, CO_2 and CH_4. In case of the steam gasification operation one analyser can be used preferentially for this sample stream.

Figure D.1. Process flow diagram for the pilot plant

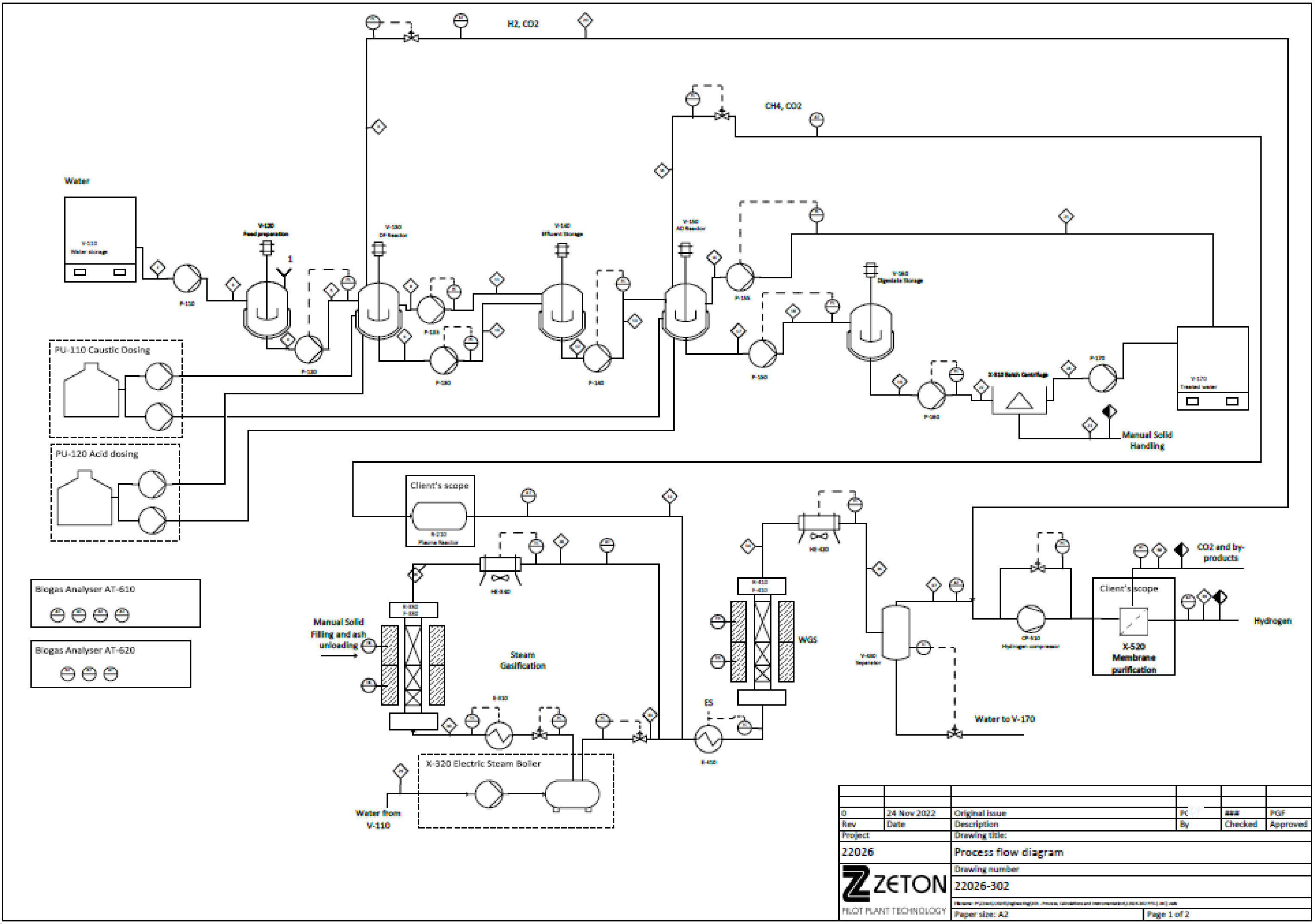
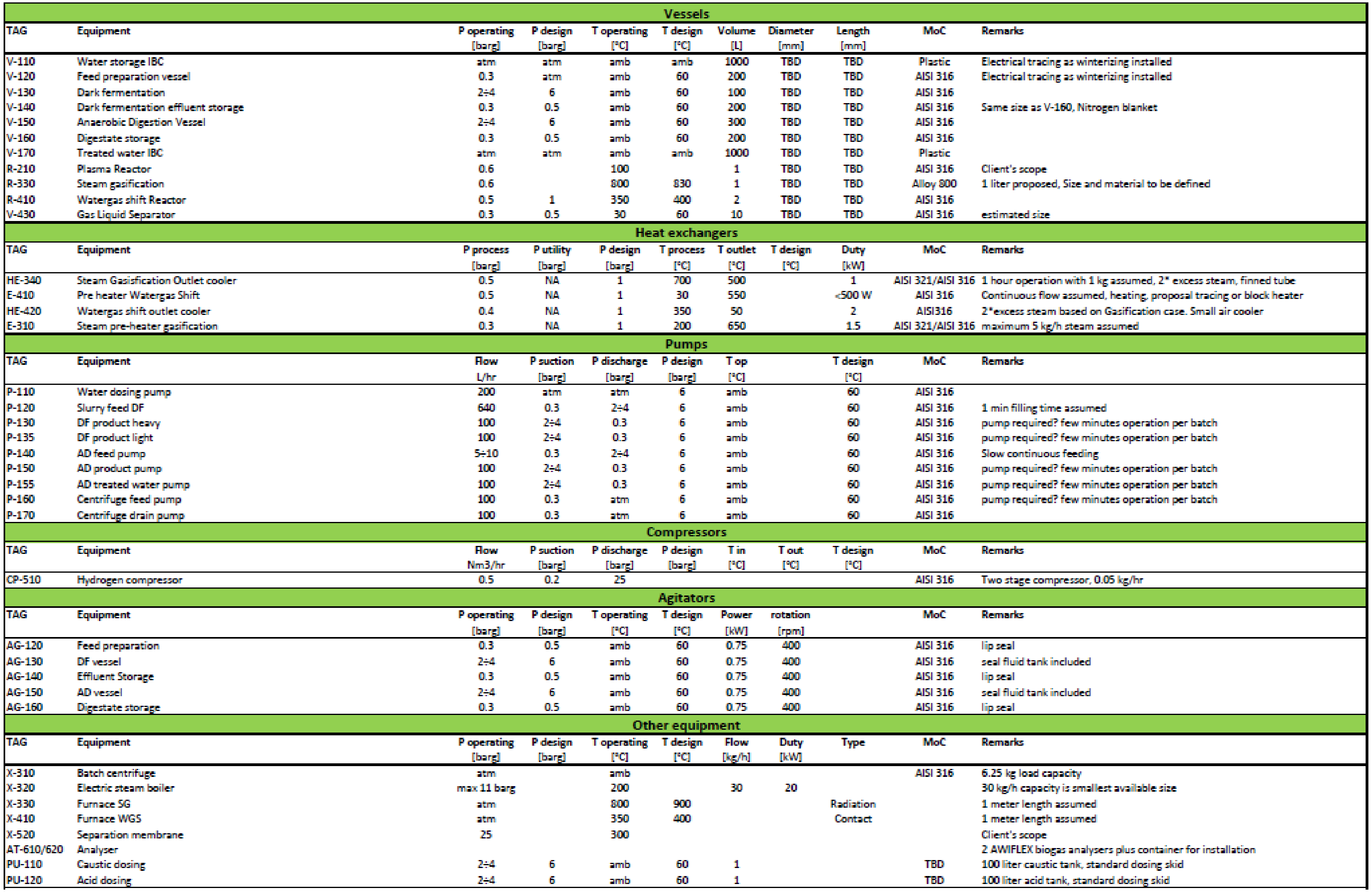


Figure D.2. Equipment list for the pilot plant



Vessels

TAG	Equipment	P operating [barg]	P design [barg]	T operating [°C]	T design [°C]	Volume [L]	Diameter [mm]	Length [mm]	MoC	Remarks
V-110	Water storage IBC	atm	atm	amb	amb	1000	TBD	TBD	Plastic	Electrical tracing as winterizing installed
V-120	Feed preparation vessel	0.3	atm	amb	60	200	TBD	TBD	AISI 316	Electrical tracing as winterizing installed
V-130	Dark fermentation	2÷4	6	amb	60	100	TBD	TBD	AISI 316	
V-140	Dark fermentation effluent storage	0.3	0.5	amb	60	200	TBD	TBD	AISI 316	Same size as V-160, Nitrogen blanket
V-150	Anaerobic Digestion Vessel	2÷4	6	amb	60	300	TBD	TBD	AISI 316	
V-160	Digestate storage	0.3	0.5	amb	60	200	TBD	TBD	AISI 316	
V-170	Treated water IBC	atm	atm	amb	amb	1000	TBD	TBD	Plastic	
R-210	Plasma Reactor	0.6		100		1	TBD	TBD	AISI 316	Client's scope
R-330	Steam gasification	0.6		800	830	1	TBD	TBD	Alloy 800	1 liter proposed, Size and material to be defined
R-410	Watergas shift Reactor	0.5	1	350	400	2	TBD	TBD	AISI 316	
V-430	Gas Liquid Separator	0.3	0.5	30	60	10	TBD	TBD	AISI 316	estimated size

Heat exchangers

TAG	Equipment	P process [barg]	P utility [barg]	P design [barg]	T process [°C]	T outlet [°C]	T design [°C]	Duty [kW]	MoC	Remarks
HE-340	Steam Gasisfication Outlet cooler	0.5	NA	1	700	500		1	AISI 321/AISI 316	1 hour operation with 1 kg assumed, 2* excess steam, finned tube
E-410	Pre heater Watergas Shift	0.5	NA	1	30	550		<500 W	AISI 316	Continuous flow assumed, heating, proposal tracing or block heater
HE-420	Watergas shift outlet cooler	0.4	NA	1	350	50		2	AISI316	2*excess steam based on Gasification case. Small air cooler
E-310	Steam pre-heater gasification	0.3	NA	1	200	650		1.5	AISI 321/AISI 316	maximum 5 kg/h steam assumed

Pumps

TAG	Equipment	Flow L/hr	P suction [barg]	P discharge [barg]	P design [barg]	T op [°C]	T design [°C]	MoC	Remarks
P-110	Water dosing pump	200	atm	atm	6	amb	60	AISI 316	
P-120	Slurry feed DF	640	0.3	2÷4	6	amb	60	AISI 316	1 min filling time assumed
P-130	DF product heavy	100	2÷4	0.3	6	amb	60	AISI 316	pump required? few minutes operation per batch
P-135	DF product light	100	2÷4	0.3	6	amb	60	AISI 316	pump required? few minutes operation per batch
P-140	AD feed pump	5÷10	0.3	2÷4	6	amb	60	AISI 316	Slow continuous feeding
P-150	AD product pump	100	2÷4	0.3	6	amb	60	AISI 316	pump required? few minutes operation per batch
P-155	AD treated water pump	100	2÷4	0.3	6	amb	60	AISI 316	pump required? few minutes operation per batch
P-160	Centrifuge feed pump	100	0.3	atm	6	amb	60	AISI 316	pump required? few minutes operation per batch
P-170	Centrifuge drain pump	100	0.3	atm	6	amb	60	AISI 316	

Compressors

TAG	Equipment	Flow Nm3/hr	P suction [barg]	P discharge [barg]	P design [barg]	T in [°C]	T out [°C]	T design [°C]	MoC	Remarks
CP-510	Hydrogen compressor	0.5	0.2	25					AISI 316	Two stage compressor, 0.05 kg/hr

Agitators

TAG	Equipment	P operating [barg]	P design [barg]	T operating [°C]	T design [°C]	Power [kW]	rotation [rpm]	MoC	Remarks
AG-120	Feed preparation	0.3	0.5	amb	60	0.75	400	AISI 316	lip seal
AG-130	DF vessel	2÷4	6	amb	60	0.75	400	AISI 316	seal fluid tank included
AG-140	Effluent Storage	0.3	0.5	amb	60	0.75	400	AISI 316	lip seal
AG-150	AD vessel	2÷4	6	amb	60	0.75	400	AISI 316	seal fluid tank included
AG-160	Digestate storage	0.3	0.5	amb	60	0.75	400	AISI 316	lip seal

Other equipment

TAG	Equipment	P operating [barg]	P design [barg]	T operating [°C]	T design [°C]	Flow [kg/h]	Duty [kW]	Type	MoC	Remarks
X-310	Batch centrifuge	atm		amb					AISI 316	6.25 kg load capacity
X-320	Electric steam boiler	max 11 barg		200		30	20			30 kg/h capacity is smallest available size
X-330	Furnace SG	atm		800	900			Radiation		1 meter length assumed
X-410	Furnace WGS	atm		350	400			Contact		1 meter length assumed
X-520	Separation membrane	25		300						Client's scope
AT-610/620	Analyser									2 AWIFLEX biogas analysers plus container for installation
PU-110	Caustic dosing	2÷4	6	amb	60	1			TBD	100 liter caustic tank, standard dosing skid
PU-120	Acid dosing	2÷4	6	amb	60	1			TBD	100 liter acid tank, standard dosing skid

D.2 Plant layout and solar panels

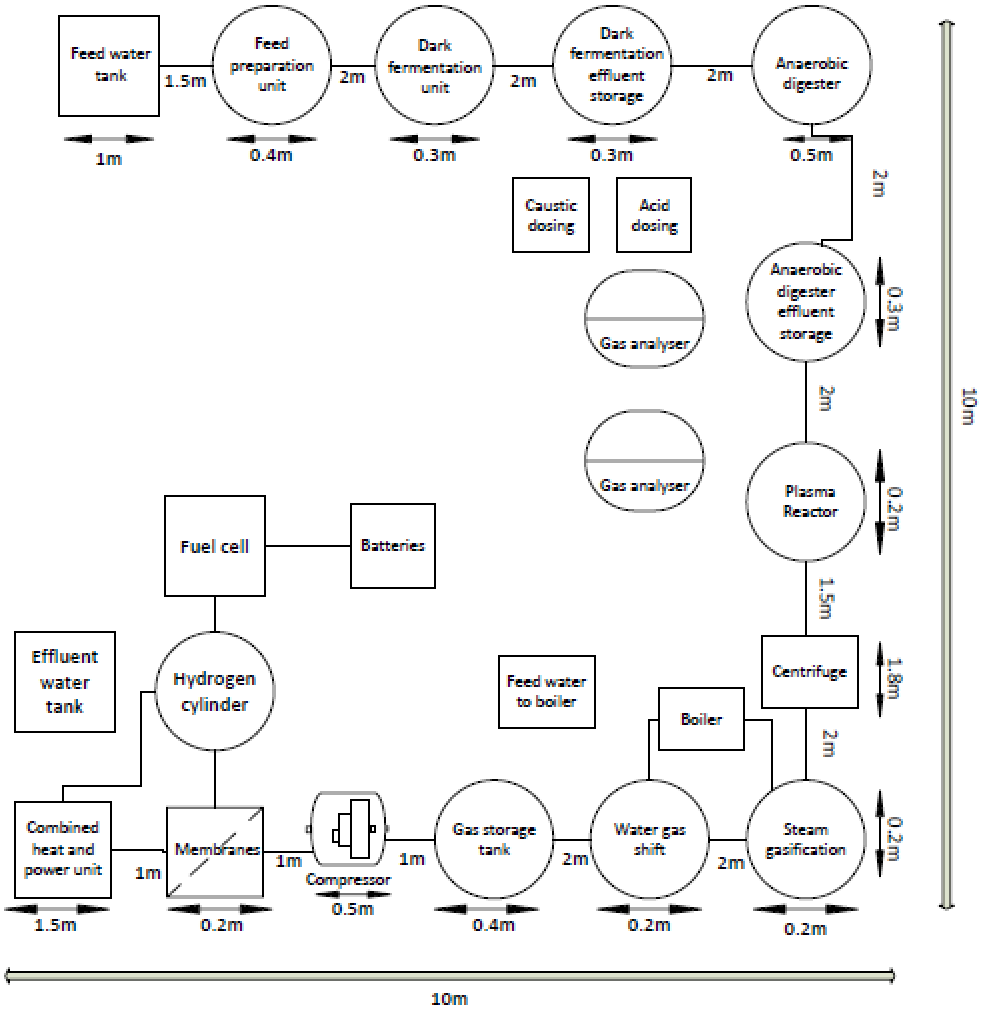
Figure D.3 shows the proposed layout of the pilot plant. It is estimated that the plant will occupy a space of 10x10 m (100 m^2) and will be located on the premises of University of Aberdeen, Old Aberdeen campus.

The roof of the pilot plant will be used to install solar PV panels which will provide electricity for the plant. Based on the energy balances done in WP1, the energy requirement for the chemical reaction stages of the plant can be estimated as 0.33 kWh/kWh$_{H2}$, based on the HHV of H2. Assuming a 50 % additional energy consumption due to compression, pumping and purification, the total energy consumption of the pilot plant can be estimated as approximately 0.50 kWh/kWh$_{H2}$. The pilot plant is estimated to produce 0.52 kg$_{H2}$/d, i.e. 20.5 kWh$_{H2}$, with an energy consumption of 10.25 kWh/d.

The electricity generation by the solar panels has been estimated with the following considerations. Assuming that 10 % of the roof surface will not be available for PV panels (e.g. due to vents and gas discharges), the available area for the solar panels will be 90 m^2. Considering, e.g. the commercial PV panels Hi-MO4 by Longi (https://www.longi.com/en/products/modules/hi-mo-4/) of the size of 2.17 m^2 and of power rating 445 W, at least 40 panels can be installed on the roof. The total installed power would be therefore approximately 17.8 kW. Assuming a load factor of 0.1076 (average yearly load factor for solar PV panels in the UK, used in our study [D.1] from analysis of published data), the installation would be able to generate an average of approximately 46 kWh/d (yearly average on a daily basis) which would be more than enough for the energy requirements of the plant, even in the case of lower energy efficiency of the panels or of higher energy consumption by the plant. Clearly, battery storage will be needed and will be installed to store the PV energy and to allow continuous operation of the plant without use of the electricity grid.

Furthermore, the battery charge will be supplemented by the electricity generated by the CHP unit which will burn any combustible by-products (e.g. residual CO and CH_4 from incomplete conversion in the PR and WGS units) and, if necessary, by converting part of the produced hydrogen into electricity in a fuel cell unit.

Figure D.3. Proposed layout of the pilot plant



D.3 Design of individual unit operations

D.3.1 Feed preparation unit

The feed preparation unit is used to process organic waste for optimal yield in the dark fermentation and anaerobic digestion unit. Processing organic waste is done by grinding and mixing of the substrate to better microbial interaction that improves reaction kinetics for shorter retention time [D.2].
The organic waste fed to the pilot plant will be taken from kitchen waste from University of Aberdeen's outlets. Due to the relatively small capacity of the pilot plant, which should process 20 kg/d of food waste, the grinding of the waste will be done in the lab using large commercial kitchen mixers. The energy consumption by these mixers will be measured and considered in the energy balances of the plant. The ground and blended kitchen waste will be added to the feed vessel in the pilot plant (section D.3.3), where the waste will be diluted with water from the water storage tank. The water storage tank will be an IBC plastic tank with capacity of 1,000 litres from which water will be fed via a pump to the mixing tank.

D.3.2 Pumps

Pumps are installed to aid fluids overcome the static lift, frictional losses in pipes and also the fittings loss due to bends, valves and other components. In this section we report the calculations for the design of the pump for feeding and withdrawing to/from the biological stages DF and AD of the pilot plant.

D.3.2.1 Equations for pump design

Governing Equations

$$Total\ pump\ head = static\ lift + system\ losses \tag{D.1}$$

Assuming static lift = 0
And,

$$system\ losses = frictional\ losses + component\ losses \tag{D.2}$$

Frictional losses is given by,

$$\Delta H_f = f\frac{l}{d}\frac{u^2}{2g}\ (frictional\ losses) \tag{D.3}$$

And component losses,

$$\Delta H_c = K\frac{u^2}{2g}\ (component\ losses) \tag{D.4}$$

Thus,

$$pump\ head\ required, H = \left(\Delta H_f + \Delta H_c\right) = \left(f\frac{l}{d} + K\right)\frac{u^2}{2g} \tag{D.5}$$

The pumping power is found by:

$$Pump\ power = \frac{\rho g H Q}{\eta} = \frac{\Delta P Q}{\eta} \tag{D.6}$$

Where,

f	Friction factor
u	Average velocity, ms^{-1}
l	Pipe length, m
d	Pipe diameter, m
K	Component loss coefficient

H Pump head, m
Q Flow rate, m^{3}s^{-1}
η Pump efficiency

D.3.2.2 Feed to DF

Volumetric flow rate: 100 L/day - 12 cycles in 1 minute: 100/12=8.3L/min= 0.00013833333 m^3/s
Density of organic matter = 1100 kg/m^3 [D.3]
Dynamic viscosity of organic matter= 125*10^{-3} Nm^{-2}s [D.4]
Mixture density = (96/100*1000) + (4/100*1100) = 1004 kg/m^3
Mixture dynamic viscosity = (80/100*8.90*10^{-4}) + (20/100*125*10^{-3}) = 0.0257 Nm^{-2}s
Assume pipe diameter, D = 0.0064 m
From equation D.5,

$$pump\ head\ required, H = \left(0.0593 \times \frac{2}{0.0064} + 0.15\right)\frac{4.317^2}{2 \times 9.81}$$
$$= 17.753\ m$$

Substituting in equation D.6,

$$Pump\ power = \frac{1004 \times 9.81 \times 17.753 \times 0.000139}{0.80} = 30.4\text{W}$$

D.3.2.3 Effluent withdrawal from DF

Volumetric flow rate: 400mL/min for 5 minutes = 2L/min= 0.0000333333 m^3/s
Density of organic matter = 1100 kg/m^3 [D.3]
Dynamic viscosity of organic matter= 125*10^{-3} Nm^{-2}s [D.4]
Mixture density = (98/100*1000) + (2/100*1100) = 1001 kg/m^3
Mixture dynamic viscosity = (98/100*8.90*10^{-4}) + (2/100*125*10^{-3}) = 0.00325 Nm^{-2}s
Assume pipe diameter, D = 0.0064 m

$$pump\ head\ required, H = \left(0.03 \times \frac{2}{0.0064} + 0.15\right)\frac{1.036^2}{2 \times 9.81} = 0.5436m$$

$$Pump\ power = \frac{1000 \times 9.81 \times 0.5436 \times 0.0000333333}{0.80} = 0.2\text{W}$$

D.3.2.4 Sludge withdrawal from DF

Volumetric flow rate: 640mL/min for 10 minutes = 6.4L/min= 0.000106667 m^3/s
Density of organic matter = 1100 kg/m^3 [D.3]
Dynamic viscosity of organic matter= 125*10^{-3} Nm^{-2}s [D.4]
Mixture density = (90/100*1000) + (10/100*1100) = 1010 kg/m^3
Mixture dynamic viscosity = (90/100*8.90*10^{-4}) + (10/100*125*10^{-3}) = 0.0133 Nm^{-2}s
Assume pipe diameter, D = 0.0064 m

$$pump\ head\ required, H = \left(0.04 \times \frac{2}{0.0064} + 0.15\right)\frac{3.3157^2}{2 \times 9.81} = 7.039m$$

$$Pump\ power = \frac{1010 \times 9.81 \times 7.039 \times 0.000106667}{0.80} = 9.3\text{W}$$

D.3.2.5 Feed pump to AD

Volumetric flow rate: 110mL/min for 75 minutes = 8.25L/min= 0.0001375 m^3/s
Density of organic matter = 1100 kg/m^3 [D.3]
Dynamic viscosity of organic matter= $125*10^{-3}$ $Nm^{-2}s$ [D.4]
Mixture density = (96/100*1000) + (4/100*1100) = 964 kg/m^3
Mixture dynamic viscosity = $(96/100*8.90*10^{-4}) + (4/100*125*10^{-3})$ = 0.0257 $Nm^{-2}s$
Assume pipe diameter, D = 0.0064 m

$$pump\ head\ required, H = \left(0.06 \times \frac{2}{0.0064} + 0.15\right)\frac{4.2742^2}{2 \times 9.81} = 18.294\ m$$

$$Pump\ power = \frac{964 \times 9.81 \times 18.294 \times 0.0001375}{0.80} = 29.7\mathrm{W}$$

D.3.2.6 Effluent withdrawal from AD

Volumetric flow rate: 780mL/min for 10 minutes = 7.8L/min= 0.0001267 m^3/s
Density of organic matter = 1100 kg/m^3 [D.3]
Dynamic viscosity of organic matter= $125*10^{-3}$ $Nm^{-2}s$ [D.4]
Mixture density = (90/100*1000) + (10/100*1100) = 1010 kg/m^3
Mixture dynamic viscosity = $(90/100*8.90*10^{-4}) + (10/100*125*10^{-3})$ = 0.0133 $Nm^{-2}s$
Assume pipe diameter, D = 0.0064 m

$$pump\ head\ required, H = \left(0.03 \times \frac{2}{0.0064} + 0.15\right)\frac{3.9374^2}{2 \times 9.81} = 8.3775\ m$$

$$Pump\ power = \frac{1010 \times 9.81 \times 8.3775 \times 0.0001267}{0.80} = 13.1\mathrm{W}$$

D.3.2.7 Sludge withdrawal from AD

Volumetric flow rate: 110mL/min for 5 minutes = 0.55L/min= 0.000009167 m^3/s
Density of organic matter = 1100 kg/m^3 [D.3]
Dynamic viscosity of organic matter= $125*10^{-3}$ $Nm^{-2}s$ [D.4]
Mixture density = (90/100*1000) + (10/100*1100) = 1010 kg/m^3
Mixture dynamic viscosity = $(90/100*8.90*10^{-4}) + (10/100*125*10^{-3})$ = 0.0133 $Nm^{-2}s$
Assume pipe diameter, D = 0.0064 m

$$pump\ head\ required, H = \left(0.46 \times \frac{2}{0.0064} + 0.15\right)\frac{0.2849^2}{2 \times 9.81} = 0.5983\ m$$

$$Pump\ power = \frac{1010 \times 9.81 \times 0.5893 \times 0.000009167}{0.80} = 0.07\mathrm{W}$$

D.3.3 Feed vessel

A cylindrical steel mixing tank would be used to ensure proper mixing between the organic waste and dilution water as shown in Figure D.4.

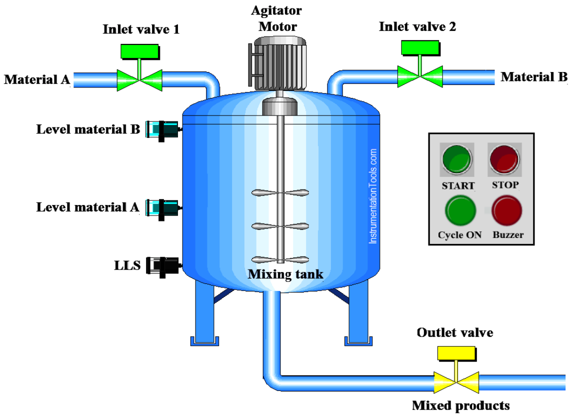


Figure D.4 Scheme of the feed vessel

The tank was designed according with the considerations below
Volumetric flow rate of organic waste into the mixing tank= 20 L/day
Volumetric flow rate of water into the mixing tank = 80 L/day
Total volumetric flow rate of waste + water in the mixing tank = 100 L/day
Volume of slurry after 1 day = 100/1000 = 0.1 m^3
Assuming a loading capacity of 80 %,

$$\text{Mixing tank volume is } = \frac{0.1}{0.8} = 0.125\, m^3$$

$$= \mathbf{125\ Litres}$$

The height to diameter ratio is typically 3 to 1 [D.5]

$$H = 3D \tag{D.7}$$

$$V = \frac{\pi D^2 H}{4} \tag{D.8}$$

By substituting,

$$V = \frac{3\pi D^3}{4} \tag{D.9}$$

$$0.125 = \frac{3\pi D^3}{4}$$

$$= \sqrt[3]{\frac{4 \times 0.125}{3\pi}}$$

$$D = 0.38m$$

$$H = 3 \times 0.38 = 1.20m$$

Where,

H	Height of the mixing tank
D	Diameter of the mixing tank
V	Volume of the mixing tank

The agitator for the mixing tank was designed with the following considerations. Mixing impellers may be radial or axial. The blades of axial flow impellers form an angle less than 90° degrees with the mixing shaft axis and find their application in simple blending, solids suspension, and flocculation. Pitched Blade Turbines (Figure D.5) with constant angle of attack is considered.

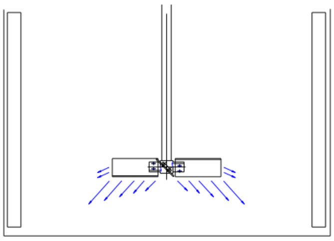


Figure D.5 Pitched Blade Turbines with constant angle of attack

The ratio of impeller diameter to tank diameter is obtained based on the slurry viscosity which is found to be ~ 25.7 CPS [D.4]. For this design, the upper limit value in the figure D.6 is utilised. Therefore, the optimum impeller diameter to tank diameter (D/T) = 0.4
This implies that Impeller diameter = 0.4 * 0.38 = 0.152 m

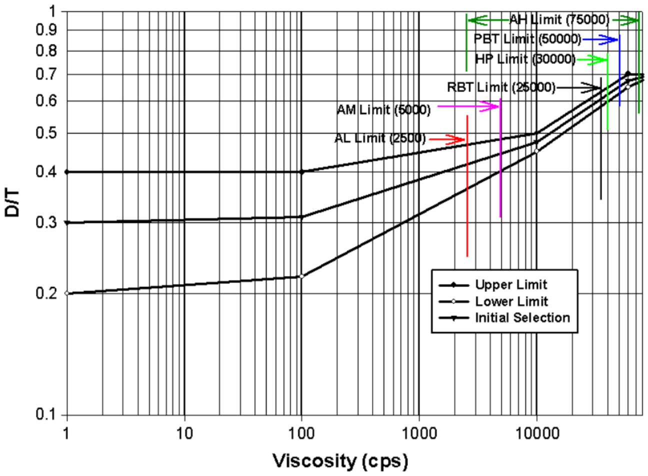


Figure D.6 Optimum D/T Vs. Viscosity [D.5]

The pumping capacity, Q was obtained from equation D.10

$$Q = 7.48 N_q \; N \; D^3 \tag{D.10}$$

Where,

N_q	Pumping number
N	Impeller rotational speed, rpm
D	Impeller diameter, feet

The impeller tip speed was obtained from equation D.11

$$TS = \pi \; D \; N \tag{D.11}$$

Where,

TS	Tip speed, fpm
N	Impeller rotational speed, rpm
D	Impeller diameter, feet

A single pitched blade impeller with pumping number 0.86 is sufficient to mix the volume of slurry at 0.4 m s^{-1}.

D.3.4 Biological stages

The dark fermentation vessel will have a volume 100 L, hydraulic residence time (HRT) 1 d, receiving a feed of 100 L/d. Agitated with a slow spinning agitator with pumps for feeding and effluent withdrawal. The DF is operated in a sequencing batch reactor (SBR), where the various required processes, i.e. feeding, reaction, sedimentation, withdrawal of the effluent and of the concentrated microorganisms, are carried out in a sequence of phases in the same vessel. The solids residence time (SRT) will be controlled by the flow rate of concentrated solids effluent (stream 6). The sequence of phases, feeding regime, etc, should be software controlled and should be adjustable during the runs. The sequence of phase will be the following (Table D.1), subject to optimisation of conditions in Phase 2.

Table D.1 Operating conditions for DF vessel in the pilot plant in Phase 2

Operating conditions for DF vessel	
HRT (d)	1
SRT (d)	10
Cycles/d	12
Length of phases (min)	
Feed	1
Reaction	74
Settling	30
Sludge withdrawal	5
Effluent withdrawal	10

The effluent storage vessel from DF will have a volume of 100 L, agitated with slow spinning anchor agitator, metallic cylinder.

The anaerobic digestion vessel Volume 300 L, hydraulic residence time (HRT) 3 d, receiving a feed (stream 7) of 100 L/d. Same design as the DF vessel. Operated as SBR similarly as the DF vessel, but with a different length of phases and operating conditions (Table D.2).

Table D.2 Operating conditions for DF vessel in the pilot plant in Phase 2

Operating conditions for AD vessel	
HRT (d)	3
SRT (d)	30
Cycles/d	12
Length of phases (min)	
Feed	75
Reaction	0
Settling	30
Sludge withdrawal	5
Effluent withdrawal	10

D.3.5 Centrifugation unit

The centrifuge would be used to separate the digestate (organic matter) from the water. This separation can be carried out in a bowl where the liquid would be filtered out to produce dry solids for further processing in the steam gasification unit.

D.3.5.1 Centrifugal bowl

The cross-sectional area of the bowl is obtained from its sigma value [D.6]

$$Q = 2u_g\Sigma \tag{D.12}$$

$$u_g = \frac{\Delta\rho d_s^2 g}{18\mu} \tag{D.13}$$

$$\frac{Q}{\Sigma} = \frac{2 \times \Delta\rho d_s^2 g}{18\mu} \tag{D.14}$$

where,

Q	volumetric flow of liquid through the centrifuge, m^3s^{-1}
u_g	terminal velocity of the solid particle settling under gravity through the liquid, ms-^{1}
Σ	sigma value of the centrifuge, m^2
$\Delta\rho$	density difference between the solid and liquid, kgm^{-3}
d_s	diameter of the solid particle, m
g	gravitational acceleration, ms^{-2}
μ	viscosity of the liquid, Ns m^{-2}

Density of water = 1000 kg/m^3
Density of solid = 1100 kg/m^3
Solid concentration = 10% by volume
Volumetric flowrate of water = 7.197×10^{-8} m^3/s
Particle size = 150×10^{-6} m
Viscosity of water = 8.9×10^{-4} N m^{-2} s

The slurry in the centrifuge exerts pressure on the walls of the bowl and the minimum wall thickness required to contain this pressure load is determined with the following equations.

The pressure drop across the centrifuge was obtained from [D.6]

$$\Delta P = \frac{1}{2}\rho\omega^2(r_2^2 - r_1^2) \tag{D.15}$$

where,

ΔP	Pressure drop, Pa
ρ	Liquid density, kgm^{-3}
ω	Angular velocity, $rads^{-1}$
r_2	Inner bowl radius, m
r_1	Outer bowl radius, m

The bowl thickness is given by:

$$t = \frac{\Delta P\ D}{2\sigma} + 3 \tag{D.16}$$

where,

t	Thickness, mm
D	Bowl diameter, mm
σ	Allowable stress

To handle the amount of digestate, we require a minimum bowl volume of 0.006 m^3 and wall thickness of 0.003 m.

D.3.5.2 Centrifugal power

The required power for operation is obtained from equation D.17

$$P = T\omega \tag{D.17}$$

where,

P	Power, w
T	Torque, Nm
ω	Angular velocity, rads^{-1}

And,

$$T = I\alpha \tag{D.18}$$

$$I = 2\pi\rho_{steel} t r_2^3 L + \frac{M}{2}(r_1^2 - r_2^2) \tag{D.19}$$

$$M = \pi\rho_f L(r_2^2 - r_1^2) \tag{D.20}$$

where,

I	Moment of inertia, kg m^2
α	Angular acceleration, rads^{-2}
L	Length of the bowl, m
M	Mass of liquid, kg

The power required to hold the volume of slurry per day for centrifugation is 120 Watt.

The summary of the calculations for the centrifuge unit is shown in Table D.3.

Table D.3. Summary of centrifuge calculations

Particle size (m)	0.00015
Liquid density (kg/m^3)	1000
Solid density (kg/m^3)	1100
Liquid viscosity (Ns/m^2)	0.00089
Liquid vol. flow rate (m^3/s)	7.2E-08
Speed of rotation (RPM)	3000
Allowable stress in bowl (Pa)	210000000
Density of stainless steel (kg/m^3)	7800
Time from rest to angular speed (s)	4
Power transmission efficiency	0.5
Assume basis of 1 day operation	
Volume (m^3)	0.0062
Q/E (m/s)	0.00275
A (m^2)	2.61E-05
ω (rad/s)	314
L (m)	238
R1 (m)	0.00288
R2 (m)	0.00408
∆P (Pa)	410
t (mm)	3.00
I1 (kgm^2)	2.37E-03
M (kg)	6.22
I2	7.75E-05
I (kgm^2)	2.45E-03
Angular acceleration	78.5
T (Nm)	1.92E-01
Power (W)	120.9

D.3.6 Water gas shift reactor

The WGS reaction is described by the following stoichiometry

$$CO + H_2O \rightleftharpoons H_2 + CO_2$$

$$\Delta H = -41.01\ kJ/mol$$

Relatively low temperature is favourable for H_2 production. Low temperature is thermodynamically favoured, and high temperature is kinetically favoured.
Chosen design conditions:
Temperature chosen: 350 degrees Celsius (high temperature)
Suitable catalyst: iron oxide
Packed bed reactor
Rate equation [D.7]:

$$r = kpCO^a pH_2O^b pCO_2^c pH_2^d \left(1 - \frac{pCO_2 pH_2}{K_{eq} pCO pH_2O}\right)$$

The values a, b, c, d, k_0 and Ea are obtained from literature.
$a = 1$
$b = 0$
$c = -0.36$
$d = -0.09$
$k_0 = 10^{2.845}\ \frac{mol}{gcat\ s}$
$Ea = 111\ kJ/mol$

Therefore,
$k\left(\frac{mol}{gcat\ s}\right) = k_0 e^{-\frac{Ea}{RT}} = 10^{2.845} \times e^{-\frac{111\times1000}{8.3145\times(350+273.15)}} = 3.47 \times 10^{-7}$
$K_{eq} = exp\left(\frac{4577.8}{T} - 4.33\right) = exp\left(\frac{4577.8}{350 + 273.15} - 4.33\right) = 20.4$
Assume that 99% of the inlet CO is converted. From stoichiometry:
$CO_{in} = 3.15\ kg/d = 1.30 \times 10^{-3}\ mol/s$
$H_2O_{in} = 2.02\ kg/d = 1.30 \times 10^{-3}\ mol/s$
Therefore,
$CO_{reactor} = 1.30 \times 10^{-5}\ mol/s$
$H_2O_{reactor} = 1.30 \times 10^{-5}\ mol/s$
$H_{2\,reactor} = 1.29 \times 10^{-3}\ mol/s$
$CO_{2\,reactor} = 1.29 \times 10^{-3}\ mol/s$

Assuming that the WGS reactor runs at atmospheric pressure, using the concentration ratios, the following partial pressures were obtained.
$pCO = 4.99 \times 10^{-3}\ atm$
$pH_2O = 4.99 \times 10^{-3}\ atm$
$pCO_2 = 0.495\ atm$
$pH_2 = 0.495\ atm$
Applying all the values to the rate equation,

$$r = 3.47 \times 10^{-7}(4.99 \times 10^{-3})^{1}(4.99 \times 10^{-3})^{0}(0.495)^{-0.36}(0.495)^{-0.09}\left(1 - \frac{0.495^2}{20.4(4.99 \times 10^{-3})^2}\right) = -1.14 \times 10^{-6}\ \frac{mol}{gcat\ s}$$

Material balance for the components:
Accumulation = input – output + generation – consumption
It can be assumed that the packed bed reactor is perfectly mixed.

CO:

$$Q_{in} \cdot [CO]_{in} = r \cdot m_{cat} + Q_{out} \cdot [CO]_{out}$$

$$1.30 \times 10^{-3} = 1.14 \times 10^{-6} \cdot m_{cat} + 1.30 \times 10^{-5}$$

$$m_{cat} = 1129\ g$$

Therefore, the mass of catalyst required is 1.1 kg. This mass of catalyst was calculated assuming continuous 24/7 operation of the WGS reactor. If the reactor is operated for shorter periods of time, because the gas from the previous stages are stored before being sent to the WGS unit, then the required mass of catalyst will be correspondingly larger, because the same mass of CO will need to react in a shorter time.
The following graph (Figure D.7) illustrates how the mass of the catalyst varies with the number of operating hours of the WGS reactor.

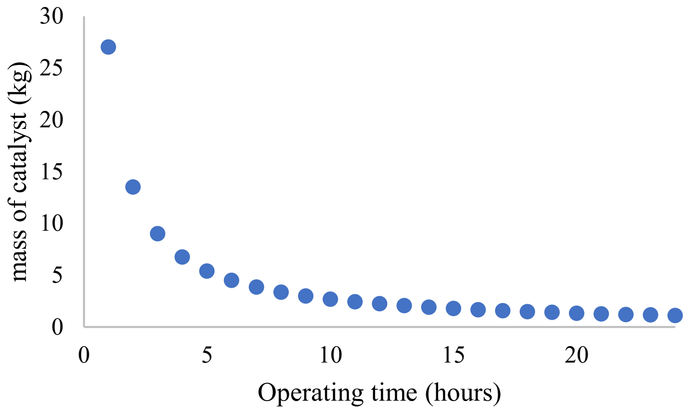


Figure D.7. Mass of catalyst required for the WGS reactor as a function of the operating time of the reactor itself.

D.3.7 Plasma reforming reactor

The reactor design for the pilot plant biogas plasma reforming stage is seen in the schematic below. The design assumes a total biogas feed of 2.8 m^3/d (Section 4, Figure 4.1, stream 21), which is equivalent to approximately 2000 ml/min. For the plasma reactor, it is necessary to maintain a small reactor tube diameter, as the electrode gap (distance between the power and ground electrodes) directly correlates to the potential that needs to be applied. The smaller this distance, the lower the voltage that is required, hence the shift to pilot scale is achieved via parallelisation instead of scaling up. In the design below, the total flowrate is delivered via a central feed line at the top of the reactor and is subsequently split to be fed to 9 equivalent reactor tubes, loaded with the same amount of catalyst. Each reactor tube operates hence at a flow of approximately 220 ml/min and is loaded with roughly 10 gr of catalyst. The products of all reactors are mixed to exit the reactor via a single line, to be further processed and fed to subsequent stages. At the centre length of the reactor assembly a single electrode is placed that is connected to the high voltage power supply. All reactors further are equipped with individual ground electrodes placed concentrically and further connected to the top and bottom steel flanges that are connected to the feed and product lines. Each reactor tube is constructed out of a dielectric material, such a PTFE or PEEK, and has external and internal diameters of 10 and 8 cm, respectively, and a length of 1 m. The length of the HV electrode relates to the catalyst bed length, and has been set at 45 cm. The diameter of the top and bottom flanges and the HV electrode are set at 50 cm.

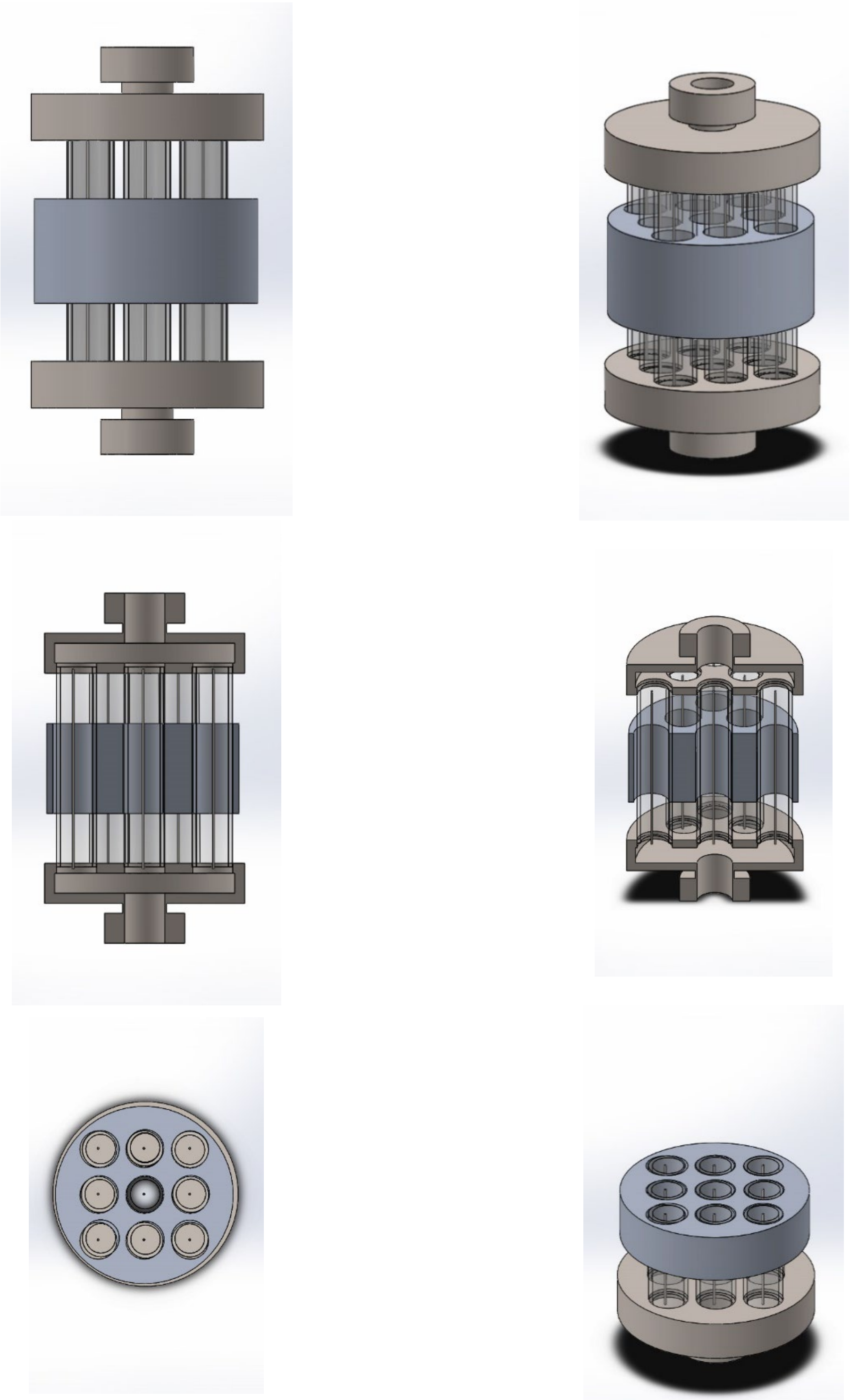


Figure D.8. Drawings of the plasma reforming reactor to be built for Phase 2.

D.3.8. Steam gasification reactor

The drawing of the steam gasification reactor to be built in Phase 2 is shown in Figure D.9. This design is obtained as a scale-up of the lab unit (Section 3), taking into account the amount of solids to be processed at pilot scale (Section 4, Figure 4.1 stream 25) and possible lower efficiency of the AD unit, with consequent higher mass of solids to be processed in the SG unit. The unit will have a total height of 2.2 m, of which 0.24 m will be for the feedstock and catalyst containers (0.12 m height for each), the rest of the volume of the unit being used for the gases.

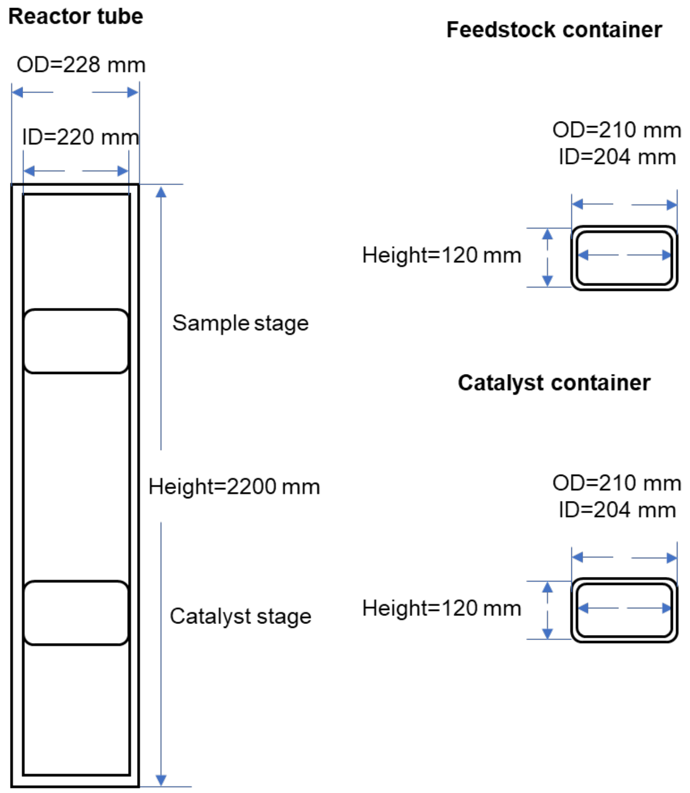


Figure D.9. Drawing of the steam gasification reactor to be built in Phase 2.

D.3.9 Membrane unit

Hydrogen and carbon dioxide gas from the dark fermentation and water gas shift units would be accumulated and stored in pressure vessels for separation through dense metallic membranes. The structure of (groups III-V) metals, such as Pd has the ability to allow hydrogen diffusion through the metal lattice, while preventing the permeation of other molecules (Figure D.10). Furthermore, dense metallic based membranes have been proposed due to their potential to transport hydrogen by solution diffusion with good perm-selectivity, high thermal stability and mechanical resistance. The membranes may be coated with gold, silver or copper to avoid embrittlement during hydrogenation cycling [D.9].

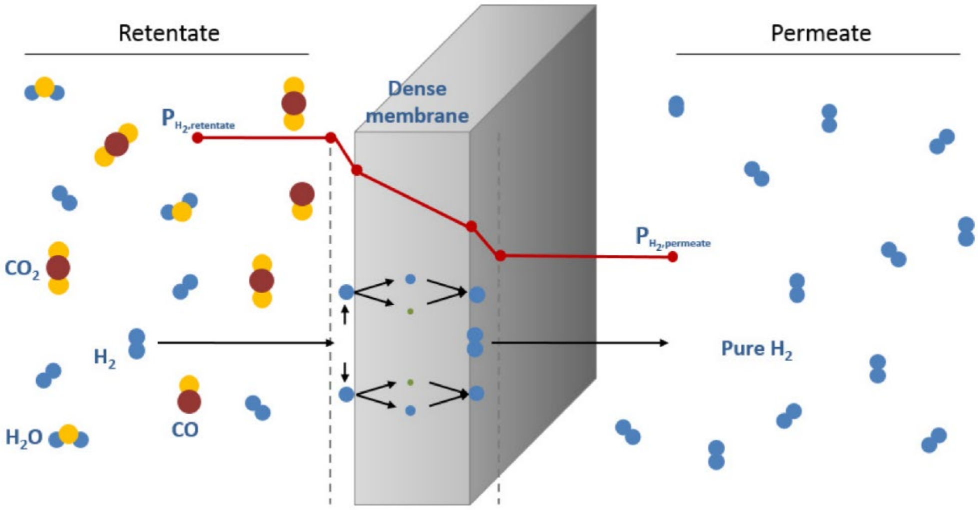


Figure D.10 Solution diffusion mechanism for hydrogen permeation

The permeation rate of hydrogen gas through palladium follows the half power law, that is, it is proportional to the difference between the square roots of the hydrogen partial pressure in the feed and permeate sides.

$$P_{eH_2} = P^{o}_{eH_2} \exp\left(\frac{-E_a}{RT}\right) \tag{D.22}$$

$$Q_{H_2} = P^{o}_{eH_2}[\exp(\frac{E_a}{RT})]\frac{\left(P^{0.5}_{H2,ret}-P^{0.5}_{H2,perm}\right)A}{\delta} \tag{D.23}$$

Where,

Q_{H_2}	Hydrogen permeation flux, kmol^{-1}
$P_{e_{H_2}}$	hydrogen permeability, kmolm m^{-2}sPa
$P^{o}_{eH_2}$	Permeability constant
E_a	Apparent activation energy
R	Gas constant
T	Permeation temperature, K
$P^{0.5}_{H2,ret}-P^{0.5}_{H2,perm}$	Pressure driving force
A	Area, m^2
δ	membrane thickness

A 0.1 m^2 membrane area with a feed pressure of 25 bar and temperature of 300 degrees C would permeate hydrogen through the membrane.
The summary of the calculations for the membrane unit are reported in Table D.4.

Table D.4. Summary of the calculation for the membrane purification unit

H2 mass flow (kg/d)	0.48
H2 mass flow (kg/s)	5.56E-06
H2 stream flowrate (L/d)	680
CO2 stream flowrate (L/d)	8278
H2 flow (kmol/s)	2.78E-06
Area (m^2)	0.1
Thickness (m)	0.000004
Absolute Pressure (Pa)	2634450
Permeate pressure (Pa)	101325
H2 fraction	0.076
CO2 fraction	0.92
H2 partial pressure in feed (Pa)	199974
H2 partial pressure in permeate (Pa)	7691
H2 Pressure drop (Pa)	359
Pre-exponential factor	1.01E-12
Ea/R	-7.67E+02
Permeation temperature (K)	573
Pe (kmol m/m^2 s Pa^1/2)	2.64E-13
Flux/pressure drop (kmol/s Pa^1/2)	6.59E-09
Flux (kmol/s)	2.37E-06

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Appendix E. WP5. Plan for operation and testing of the pilot plant

Table E.1. Gantt chart of Phase 2 activities.

Activity	2023								2024												2025		
	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar
Operation of the lab prototype	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Pilot plant process review and HAZOP analysis	■	■																					
Purchase orders for pilot plant equipment			■	■																			
Assembly of the pilot plant at University of Aberdeen									■	■	■	■											
Operation of the pilot plant with food waste													■	■	■	■							
Operation of the pilot plant with wastewater																	■	■	■	■			
Conferences and dissemination activities					■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Publication of scientific papers									■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Final report																					■	■	■

Appendix F. WP6. Costing of Phase 2

Table F.1. Labour & Overhead costs for Phase 2 (University of Aberdeen)

Name	Job Title	Role in project	Time on project (% FTE)	Labour cost (£, exc overheads)	Overheads cost (£)	Total labour cost (£)
Davide Dionisi	Personal Chair in Chemical Engineering	Project co-ordinator and scientific lead for the DF and AD stages	25	43,061	48,659	91,720
Panagiotis Kechagiopoulos	Senior Lecturer in Chemical Engineering	Scientific lead for the PR stage	15	24,334	17,520	33,024
Yeshui Zhang	Lecturer in Chemical Engineering	Scientific lead for the SG stage	15	18,024	13,578	25,594
Waheed Afzal	Senior Lecturer in Chemical Engineering	Co-lead for pilot plant design and construction	15	22,242	16,756	31,584
Aniruddha Majumder	Lecturer in Chemical Engineering	Co-lead for pilot plant design and construction	15	20,327	15,314	28,866
Claudia Fernandez Martin	Lecturer in Chemical Engineering	Pilot plant design: gas dispersion and flue design	10	13,552	7,657	14,433
Euan Bain	Senior Lecturer in Chemical Engineering	Pilot plant design: process safety	5	8,111	4,583	8,639
Ines Graca	Lecturer in Chemical Engineering	Pilot plant and lab-prototype: support for the SG/WGS stages	10	13,552	7,657	14,433
Alfonso Martinez Felipe	Senior Lecturer in Chemical Engineering	Dissemination and links with companies/academics	5	7,929	4,479	8,443
Alan McCue	Lecturer in Chemistry	Pilot plant and lab-prototype: support for the SG/WGS/PR stages	10	13,552	7,657	14,433
Israel Osofero	Senior Lecturer in Civil Engineering	Pilot plant: support for structural analysis	5	8,359	4,722	8,901
Aliakbar Jamshidi Far	Lecturer in Electrical Engineering	Pilot plant: support for solar panels, batteries and grid connection	10	13,966	7,891	14,874
Peng Li	Lecturer in Electrical Engineering	Pilot plant: support for solar panels, batteries and grid connection	5	6,825	3,856	7,268
Fabio Verdicchio	Lecturer in Electronical Engineering	Pilot plant: support for sensors and control systems	5	6,983	3,946	7,438
Raffaello Secchi	Lecturer in Electronical Engineering	Pilot plant: support for sensors and control systems	5	3,492	3,946	7,438
PDRA1	Research assistant	Lab-prototype: DF and AD stages	100	91,592	103,499	195,091
PDRA2	Research assistant	Lab prototype: PR stage	100	91,592	103,499	195,091
PDRA3	Research assistant	Lab-prototype: SG stage	100	91,592	103,499	195,091
PDRA4	Research assistant	Pilot plant: DF and AD stages	100	49,961	56,456	106,417
PDRA5	Research assistant	Pilot plant: DF, AD, WGS stages	100	49,961	56,456	106,417
Total cost				599007	676878	1,275,885

Table F.2. Labour & Overhead costs for Phase 2 (University of Cranfield, University of Verona)

Name	Job Title	Role in project	Time on project (% FTE)	Labour cost (£, exc overheads)	Overheads cost (£)	Total labour cost (£)
Luca Alibardi	Lecturer in Separation Processes	Scientific support for the biological stages, dissemination, networking events and links with academia and industry	15	19,536	14,261	33,797
Ying Jiang	Senior Lecturer in Bioenergy	Scientific support for the SG stage, links with academia and industry	10	16,060	11,724	27,784
David Bolzonella	Full Professor in Chemical Engineering	Scientific support for the biological stages and for pilot plant operation	10	18,744	3,745	22,489
Federico Battista	Assistant Professor in Chemical Engineering	Scientific support for the biological stages and for pilot plant operation	15	15,642	3,128	18,770
Total				69,982	32,858	102,840

Table F.3 Other costs and total costs for Phase 2

Budget	Justification	Cost
Total Labour & Overheads	As per tables 6.1, 6.2	1,378,725
Consumables	Consumables for lab-prototype and pilot plant runs: GF/F filters; syringe filters; COD kits; reagents and columns for analysis (GC and HPLC); membranes; Glassware, including beakers, condensers, quartz tubes; Tubes, reactor design and fittings for steam gasification; Chemicals for preparing catalysts; Lab tools, cables, PVC tubing and other consumables; Catalysts: metal precursors (salts) and supports (metal oxides); Compressed gases (CH4, CO2, H2, N2, Air, He) and other chemicals; Electrodes: copper, stainless steel, tungsten and other metals or alloys; High voltage cables for connections; Faraday Shield components: copper or aluminium meshes; Tubes for reactors: quartz, alumina and stainless steel; Fittings: Swagelok or similar for connections; Piping: Stainless steel, copper and PTFE; Lenses and optical components for optical plasma diagnostics; Electrical components, resistors, capacitors, etc. for electrical plasma diagnostics; Polymer filaments for 3D printing custom components	800,000
Travel and subsistence and dissemination events	Travel from Cranfield and Verona for project meetings and visits to the lab-prototype and pilot plant, travel to conferences and dissemination events	100,000
Capital equipment for pilot plant	Agitated vessels for DF and AD stages, feed preparation and effluent collection; Reactors for SG, WGS and PR; Piping; Membrane system for hydrogen purification; Storage vessels for intermediate stages; Solar panels; Battery pack; Fuel cell system; CHP unit	2,500,000
Total Phase 2 cost		4,778,725

Appendix G. WP7. Commercialisation plan

The report received by the company Optimat on the commercialisation plan is attached at the end of this report. This report is discussed in Section 7. WP7. Commercialisation plan.

Appendix H. WP8. Stakeholder engagement events. Workshop in Cranfield on 24th November

This section presents and summarises the final stakeholder engagement event, which was held in Cranfield on 24/11/2022. This section is followed by the slides presented at the event.

H.1 Invitation and programme

Research Development Workshop

Cranfield University - 24th November 2022

Innovation Hub – Solt Building

Hydrogen from organic waste with an integrated biological-thermal-electrochemical process

The University of Aberdeen – Cranfield University – University of Verona

Project funded by the Hydrogen BECCS Innovation Programme Phase 1. Project ID H2BECCS118

Event organised with the support of the Centre for Post-Doctoral Development in Infrastructure Cities and Energy (C-DICE)

Introduction

This project investigated the feasibility of an innovative process to produce hydrogen from biodegradable organic waste. The process (Figure 1) uses a combination of biological (dark fermentation and anaerobic digestion), thermochemical (steam gasification and water gas shift) and electrochemical (plasma reforming) stages. The process aims to maximise the hydrogen yield from the organic matter and to minimise the energy consumption.

Preliminary estimations indicated that the biodegradable organic waste produced in the UK, if collected and converted into hydrogen using optimised biological and chemical physical processes, could potentially produce in the region of 6 Mt of hydrogen per year, which would account for 26 % of the UK's energy demand for domestic heating and road transportation in renewable energy scenarios. The proposed process delivers on the possibility to exploit this large renewable energy potential.

The research development workshop aims to:

- Analyse the key points of the feasibility study to explore the technological, commercial and academic development opportunities linked to this project.
- Investigate, through collaborative discussion, the opportunities the process can deliver.
- Engage for next steps and implications for research or commercial work linked to your expert research fields/businesses.

- Investigate opportunities for cross-sector collaborations linked to this research project.

The feasibility study delivered mass and energy balances, carbon life cycle assessment, engineering design of the pilot plant, plan for the operation of the pilot plant, lab scale prototype and a commercialisation plan and the outcomes of the project will be shared during the workshop.

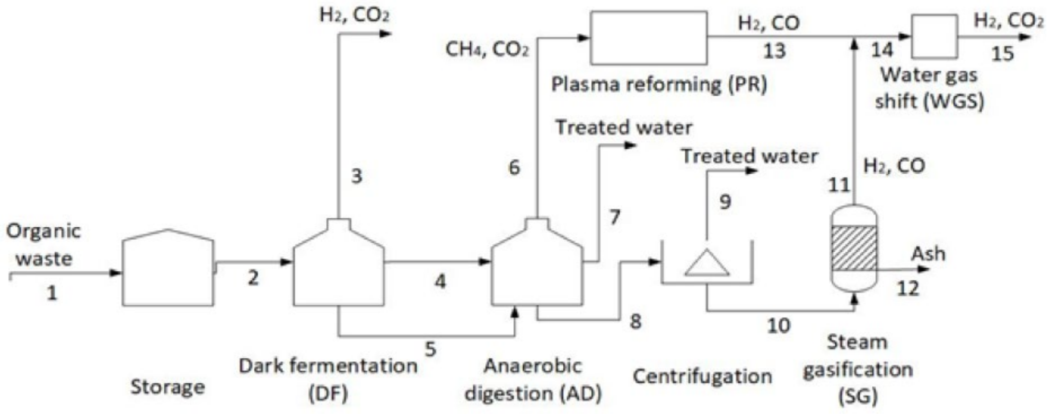


Figure 1. Scheme of the proposed process for hydrogen production from biodegradable organic waste. Stream numbers: 1. Organic waste to the storage vessel; 2. Organic waste to the DF stage; 3. Biogas (mainly hydrogen and carbon dioxide) from the DF stage; 4. Clarified liquid (mainly organic acids in water) from the DF stage; 5. Concentrated suspended solids from the DF stage; 6. Biogas (mainly methane and carbon dioxide) from the AD stage; 7. Treated water from the AD stage; 8. Concentrated suspended solids from the DF stage; 9. Treated water from the centrifuge; 10. Concentrated suspended solids to the SG stage; 11. Gases (mainly hydrogen and carbon monoxide) from the SG stage; 12. Ash (mineral elements, e.g. N, P, K, Mg) to reuse (e.g. in agriculture); 13. Gas products (mainly hydrogen and carbon monoxide) from the PR stage; 14. Gas stream combination of streams 11 and 13; 15. Gas stream (mainly hydrogen and carbon dioxide) from the WGS stage.

Programme

9:00 – 9:30 Registration and coffee
9:30 -9:45 Welcome and introduction
Professor Phil Longhurst and Dr Luca Alibardi will introduce the day.
9:45-10:00 Expectations
Professor Phil Longhurst
10:00-10:45 Overview of the project

1. An overview of the system and techno-economics – University of Aberdeen
2. Dark fermentation, plasma reforming and gasification – HEI project partners
3. Commercialisation – Commercial project partner

10:45-11:00 Coffee break
11:00-12:30 Group discussions

1. Technology vulnerability and resilience – strengths and weaknesses of the technology
2. Techno-economic performance – operational requirements and cost drivers
3. Business case – what would convince you to invest?

12:30-13:30 Lunch
13:30-14:30 Group feedback

1. Technology vulnerability and resilience
2. Techno-economic performance
3. Business case

14:30-15:00 Review expectations and formal closure with coffee and networking

OPTIONAL 15:00-16:00 Facilities tours (x2) and **Collaboration/networking discussions**

H.2 Aims and outcomes

The purpose of the event was to critically consider the technical aspects of the processes making up this complex project and evaluate and explore opportunities three key themes (technical vulnerability and resilience, techno-economic aspects, and commercialisation opportunities). The workshop aimed to:

- Analyse the key points of the feasibility study to explore the technological, commercial and academic development opportunities linked to this project.
- Investigate, through collaborative discussion, the opportunities the process can deliver.
- Engage for next steps and implications for research or commercial work linked to your expert research fields/businesses.
- Investigate opportunities for cross-sector collaborations linked to this research project.

The project team managed to received support to promote the event from the UKRI Centre for Postdoctoral Development in Infrastructure Cities and Energy (C-DICE). C-DICE offered to promote the event through their network (industry, academia, post-doctoral researchers and research students) and also offered in-kind help by hosting the registration page to the event on their website (https://www.cdice.ac.uk/events/h2beccs/). The workshop was also promoted via the UK Wastewater Network that Cranfield University leads and have an audience from all the UK Water companies, engineering and consultancy companies active in the UK water sector.

The workshop was attended by 20 delegates and representatives of the UK water companies (Yorkshire Water), waste management consultancies (WRM-Environmental Consultancy) and universities (Birmingham, Keele, Loughborough, Aberdeen, Cranfield).

The expectations for the workshop from the delegates are reported below:

- Meeting the research group
- Details and info on dark fermentation
- Info on carbon capture
- Info on energy balance
- Technology selection and drivers
- Industrial applications and end-users requests
- Wider application and links to other processes
- Economies of scale
- Energy value for rural/remote areas
- Public perception and opinion on hydrogen
- Viable and available waste resources/feedstock
- Contribution to business case for sludge management
- End products utilisation like char
- Key blockers to process implementation and scale-up
- Networking and collaboration opportunity

The workshop was structured as a collaborative activity to review the outcome of the project and provide feedback on the development of processes. The interactive nature of the workshop allowed for diverse discussions around the technicalities of the project processes as well as capacity for augmenting/complementing existing technologies.

The wide variety of stakeholders including the project team, key academics, industrial partners from the water and waste sector, postdoctoral researchers, PhD students and members of the C-DICE team led to a variety of discussion points, maximising the available time. These discussions benefitted all stakeholders and led to comprehensive feedback for the project team.

The day started with an overview of the technical aspects of the processes, led by academics from Aberdeen and Cranfield Universities. Professor Davide Dionisi gave an overview of the whole project, signposting the benefits of a smaller plant, meaning a lower carbon footprint. Dr Luca Alibardi expanded on this, explaining the rationale for using biological processes and the role of dark fermentation for hydrogen production. Dr Yeshui Zhang introduced functional catalyst in steam gasification, highlighting its ability to boost hydrogen production. Dr Panos Kechagiopoulos outlined the non-thermal/non-equilibrium plasmas involved in this process, which utilise the relatively high energy to break bonds at lower temperatures, leading to energy efficiencies in comparison to traditional processes. Kayleigh Nelson described the existing competitive market and high demand for organic waste, impacting on commercialisation opportunities. With H2 tech becoming increasingly attractive there is commercialisation potential and good alignment with current policy thinking and direction.

The presentations shared with the delegates are reported after this section. Figures H1 and H2 show the participants and the posters during the workshop.

Following the input during the first part of the morning, groups were established to include a range of stakeholders to discuss the details, barriers, and solutions around the key themes. The delegates were split in three working groups and discussed collectively to provide their feedback on the following points of review of the proposed process:

- Technology vulnerability and resilience – strengths and weaknesses of the technology
- Techno-economic performance – operational requirements and cost drivers
- Business case – what would convince you to invest?

The summary of all the answers emerged from the working groups are reported in Table H1.

Finally, the benefits of the day were identified, which included positive networking opportunities, leading to potential future collaborations. Highlights of the discussions included resource availability and competition for these resources over time, discussions around quality and purification of hydrogen as well as feedstocks and products. Local and national applications were explored in greater depth and issues around transporting hydrogen discussed. Technology readiness levels of the range of processes were considered and links to other projects or existing infrastructure were explored. Scalability and economies of scale as well as energy efficiencies for each process were raised as points for further clarification. Specific feedback on the content and structure of the workshop are reported in Table H2.

Table H1. List of the contributions and discussion during the working groups.

Technology vulnerability and resilience – strengths and weaknesses of the technology	
Positive	**Negative**
Variability in conversion Good as means of sludge treatment Integration with biofuel production Feedstock flexibility Overall process can counterbalance inefficiencies of individual steps Integrating multiple processes Multi-use fuel Utilise existing infrastructure Each process produces some hydrogen. Allows process downtime Scalability Local solutions Some tech well understood – AD Renewable direction Experience with pilot plant Augmentation/adaptation of AD Abundance of waste Applicable to a wide range of waste Optimisation at lab scale Water electrolysis needs water. Ok if recycled otherwise not Portable technology. DF can be brought to site Hydrogen future energy vector Ability to optimise hydrogen production Demand and legislation for end products	Current limitations of hydrogen infrastructure Unwillingness of industry to take up limited full-scale operation Uncertainty of effectiveness of steam gasification versus biochar production knowledge Limitation of substrate Uncertainty on how dark fermentation compare with other fermentation processes Complexity of the overall process Cost compared with status quo Uncertainty of overall efficiency Different TRL for different processes Energy cost for de-watering Quality of biogas can be limiting – need for additional treatment? Hydrogen purification Knowledge gaps Safety Feedstock consistency and availability Cost of multiple plants Training needs Development needed ABPR regulation for food Operability of 3-4 processes Complexity Unknowns Competition Contaminants of stocks How controllable is plasma reforming Different technologies involved Non-biodegradable fraction Yield to be optimised Steam methane reforming as alternative Separation of waste Feedstock variability Can you convince the public to adapt Perception, NIMBY Changing energy market Varied set of skills Varied set of technologies
Techno-economic performance – operational requirements and cost drivers	
Positive	**Negative**
Find additional outlets to use ash Phosphorus recovery from ash (P in centrate) Recovery of heat flows through out process Valorise volatile fatty acids separately Use CO2 produces Additional type of feedstock A route to reduce sludge volume Can be retrofitted Free raw material Multi-stage process maximise hydrogen Waste management to hydrogen Aligns with policy direction Renewable energy Oil price high Hydrogen fuel incentives Markets for other products Grant/subsidies as ROCs Heat recovery VFA recovery	Centrate treatment needed Odour treatment for dark fermentation Low H2 yield from some feedstock Single stage is inefficient/fails, need for bypass Optimisation of process stages Multi-stage complex process High capex High opex Value of hydrogen Transportation of raw materials Cost of purification High purity of hydrogen needed for fuel cells Tech failure Low oil price Bank confidence Transport costs Uncertainty for capital costs Energy consumption and costs Operation/intervention during processes

Biosolids to land threated full destruction maximised More use of hydrogen High cost of waste disposal Low carbon hydrogen Increase plant capacity Nutrient recovery Economy of scale Value from manure, municipal waste, sewage sludge Industries and local authorities should play you to take the waste products Can eld waste products be sold? Waste management reduced costs New green workforces for every stages of the process Quality of hydrogen Training and knowledge development	Complexity Management/integration of the various processes Process control and operation Business model, capex equipment costs Rental model maintenance
Business case – what would convince you to invest?	
Positive	**Negative**
Need good pilot-scale/full scale data Alternative energy source not dependent on other countries Increasing costs of energy and gas A means of reducing sludge volume AD stage well established Modular stages Meeting net zero target (cost comparison) Look at what factors might change in world energy/costs – what gives incentive to taking this forward Feasibility of the technology, lab prototype has been completed Lower energy costs Industry-scale demo plant Transparency of the technology Acknowledgement of the existing technology that works Government commitments and support for renewables Confidence in process performance asset resilience operability Multiple products to increase business case for development Potentially addressing a significant business risk for water companies i.e. disposal of sludge to agricultural land Potential for service commercial model (design, build, own, operate) Valorising waste products Experience at pilot scale No large mass end products Mass and energy balance at pilot scale CO2 capture carbon negative process carbon trading credits Low carbon hydrogen Yield per kg of waste Diversity of waste and its applicability to process Low carbon hydrogen, incentives and premium price	Complexity of process Uncertainty over government incentives Perception of safety Cost of additional resources needed Transition to use of hydrogen in energy mix Lack of training/knowledge in operation Cost of hydrogen production Cost of multiple stage process Complexity of process Safety risks Ability to integrated into existing asset Bank confidence No models for hydrogen Cost of regulatory framework for feedstock Lack of experience at pilot scale TRL Process complexity engineering complexity High capital investment Novel ideas goes against status quo Understanding of the magnitude of hydrogen need as energy vector Hydrogen supply chain and use

Table H2. Feedback from the attendees on the content and structure of the workshop

Please tell us what was most useful and what you gained from attending the workshop	**Please tell us what we could have done better or differently**	**What actions will you take following the workshop**
overview of project and attendance from people of different sector	it was good	engage with project members re potential collaborations
Getting together, some of the conversations that wouldnt otherwise have happened, access to more varied perspectives within the team. I enjoyed the workshop exercise and think this is a valuable way to collate thoughts and determine next priorities.	Discussion time felt short at times (could've done with say another 5 minutes per category), if you pre-emptively draw on the flipcharts, you may get more consistency, and can add an area on the sheet for thoughts/questions that don't quite fit but are relevant, a number of these were identified within the group. Overall was insightful and well put together.	Review notes in line with commercialisation strategy and see if any gaps/areas to improve, Share some information requested with individuals after discussions.
It was useful hearing about the overall project and in particular the lower TRL stages (e.g. plasma). Networking was valuable so we know who is involved and who we can contact in the future about these areas of research.	It would have been useful to see a copy of the slides upfront as some of the presentations were very quick and I didn't capure all that was being reported, though it looked like a huge amount of work has already been done. A summary of the main achievements in terms of efficiencies, power output from H2 sources, comparisons with other energy sources e.g. AD to biogas to CHP as currently used, would have been useful to set the scene.	My colleague and I have written up notes to pass on to others at Yorkshire Water who hopefully will follow this up. It would be useful to keep in touch with the project and see how it progresses to Phase 2.
Better understanding of the process and project aspirations	More detail on the tech, although really this would more than likely push the event into two days	Develop industry and Acedemic research links
Getting together, some of the conversations that wouldn’t otherwise have happened, access to more varied perspectives within the team. I enjoyed the workshop exercise and think this is a valuable way to collate thoughts and determine next priorities		

Figure H1. Pictures of the workshop at Cranfield University

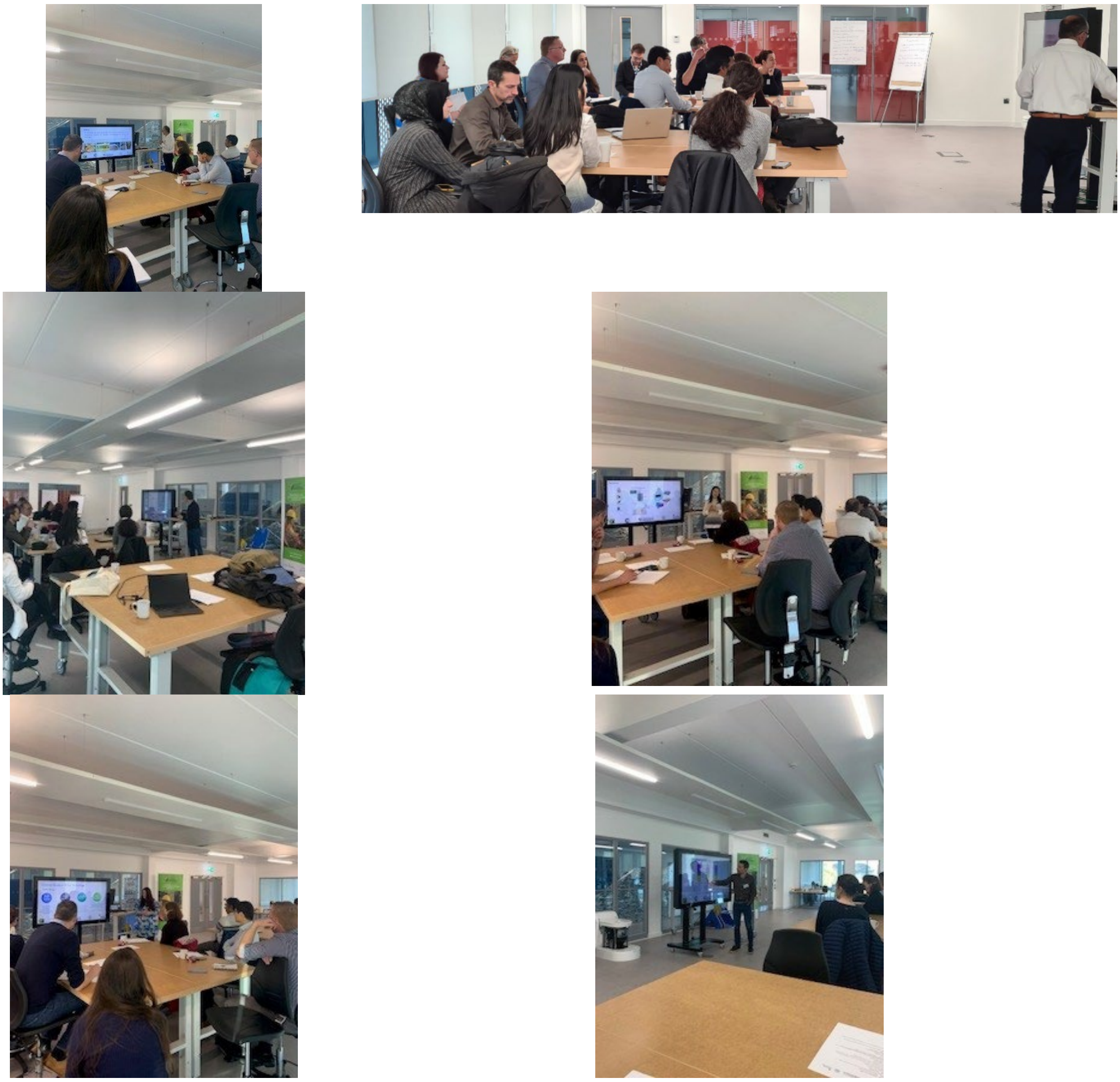
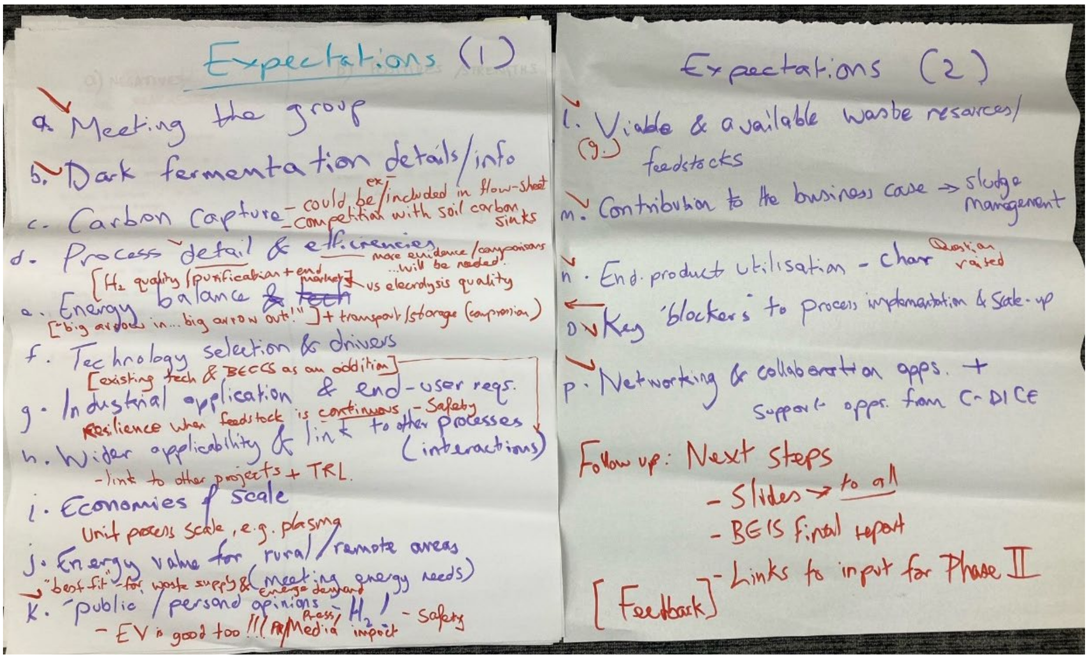


Figure H2. Pictures of the posters generated during the workshop discusion



Expectations (1)

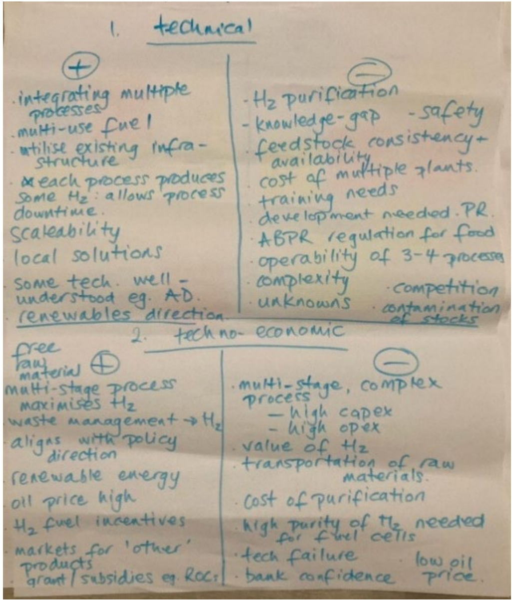
a. Meeting the group
b. Dark fermentation details/info
c. Carbon capture - could be ex/included in flow-sheet - competition with soil carbon sinks
d. Process detail & efficiencies - more evidence/comparisons ...will be needed.
[H_2 quality (purification + end market)] vs elecrolysis quality
e. Energy balance ~~& tech~~
["big arrow in... big arrow out!"] + transport/storage (compression)
f. Technology selection & drivers
[existing tech & BECCS as an addition]
g. Industrial application & end-user reqs.
Resilience when feedstock is continuous - Safety
h. Wider applicability & link to other processes (interactions)
- link to other projects + TRL.
i. Economies of scale
Unit process scale, e.g. plasma
j. Energy value for rural/remote areas
"best fit" - for waste supply & (meeting energy needs) energy demand
k. Public/personal opinions - H_2! - Safety
- EV is good too!!! (~~PR~~ Press/Media impact

Expectations (2)

l. Viable & available waste resources/feedstocks (g.)
m. Contribution to the business case → sludge management
n. End product utilisation - char Question raised
o. Key 'blockers' to process implementation & scale-up
p. Networking & collaboration opps. + support opps. from C-DICE

Follow up: Next steps
- Slides → to all
- BEIS final report
- Links to input for Phase II

[Feedback]



1. technical

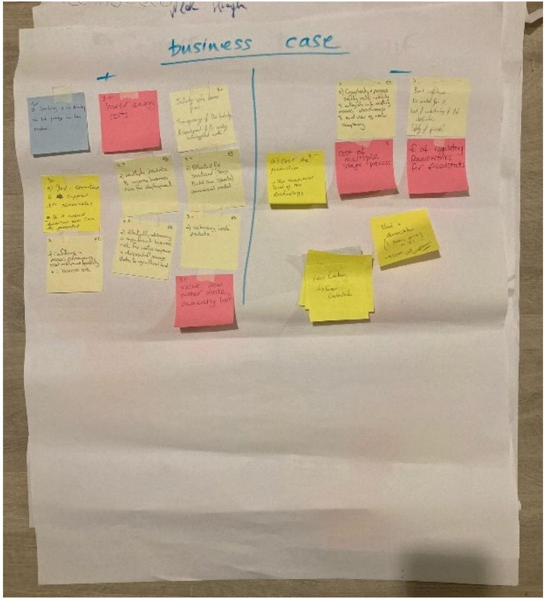
+
- integrating multiple processes
- multi-use fuel
- utilise existing infrastructure
- each process produces some H_2: allows process downtime.
- scaleability
- local solutions
- some tech. well-understood eg. AD.
- renewables direction

−
- H_2 purification
- knowledge-gap
- safety
- feedstock consistency + availability
- cost of multiple plants.
- training needs
- development needed. PR.
- ABPR regulation for food
- operability of 3-4 processes
- complexity
- competition
- unknowns
- contamination of stocks

2. techno-economic

+
- free raw material
- multi-stage process maximises H_2
- waste management → H_2
- aligns with policy direction
- renewable energy
- oil price high
- H_2 fuel incentives
- markets for 'other' products
- grant/subsidies eg. ROCs

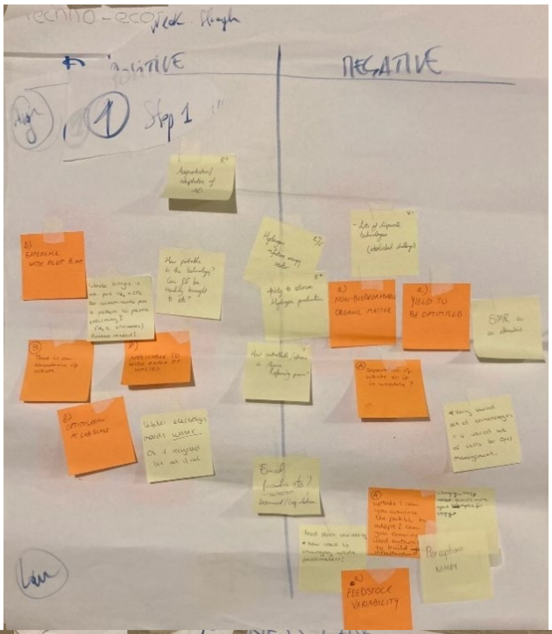
−
- multi-stage, complex process
  - high capex
  - high opex
- value of H_2
- transportation of raw materials.
- cost of purification
- high purity of H_2 needed for fuel cells
- tech failure
- low oil price.
- bank confidence

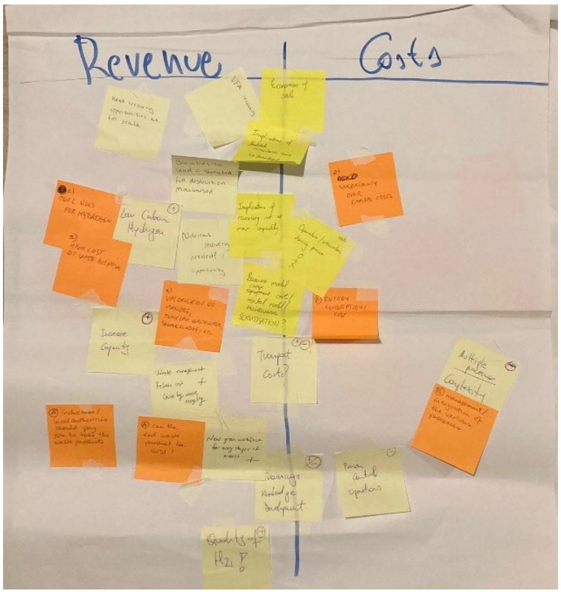


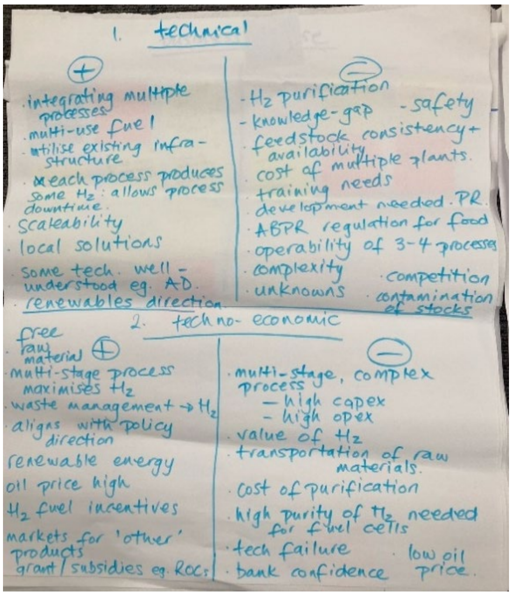
business case

+

−







1. technical

⊕

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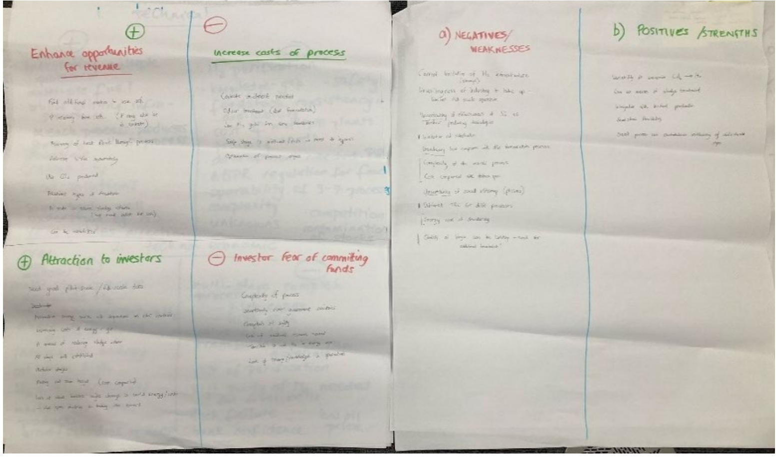

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Hydrogen from organic waste with an integrated biological-thermal-electrochemical process

Delivering net-zero,
transforming postdoctoral
development.

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& Industrial Strategy

Hydrogen from organic waste with an integrated biological-thermal-electrochemical process

Professor Davide Dionisi, School of Engineering,
University of Aberdeen

Delivering net-zero,
transforming postdoctoral
development.

Department for
Business, Energy
& Industrial Strategy

Aims

To develop an and accelerate the commercialisation of an innovative process to convert biomass/organic waste into hydrogen.

Target feedstock: biodegradable organic waste, e.g. food waste (and OFMSW), manure, industrial and municipal wastewaters, agricultural residues.

Values as DM

~10 Mt/y

~25-35 Mt/y

~19 Mt/y

~1 Mt/y

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Project data

Aim: to investigate the feasibility (Phase 1) and to build a pilot plant (Phase 2) for a new process to convert biodegradable organic waste (e.g. food waste) into hydrogen

Funded by the UK Government, Department for Business, Energy & Industrial Strategy (BEIS) under the Hydrogen BECCS Innovation Programme: Phase 1. Funding obtained for Phase 1: £220,000

Project partners: Universities of Aberdeen (UK), Cranfield (UK) and Verona (Italy).

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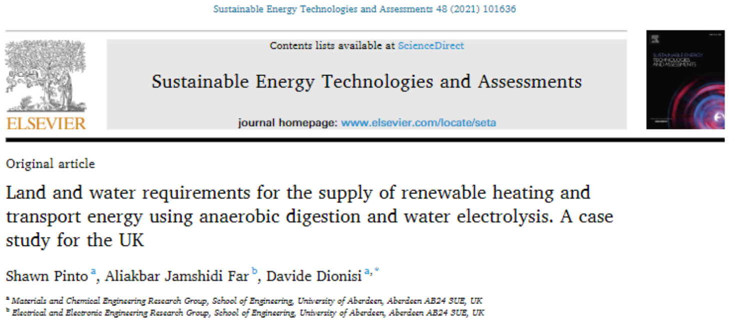
Role of hydrogen from organic waste


Sustainable Energy Technologies and Assessments 48 (2021) 101636

Contents lists available at ScienceDirect

Sustainable Energy Technologies and Assessments

journal homepage: www.elsevier.com/locate/seta

Original article

Land and water requirements for the supply of renewable heating and transport energy using anaerobic digestion and water electrolysis. A case study for the UK

Shawn Pinto[a], Aliakbar Jamshidi Far[b], Davide Dionisi[a,*]

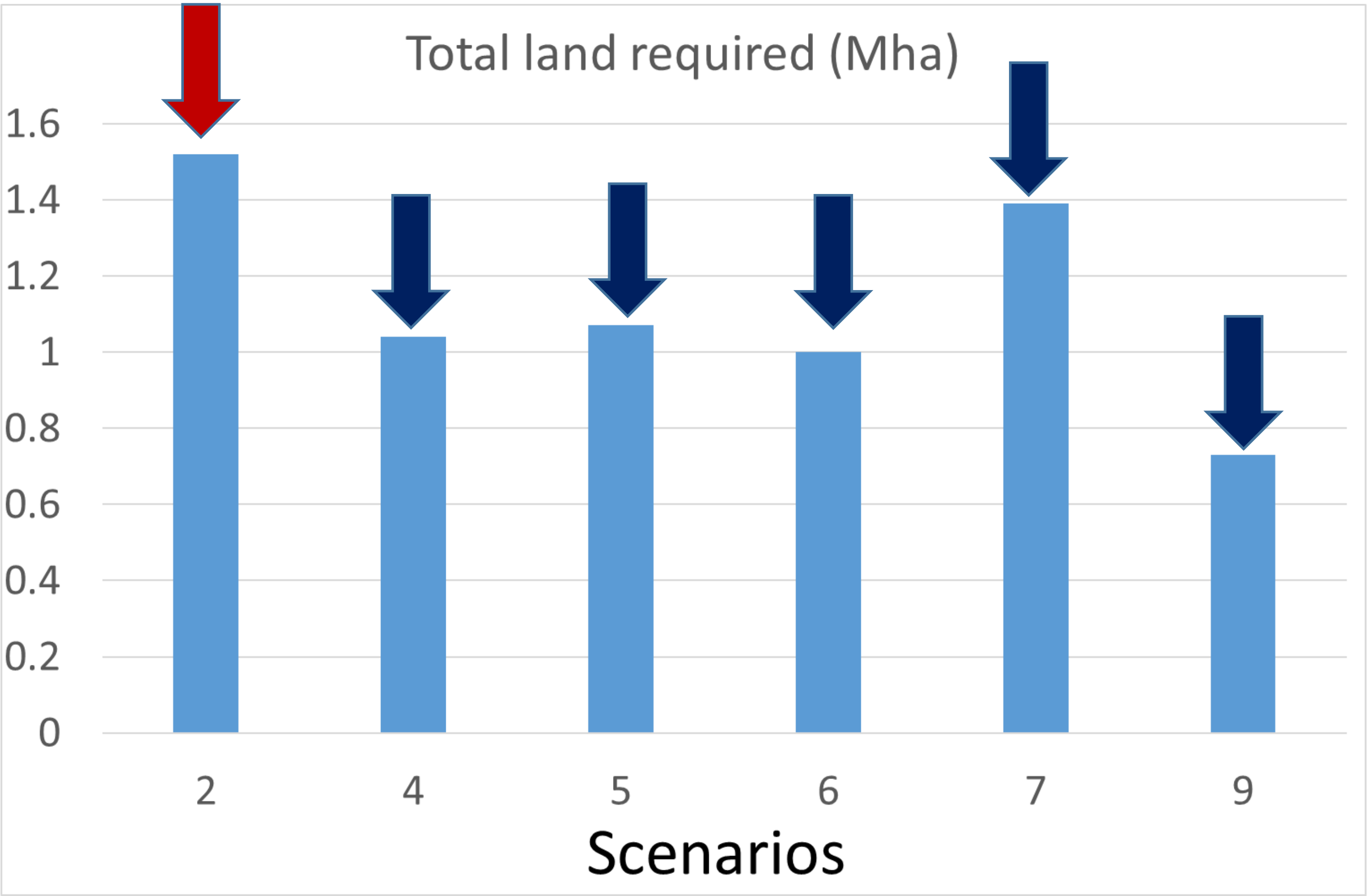
[a] *Materials and Chemical Engineering Research Group, School of Engineering, University of Aberdeen, Aberdeen AB24 3UE, UK*
[b] *Electrical and Electronic Engineering Research Group, School of Engineering, University of Aberdeen, Aberdeen AB24 3UE, UK*

Hydrogen from water electrolysis only

Hydrogen from water electrolysis and organic waste

Potential savings of ~500,000 ha with hydrogen from waste

Total land required for renewable heating and transport energy in the UK



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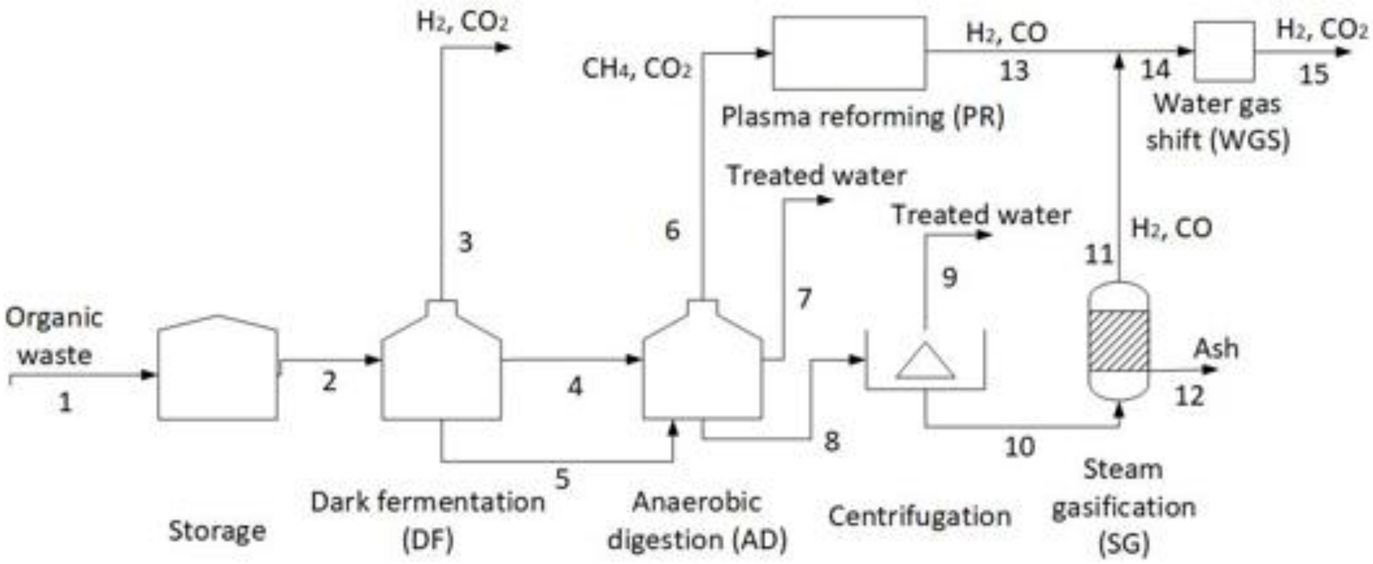
Our process

Combination of biological (dark fermentation and anaerobic digestion), thermochemical (steam gasification, water gas shift) and electrochemical (plasma reforming) stages, to maximise hydrogen yield while minimising energy consumption.



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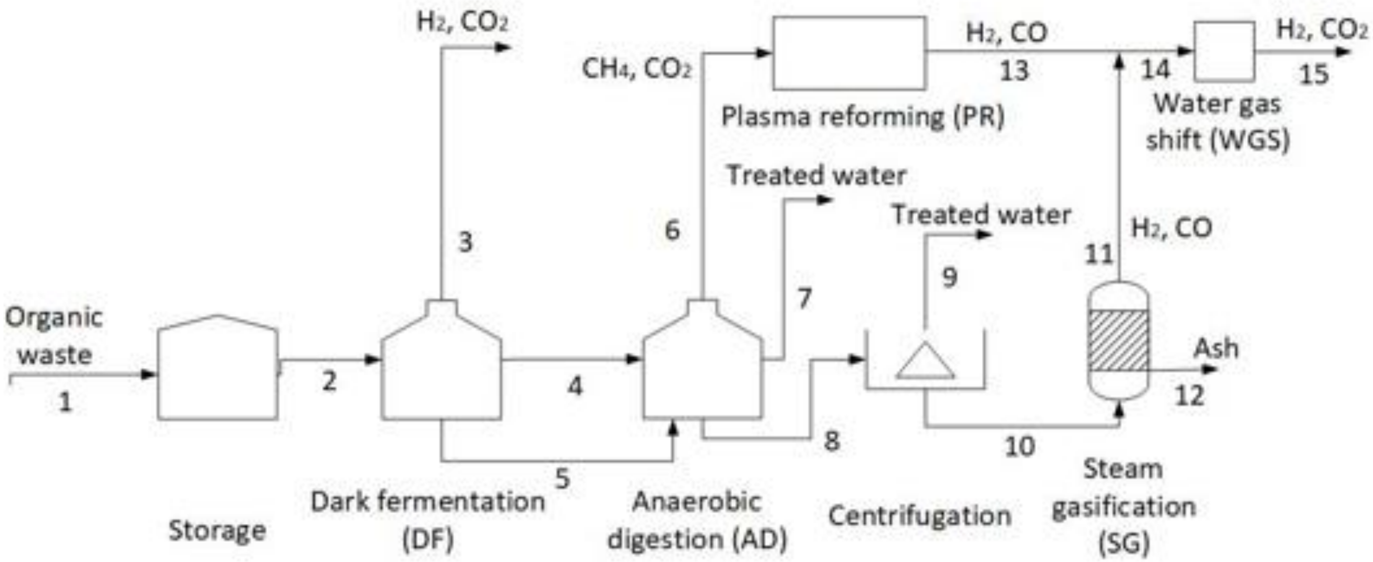
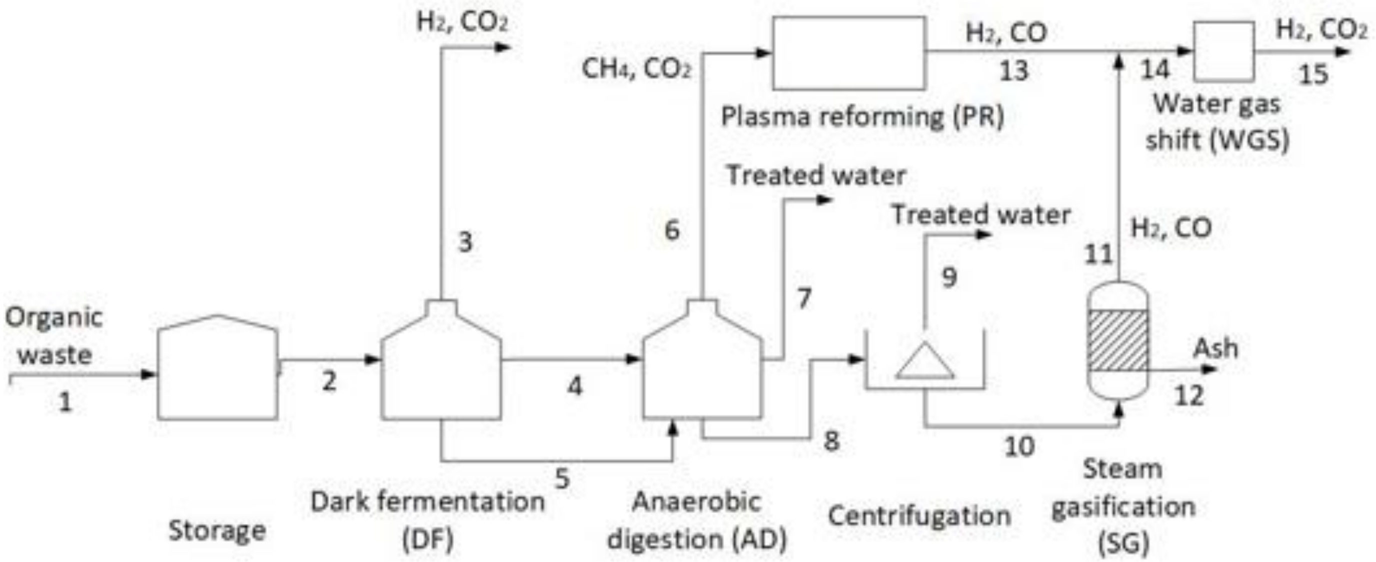
Dark fermentation (DF)

In DF, anaerobic microorganisms convert the biodegradable organic matter into hydrogen and organic acids. The target is to do this stage at ambient temperature and uncontrolled (acidic) pH.



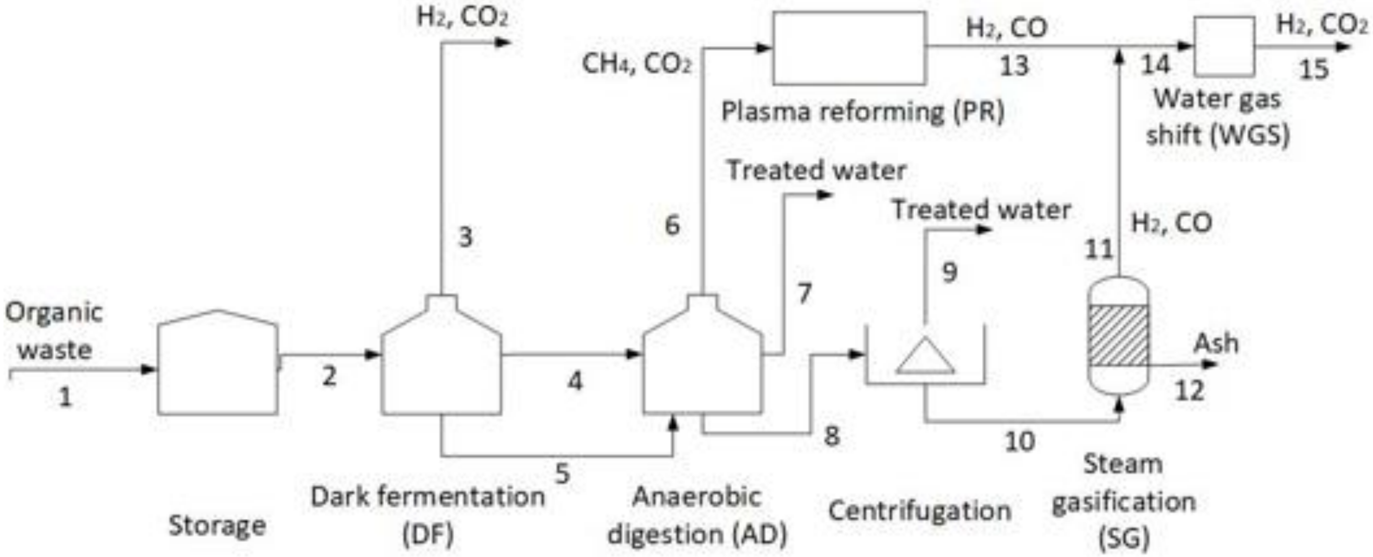
Anaerobic digestion (DF)

In AD, anaerobic microorganisms convert the organic acids and other biodegradable organic matter from DF into methane and carbon dioxide. The target is to do this stage at ambient temperature and uncontrolled (neutral) pH.



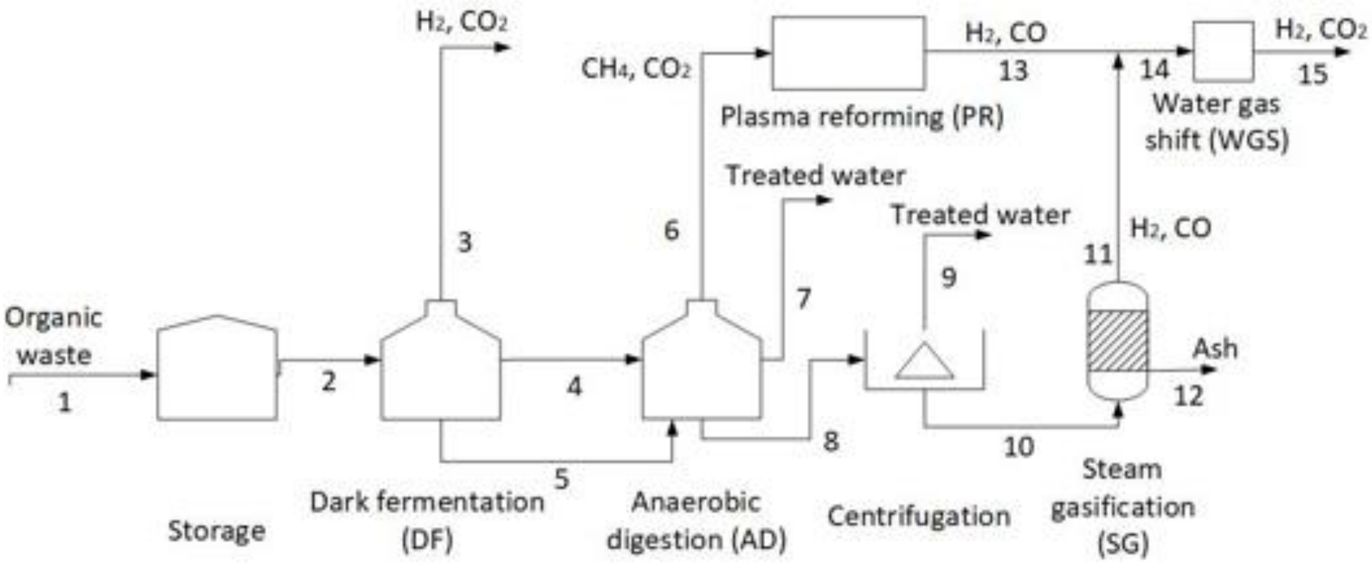
Plasma reforming (PR)

In PR, the CH_4/CO_2 mixture from AD is converted, using high voltage electricity, into H2 and CO. The stage is carried out at low temperatures (non thermal plasma, 100-200 ^{O}C) with non expensive construction materials.



Steam gasification (SG)

The SG converts the organic matter which was not converted in the biological stages into a gas mixture mainly composed of H2 and CO.



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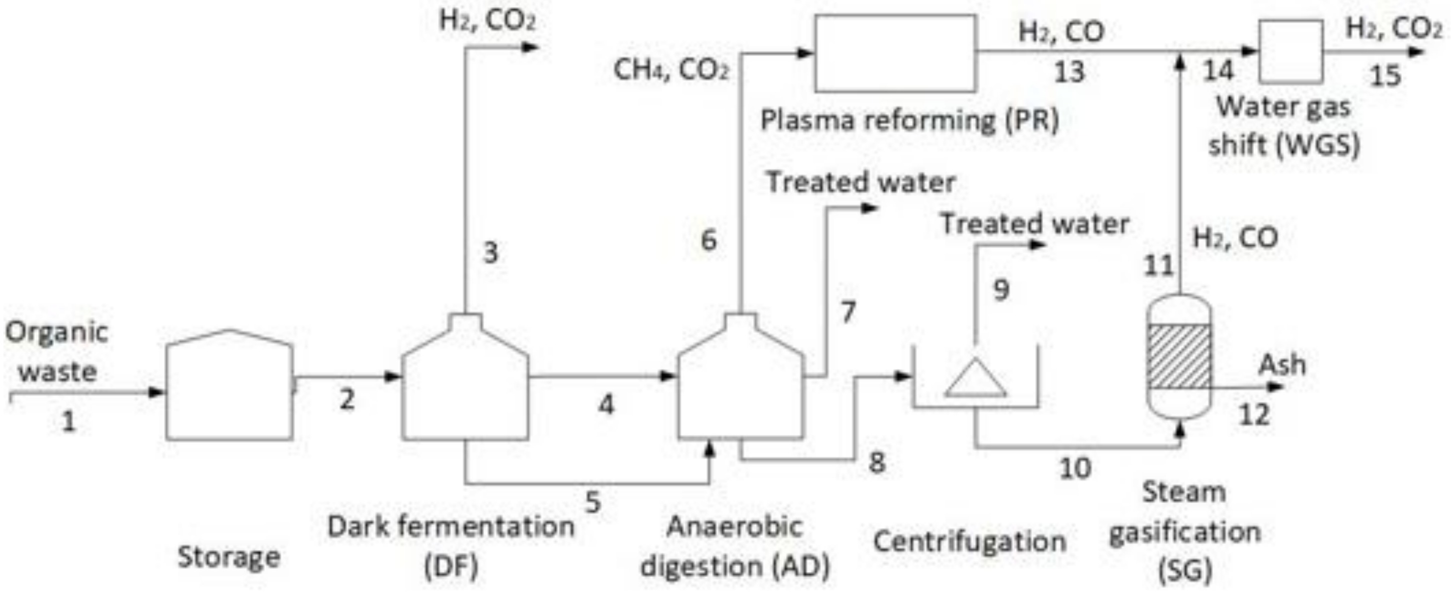
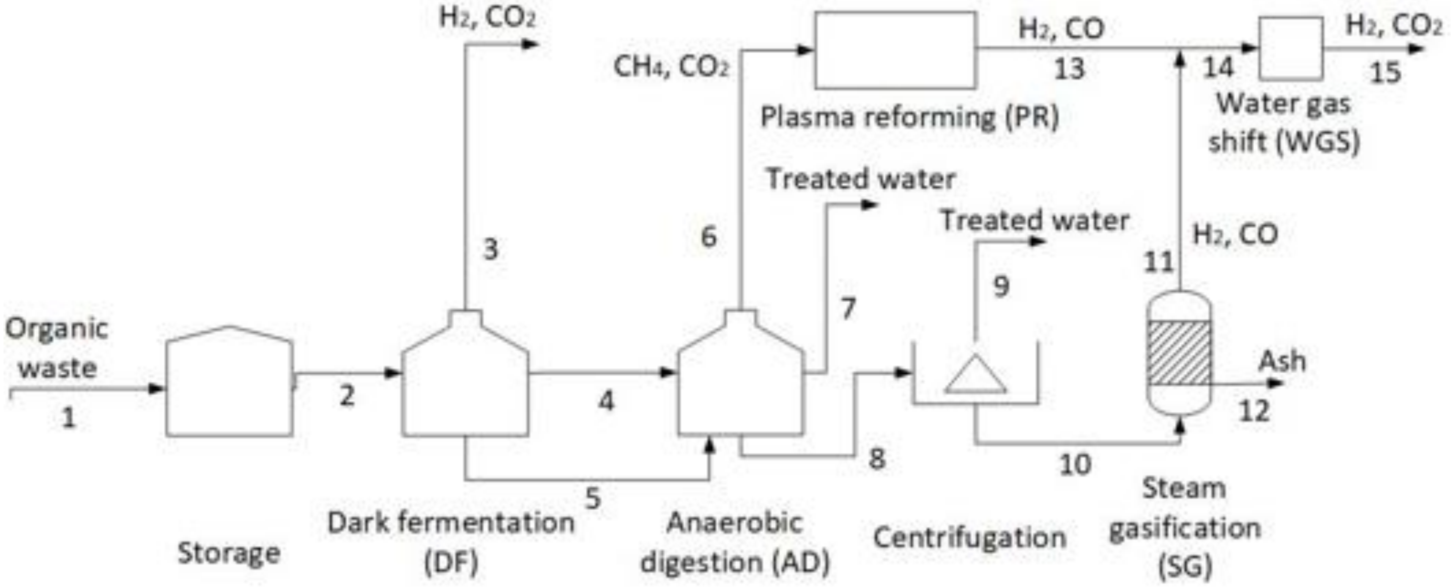
Water Gas Shift (WGS)

The WGS converts the CO from the PR and SG stages into H_2, by catalytic reaction with steam.



Hydrogen purification

The H_2/CO_2 mixture from the WGS will pass through Pd-alloy membranes, only permeable to H_2, producing H_2 at high purity (>99.99%).



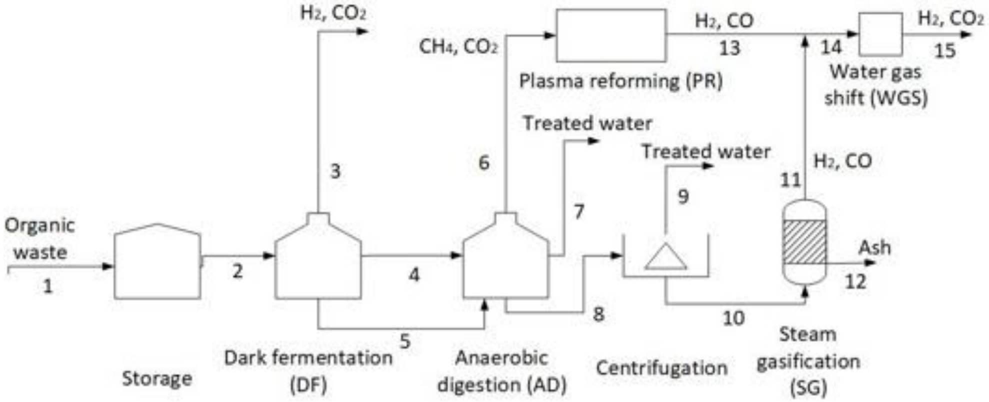
Other products

CO_2: biogenic in nature (carbon from biomass), can be captured and stored with existing processes (carbon negative process)

Combustible gases: CH_4 and CO from incomplete conversions in PR and WGS, they will be combusted in a CHP (combined heat and power) for energy recovery

Ash: nutrient-rich (N, P, Ca, Mg, etc) inorganic matter to be used in agriculture

Water: treated water for disposal or further treatment (e.g. biological treatment)



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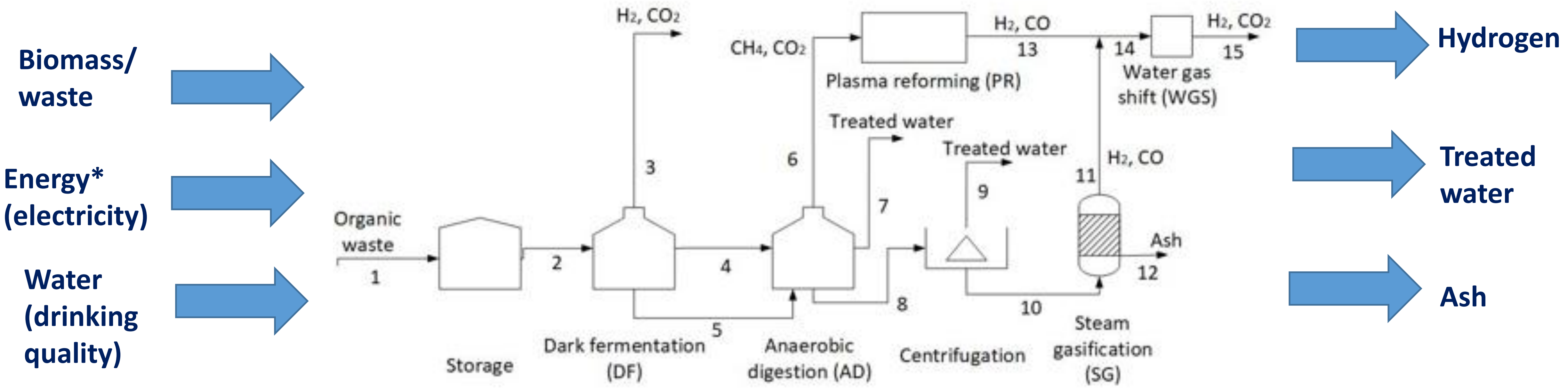
Summary



Biomass/ waste

Energy* (electricity)

Water (drinking quality)

Hydrogen

Treated water

Ash

*It is expected that the plant will only use electricity for energy and that it will all its required electricity from solar panels on the plant's roof.

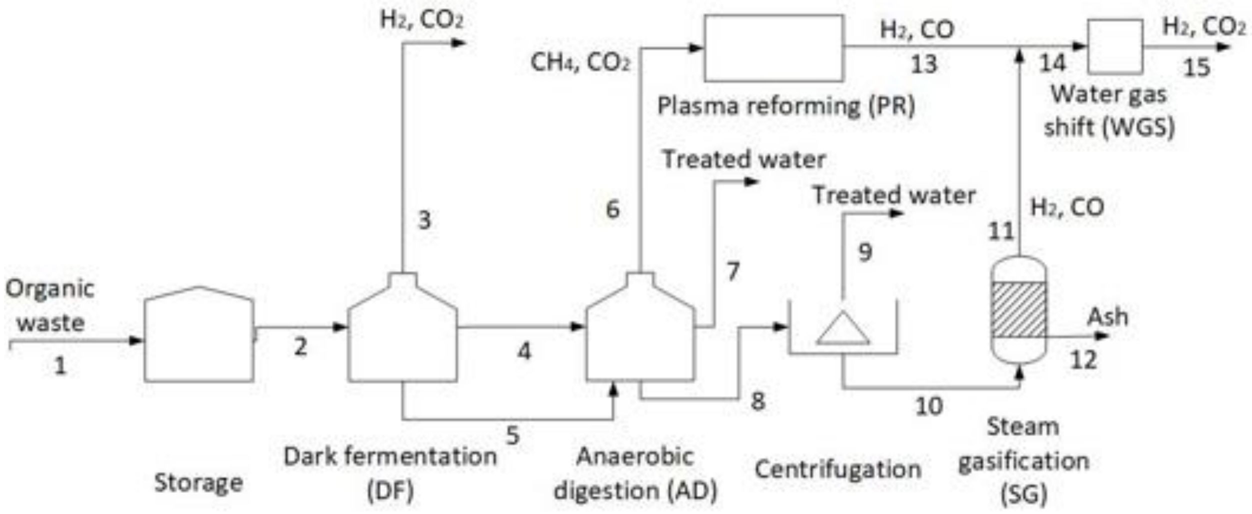
Mass and energy balances

Assumptions:

- Feed: food waste with 20% organic matter, organic matter assumed to be glucose

Assumptions for the base case

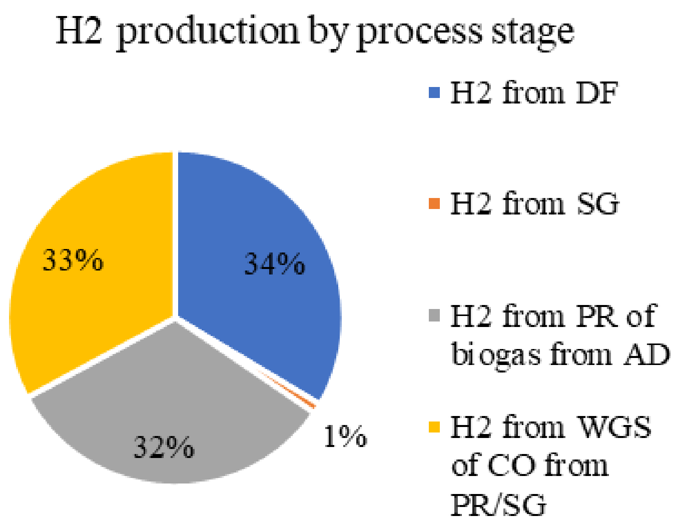
Stage	Yield	Energy consumption	Water consumption
DF	0.044 kg_{H2}/kg_{OM}	278 kWh/t_{OM}	
AD	0.25 kgC_{H4}/kg_{OM}	278 kWh/t_{OM}	
PR	0.25 kg_{H2}/kg_{CH4}	5.38 kWh/kg_{CH4}	
SG	0.05 kg_{H2}/kg_{OM}	4.23 kWh/kg_{OM}	2 kg_{H2O}/kg_{OM}
WGS	0.07 kg_{H2}/kg_{CO}	0.40 kWh/kg_{CO}	0.64 kg_{H2O}/kg_{CO}

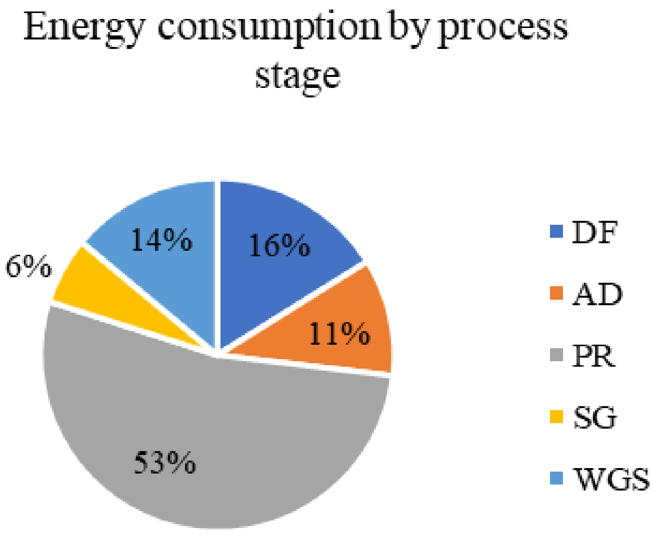


Assumptions from the base case are based on the reaction stoichiometry and literature, assuming complete conversion in each stage (for DF: stoichiometry of glucose conversion into hydrogen and acetic acid with 1% conversion into microorganisms; for AD: complete conversion of the COD into methane with 5 % into microorganisms; for PR and WGS: complete conversion according to reaction stoichiometry; for SG: experimental published yield)

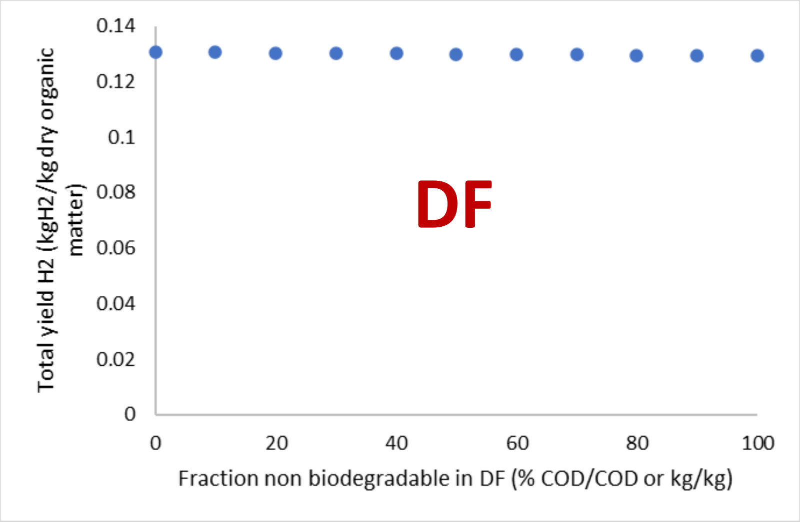
Simulations for the base case

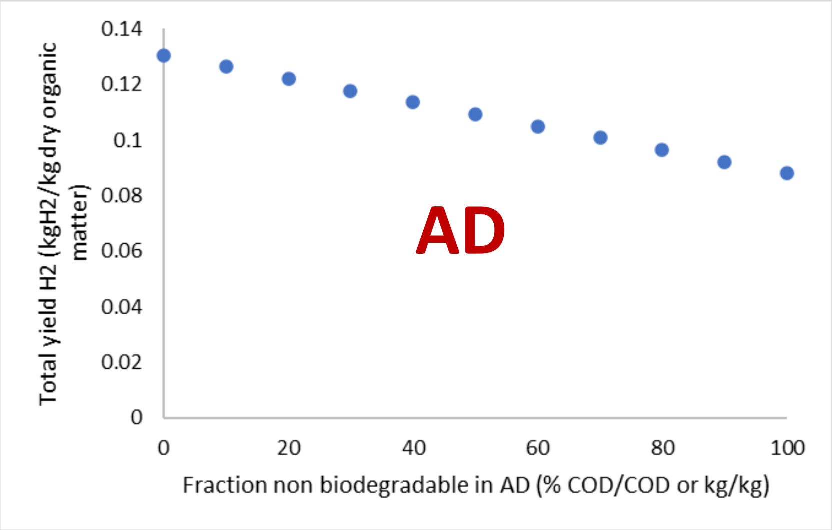
Total hydrogen yield: 0.13 kg_{H2}/kg_{OM} (vs 0.11 kg_{H2}/kg_{H2O} for water electrolysis)
Total energy consumption: 0.34 kWh/kWh_{H2} (vs >1.0 kWh/kWh_{H2} for water electrolysis)
Total water consumption: 3.33 kg_{H2O}/kg_{H2} (vs 9.0 kg_{H2O}/kg_{H2} for water electrolysis)

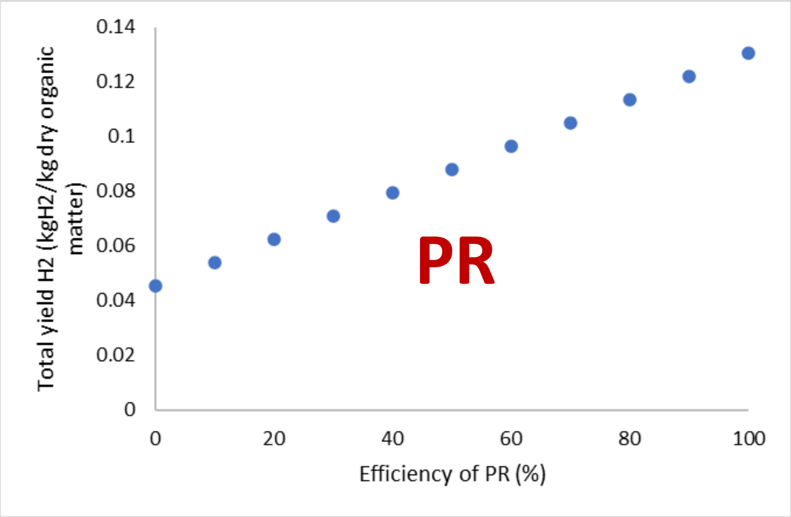

H2 production by process stage

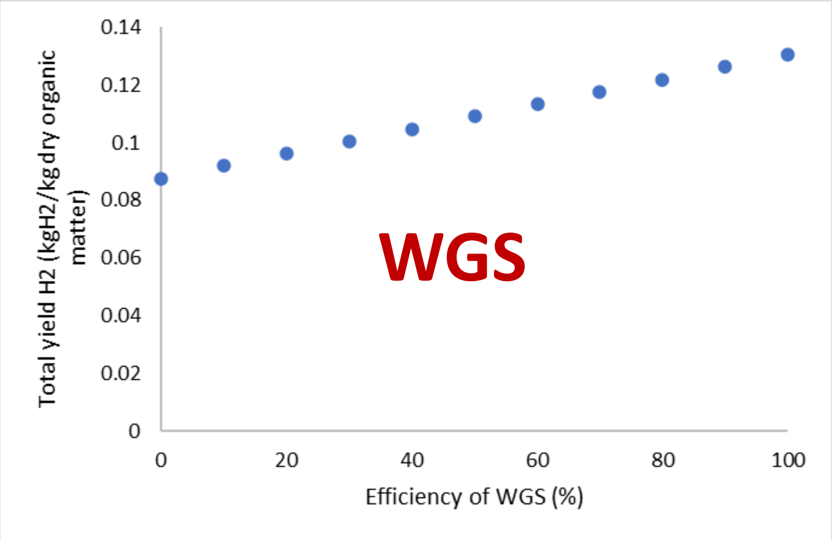

Energy consumption by process stage

Effect of stage efficiency-hydrogen yield









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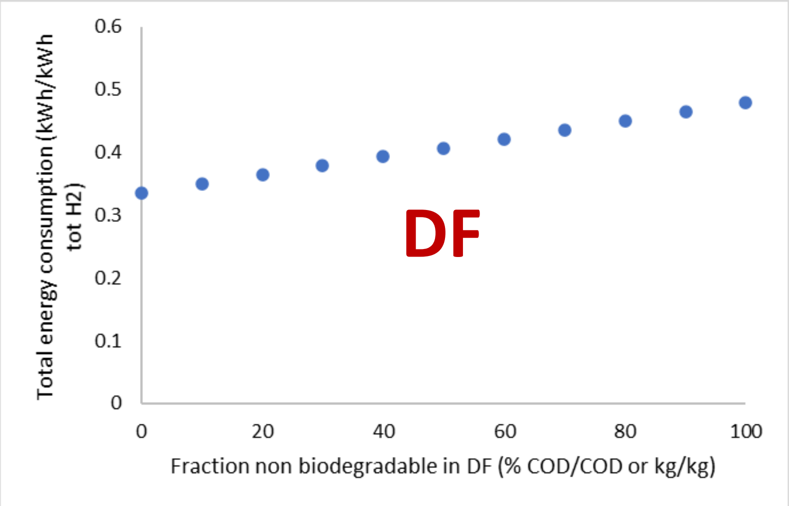
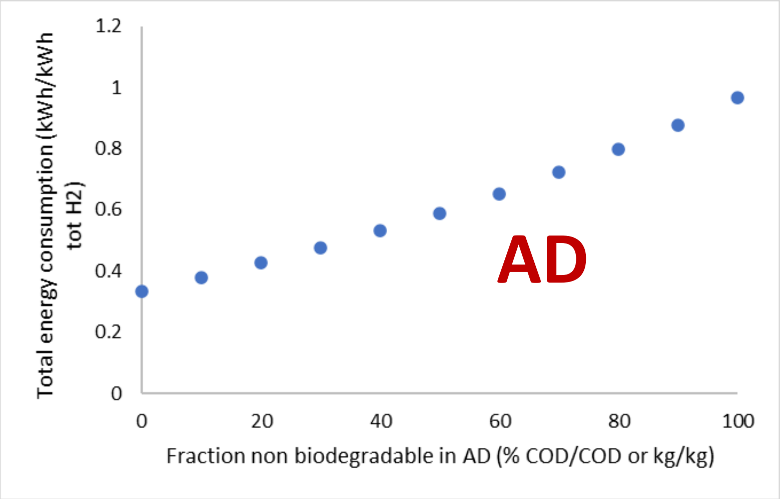
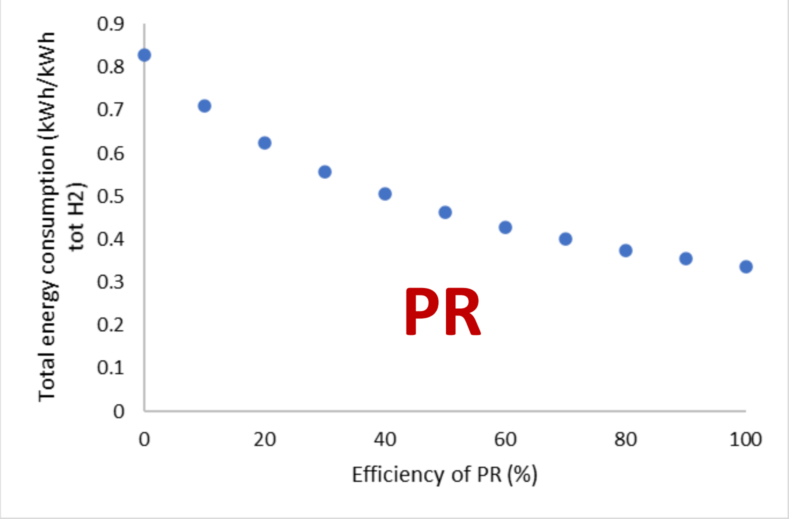
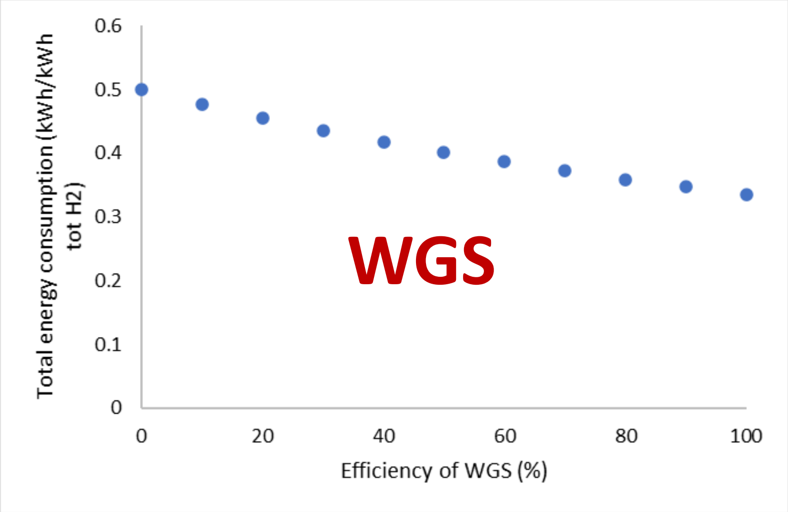
Effect of stage efficiency-Energy consumption









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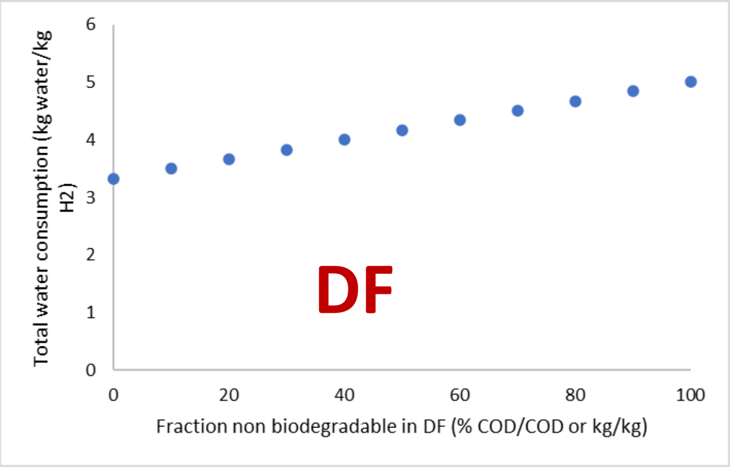
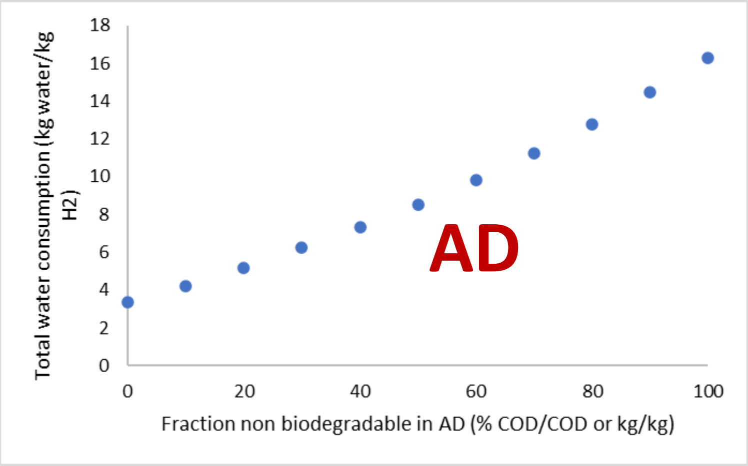
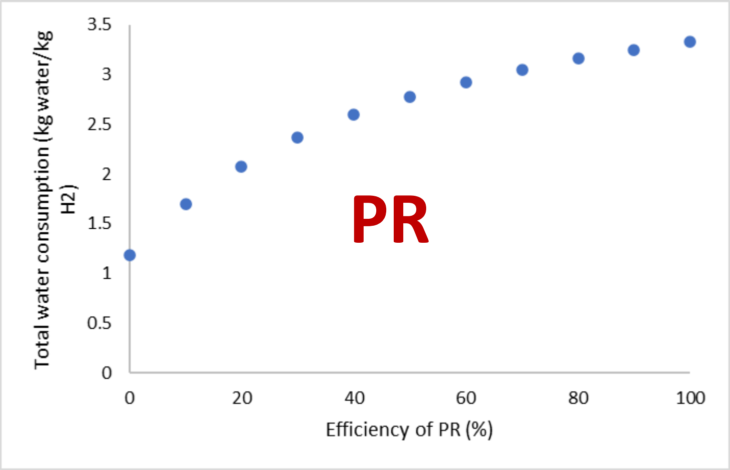
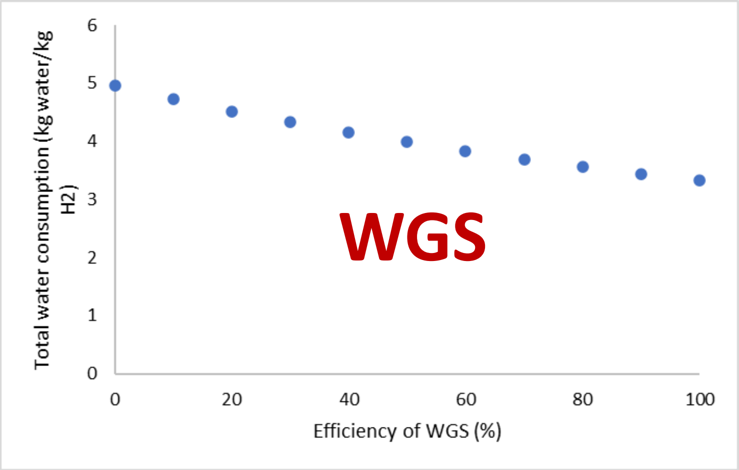
Effect of stage efficiency-Water consumption



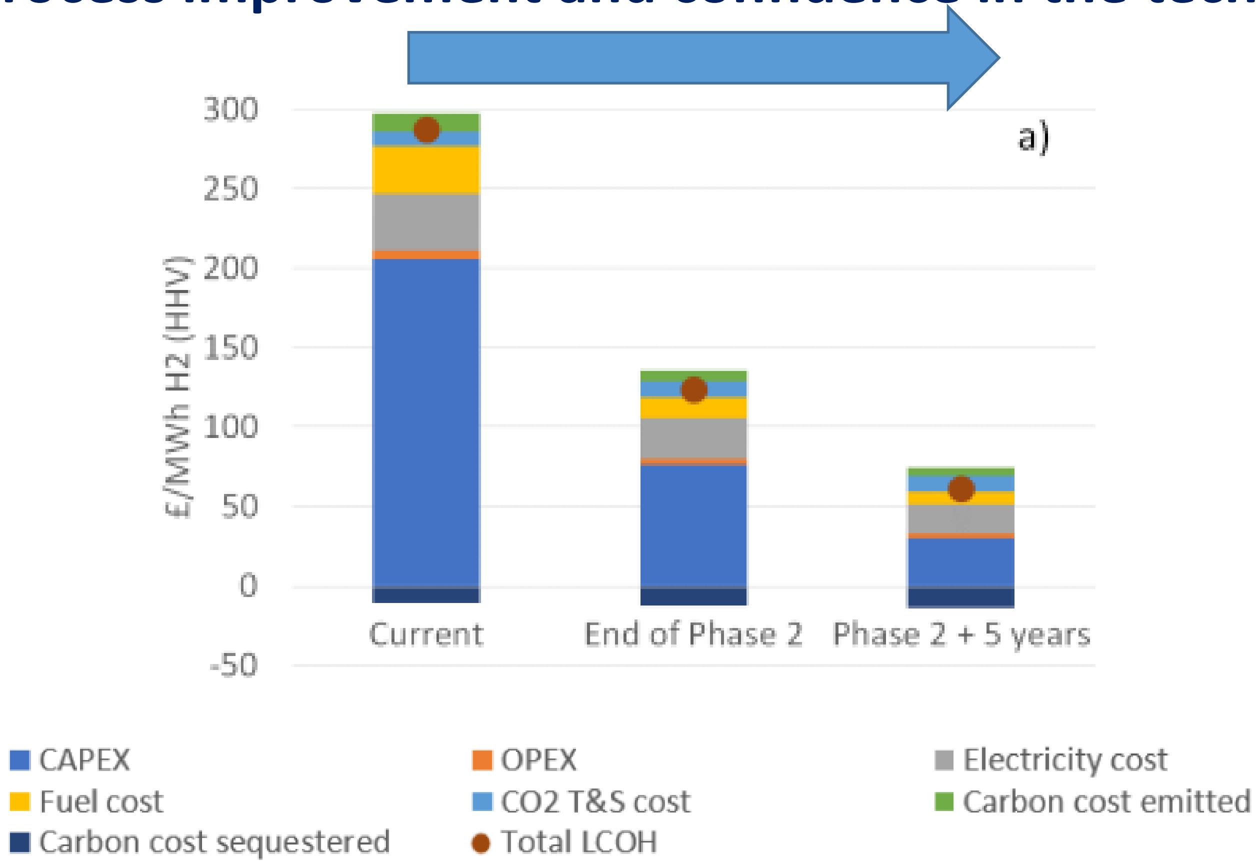




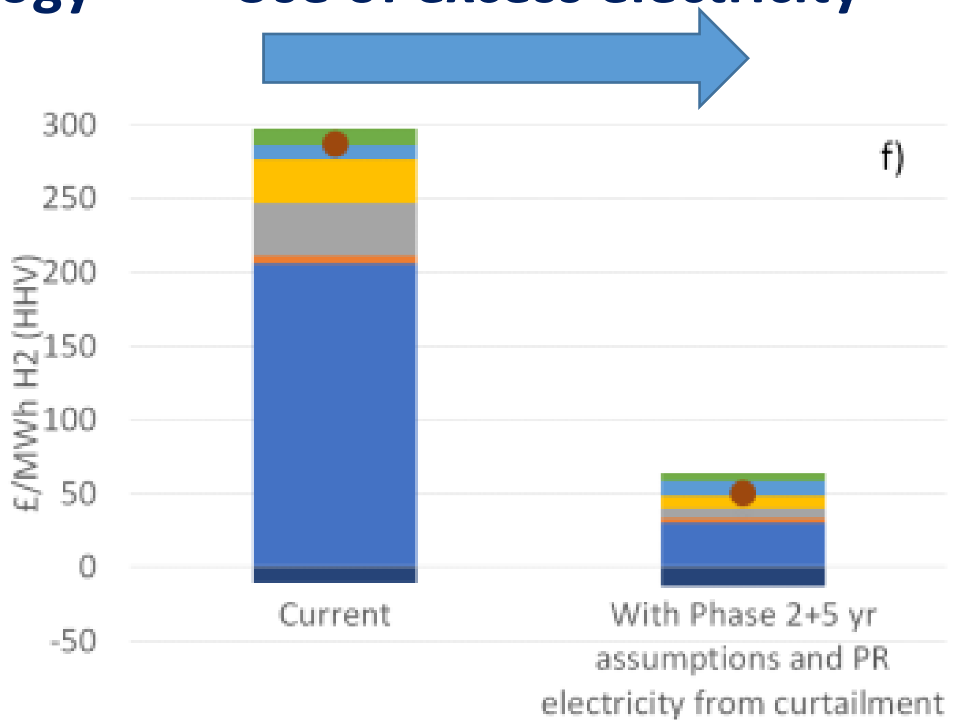


Cost estimations

Process improvement and confidence in the technology



Use of excess electricity



BEIS estimates:

Hydrogen from water electrolysis: £50-200 MWh

Hydrogen from biomass gasification: £100-200 MWh

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Conclusions

New process to produce hydrogen from biodegradable organic waste.

Integration of biological and chemical technologies.

Plan to build and run a pilot plant (subject to funding approval) in May 2023-March 2025.

Aim to measure hydrogen yield, energy and water consumption at pilot scale.

Aim to add hydrogen from waste to hydrogen from water electrolysis for reduced land requirement and energy consumption.

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BEIS BECCS project:

Dark fermentation

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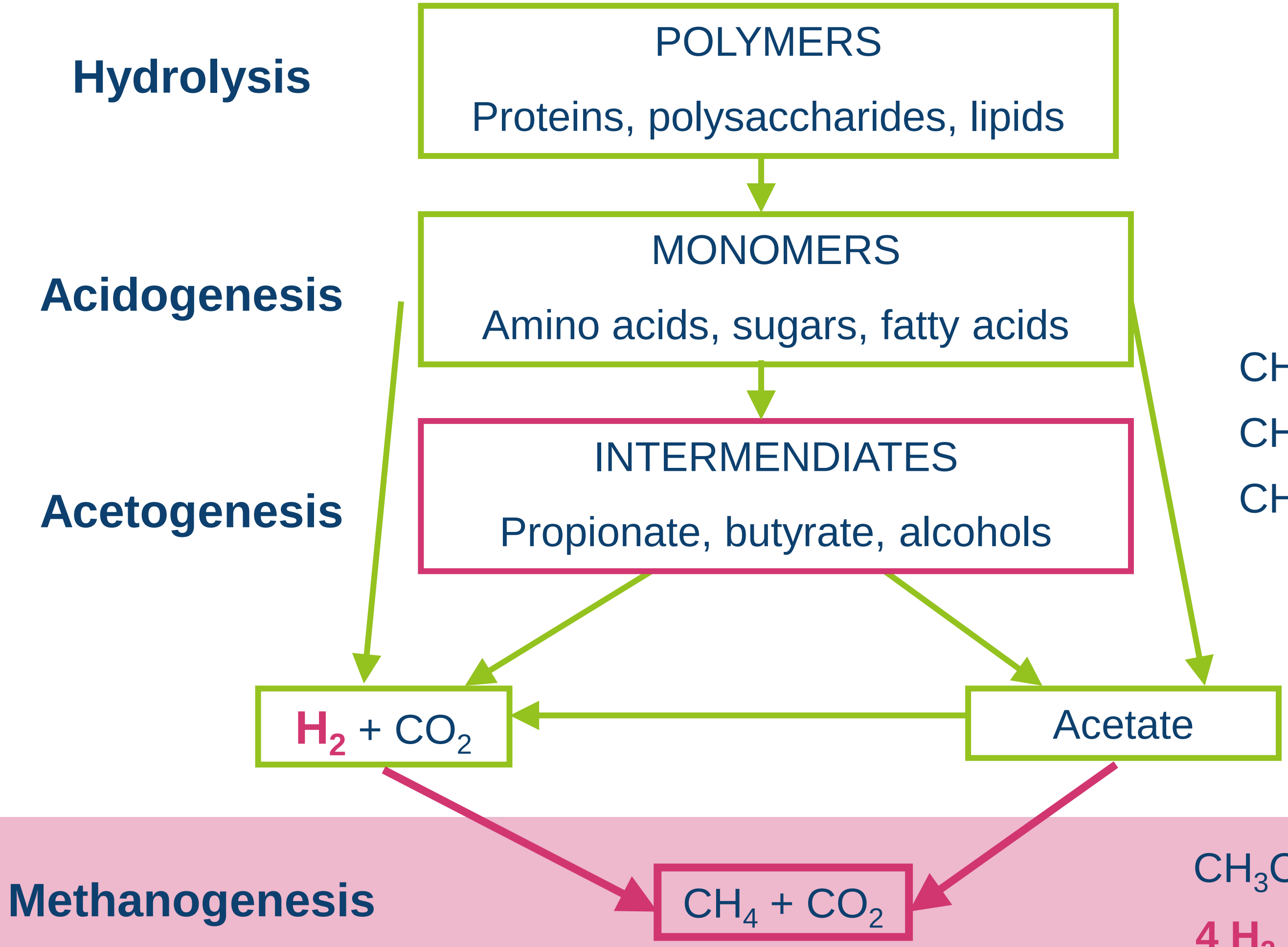
Dark Fermentation



Hydrolysis

POLYMERS

Proteins, polysaccharides, lipids

Acidogenesis

MONOMERS

Amino acids, sugars, fatty acids

Acetogenesis

INTERMENDIATES

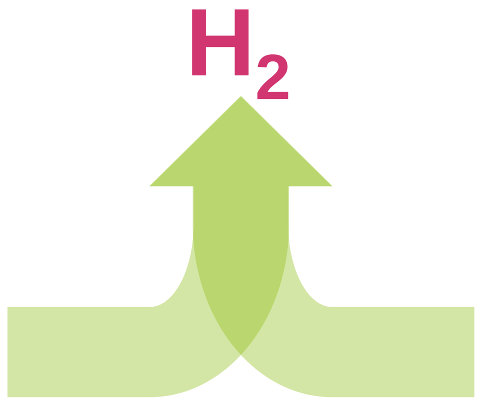
Propionate, butyrate, alcohols

$H_2 + CO_2$

Acetate

Methanogenesis

$CH_4 + CO_2$



$CH_3CH_2COOH + 2\ H_2O \rightarrow CH_3COOH + CO_2 + \mathbf{3\ H_2}$

$CH_3CH_2CH_2COOH + 2\ H_2O \rightarrow 2\ CH_3COOH + \mathbf{2\ H_2}$

$CH_3CH_2OH + H_2O \rightarrow CH_3COOH + \mathbf{2\ H_2}$

$CH_3COOH \rightarrow CH_4 + CO_2$

$\mathbf{4\ H_2} + CO_2 \rightarrow CH_4 + 2H_2O$

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Dark Fermentation

Input	Output	H_2 yield	H_2 concentration	Advantages	Disadvantages
Wet organic substrate	Biogas (H_2, CO_2) Digestate rich in short chain organics	10 - 250 NL/kg VS	20-50%	• Wet feedstock as input • Complex organics (Waste/sludge) • High rates • Residues with value • Comparable to anaerobic digestion process • “Ambient” temperature (35-50°C) and pressures • Possibility to be integrated into existing AD asset or create biorefinery chains to extract value • Possibility to optimise hydrolysis	• Relatively low H_2 yields and linked to feedstock composition • Need downstream treatment of effluent • Biogas contains CO_2, need for post-treatment for H_2 purification • Higher energy demand for H_2 pressurisation as bioreactors operate at low overpressures (order of mbars).

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Role of Dark Fermentation

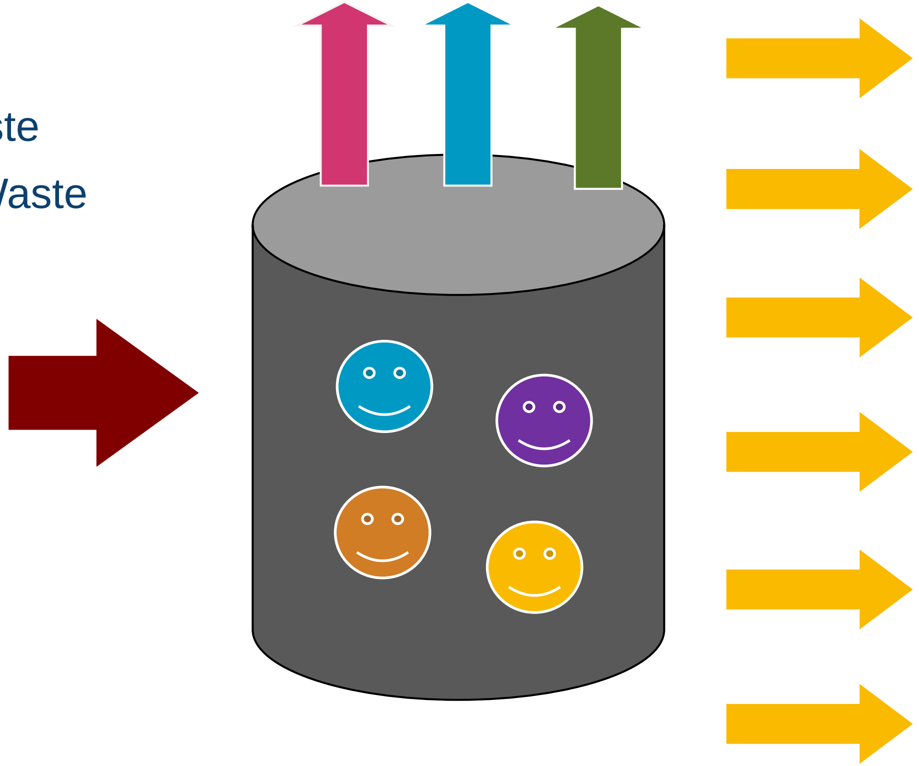
Origin:

- OFMSW
- Agricultural Waste
- Food Industry Waste

Substrates

Composition:

- Carbohydrates
- Lipids
- Proteins
- Inorganics (N, P, S, Me^+)



H_2 CO_2 Other trace gases

- VFA
- Alcohols or solvents *(e.g. Acetone, Butanol, Ethanol - ABE)*
- Long Chain Fatty Acids
- Protein and lipids
- NH_4^+
- Biomass

(Alibardi *et al*., 2020) DF can be the first step of a biorefinery chain

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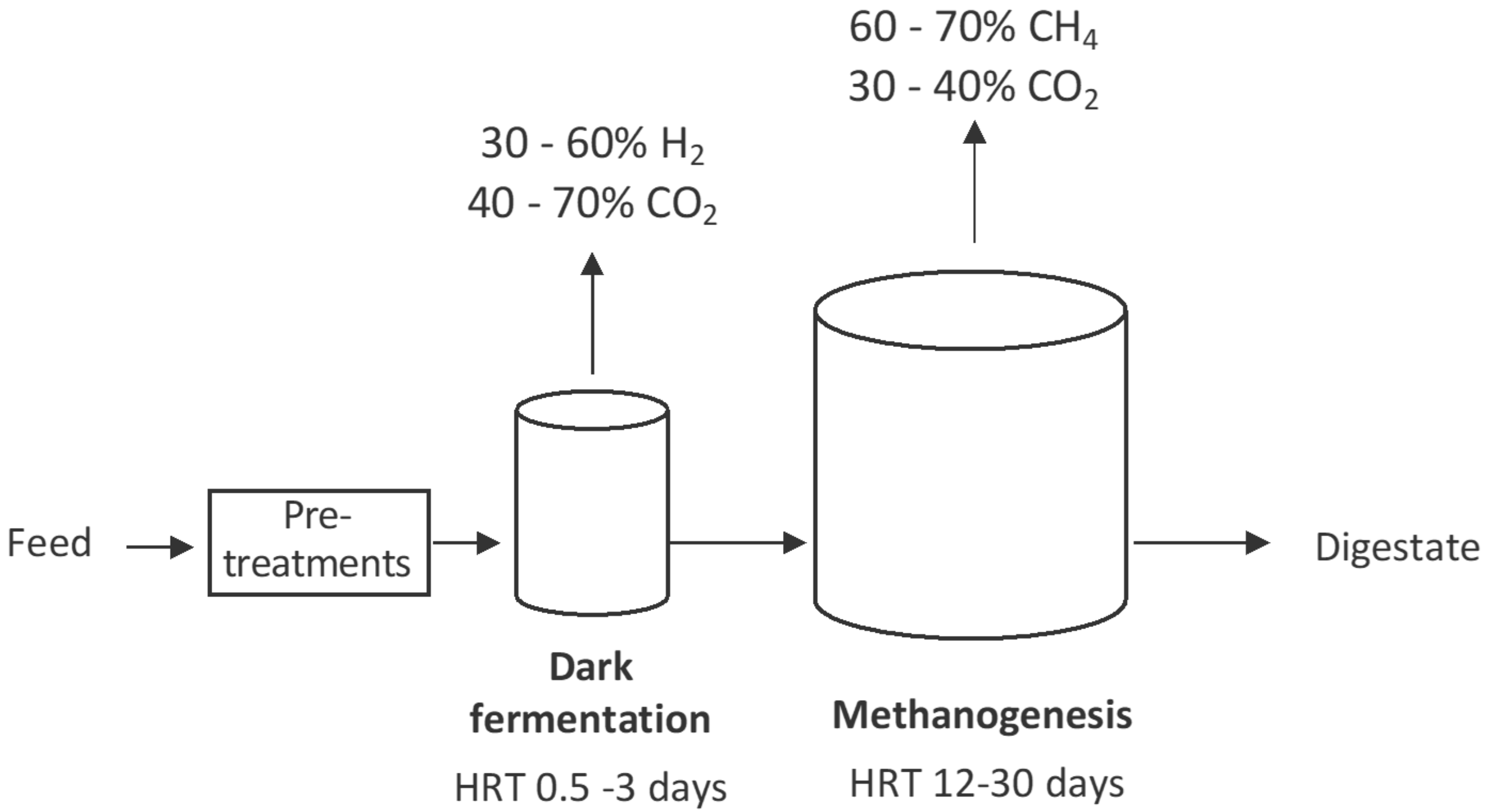
Role of Dark Fermentation

Implement two-step processes involving $BioH_2$ and CH_4 production



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BEIS BECCS project:

Gasification update

Yeshui Zhang
Lecturer in Chemical Engineering
University of Aberdeen
yeshui.zhang@abdn.ac.uk

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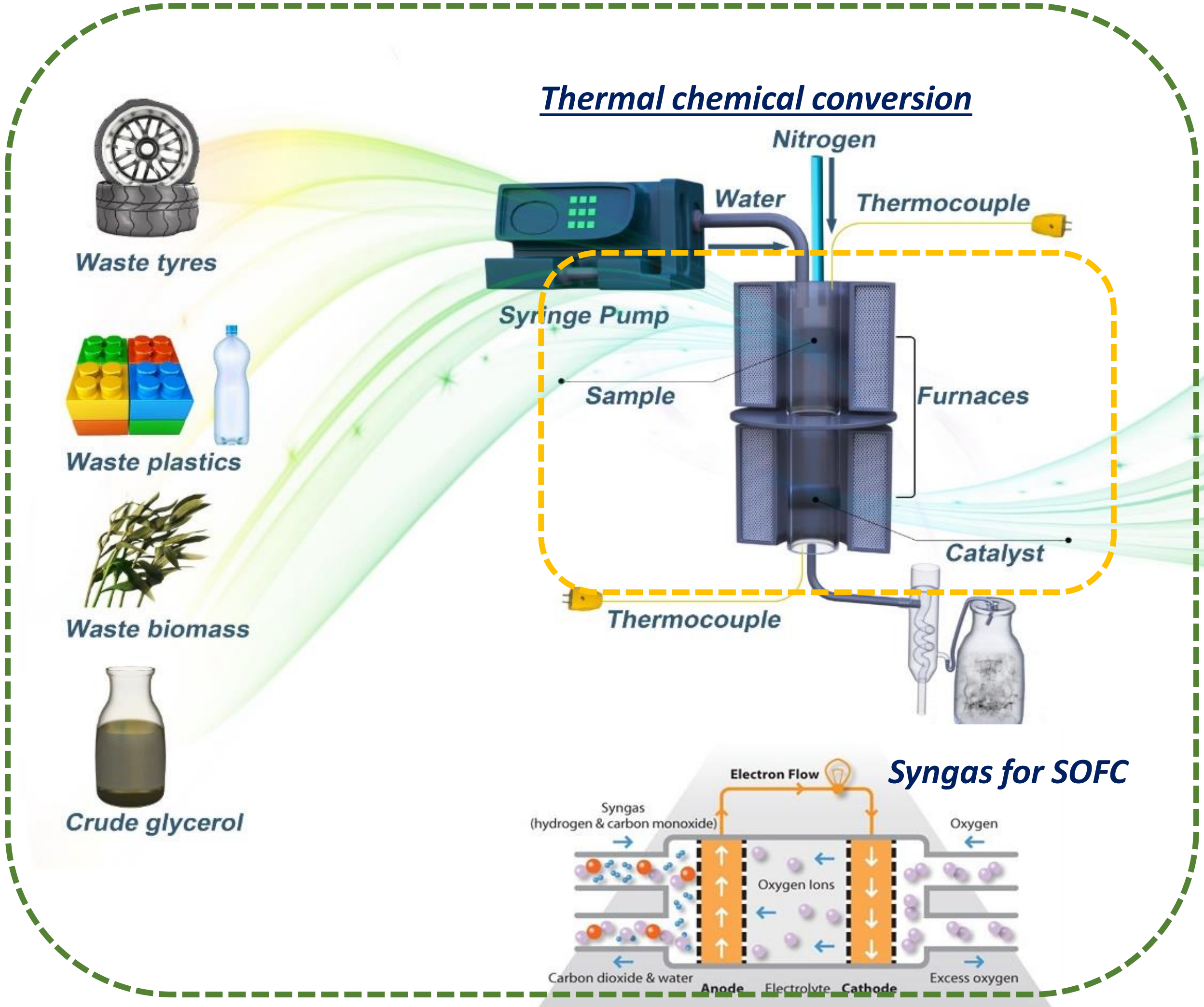
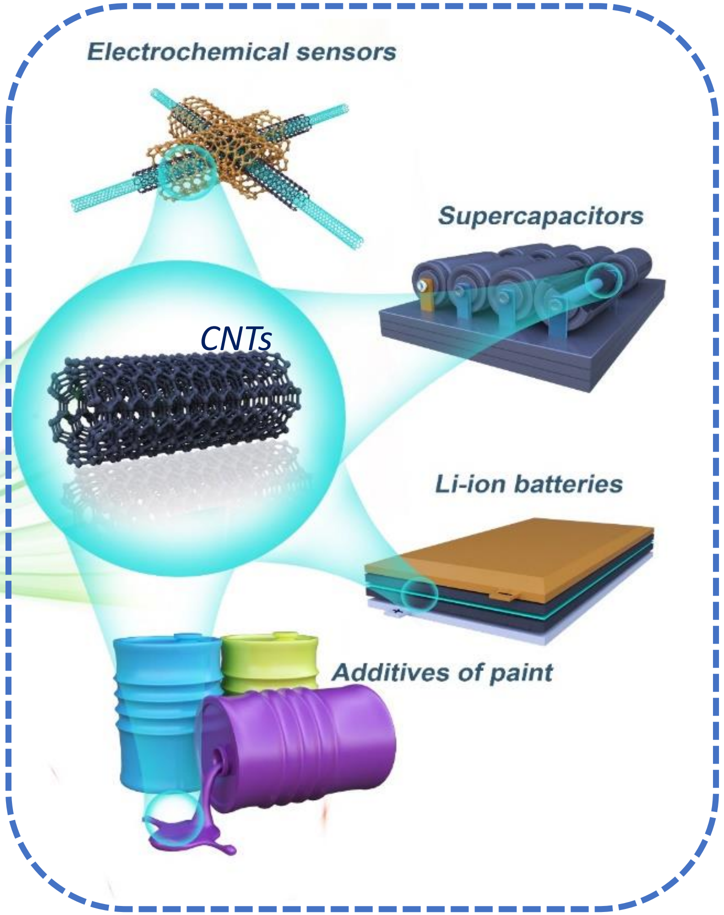
My Research

Topic 2 – Novel catalyst development, and *in-situ* metrology development to study catalyst degradation mechanism.



Topic 1 – Hydrogen rich syngas from waste and applications, including solid oxide fuel cells.



Topic3 –Energy storages materials from waste, i.e. Li-ion batteries.

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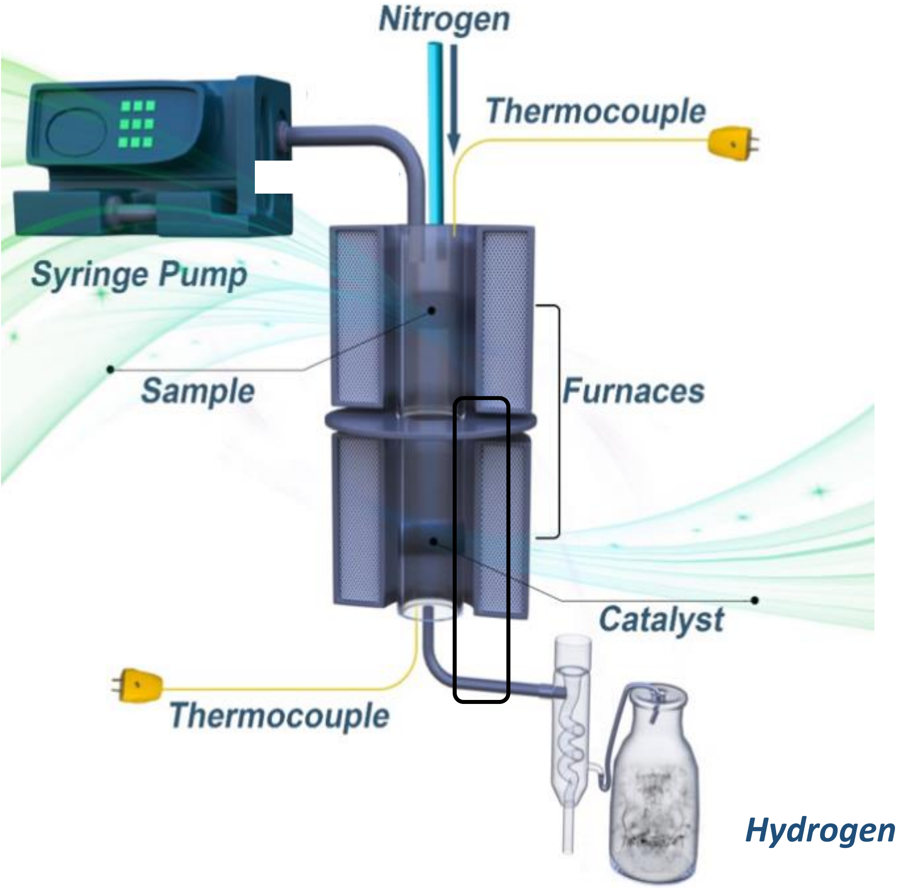
Two-stage fixed-bed reactor



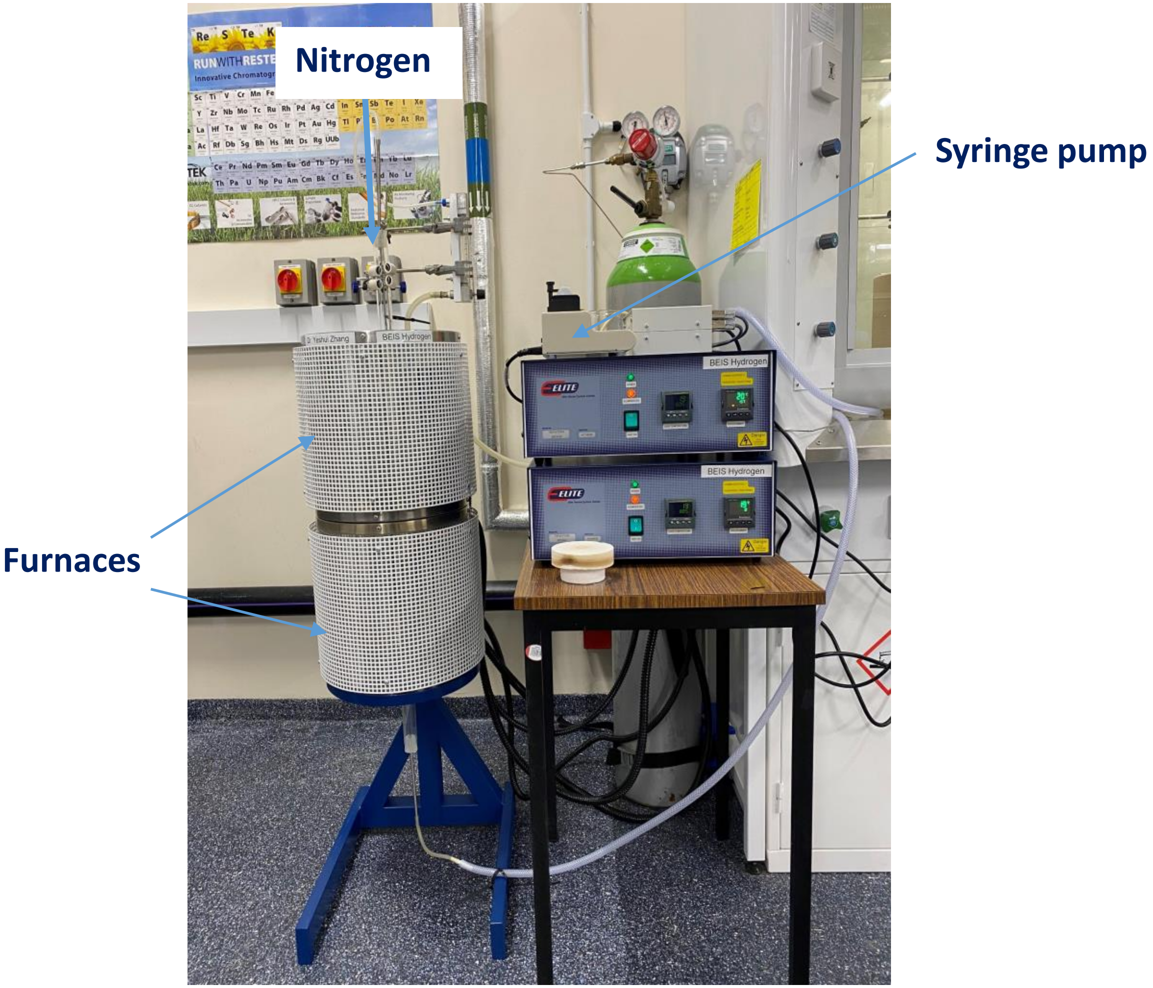


Figure left: Schematic diagram of the two-stage gasification reactor.

Figure right: Photo of the two-stage gasification reactor prototype.

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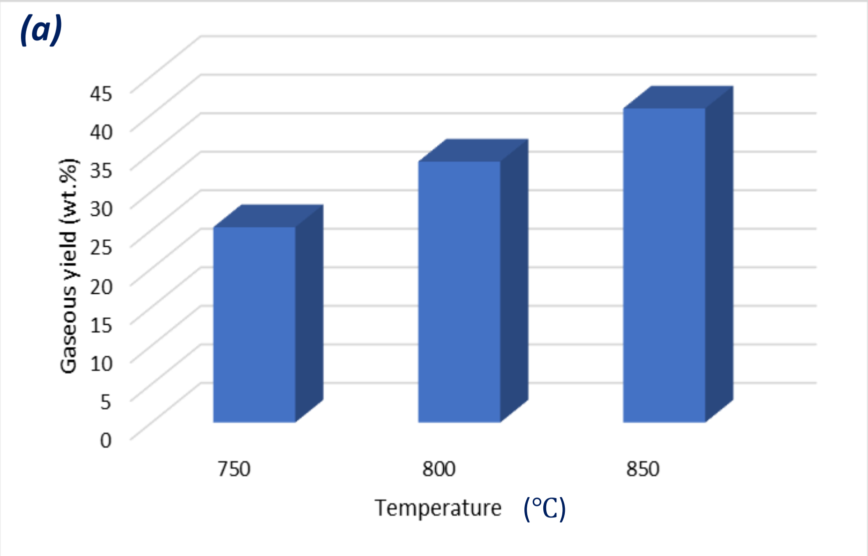
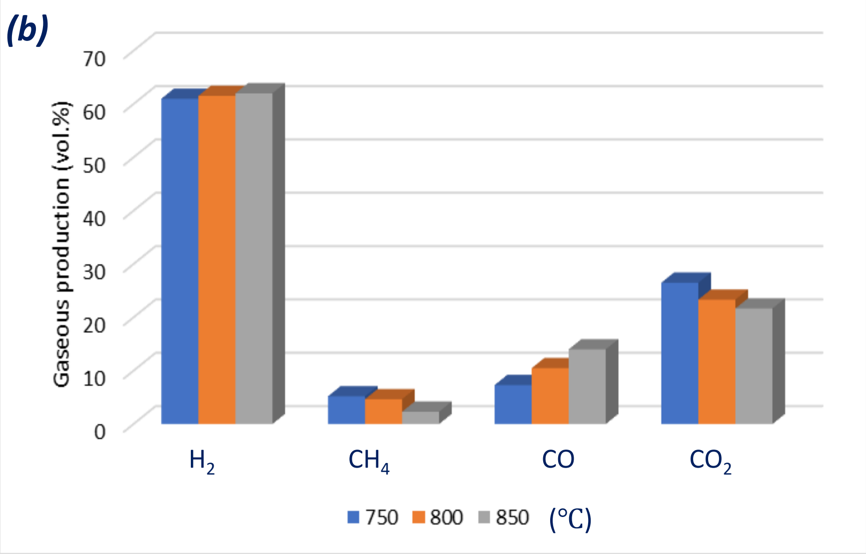
Preliminary results from gasification process

Table: Product distributions of digestate through gasification process.

Tempereture (°C)	750	800	850
Sample weight (g)	0.5	0.5	0.5
Steam ratio (g h^{-1})	3	3	3
Gaseous yield (wt.%)	25.34	33.86	40.76
Solid yield (wt.%)	36.7	34.12	30.9
Gaseous composition (vol.%)			
H_2	60.99	61.53	62.01
CH_4	5.2	4.66	2.31
CO	7.31	10.48	14.01
CO_2	26.5	23.33	21.67
Hydrogen production (mmol g^{-1})	**11.53**	**13.15**	**15.73**





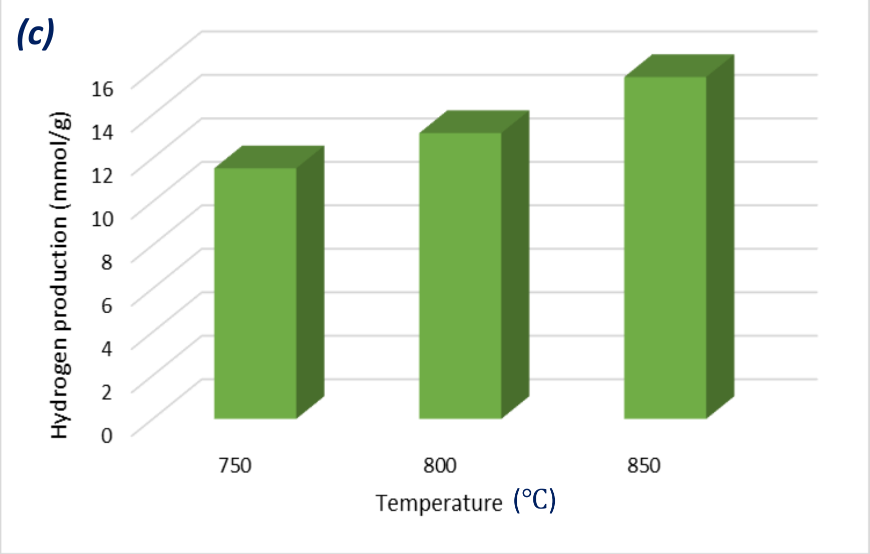


Figure (a): Gaseous yields, **(b)** gaseous productions and **(c)** hydrogen productions at different temperatures.

Pilot-plant and tri-functional catalyst development for Phase 2

Objective 1: To build up a pilot–scale gasification unit.

Objective 2: To develop tri-functional catalysts to enhance hydrogen production with simultaneous CO_2 capture.

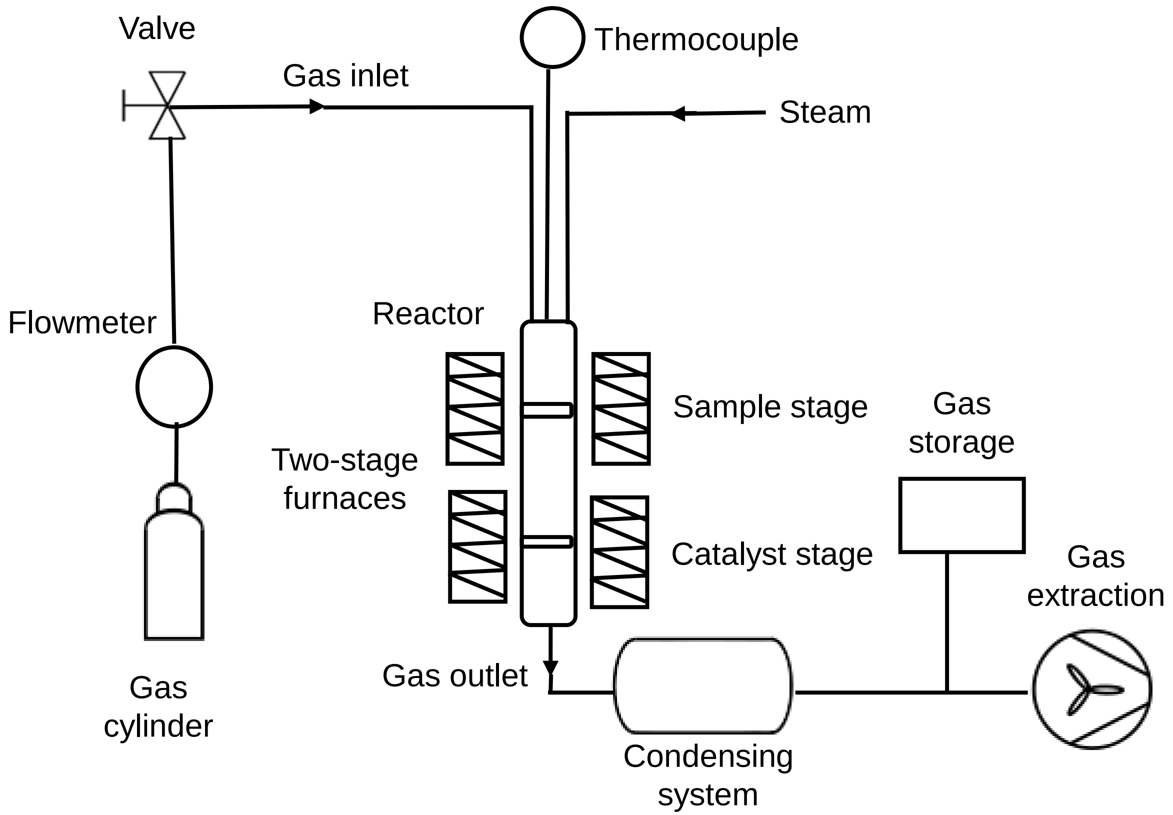


Figure left: Schematic diagram of the pilot-scale gasification system.

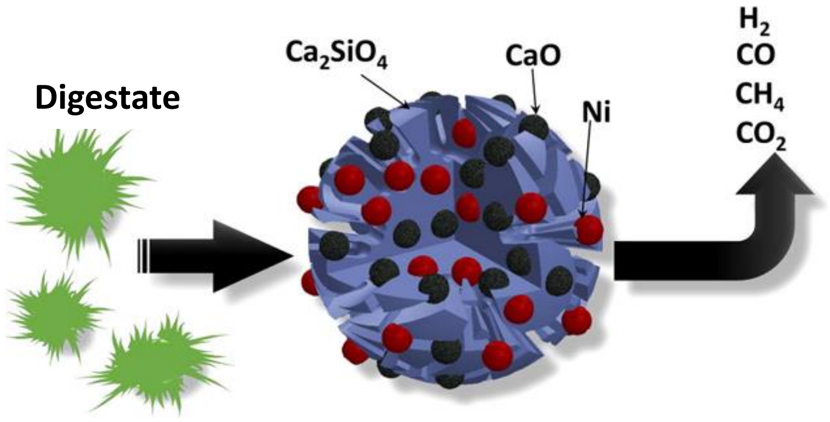


Figure right: Model of tri-functional catalyst.

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BEIS BECCS project:

Biogas upgrading via plasma technologies

Dr Panagiotis Kechagiopoulos
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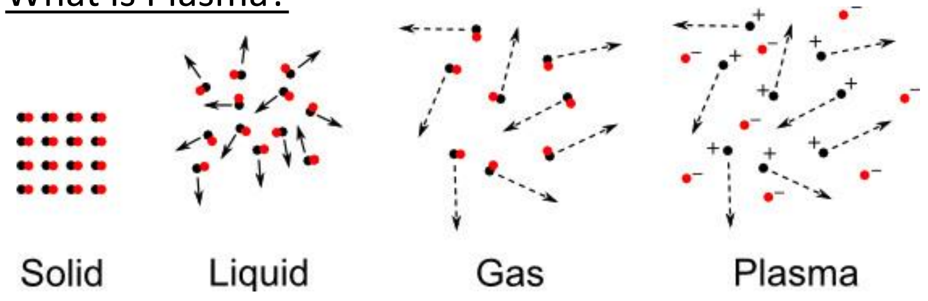
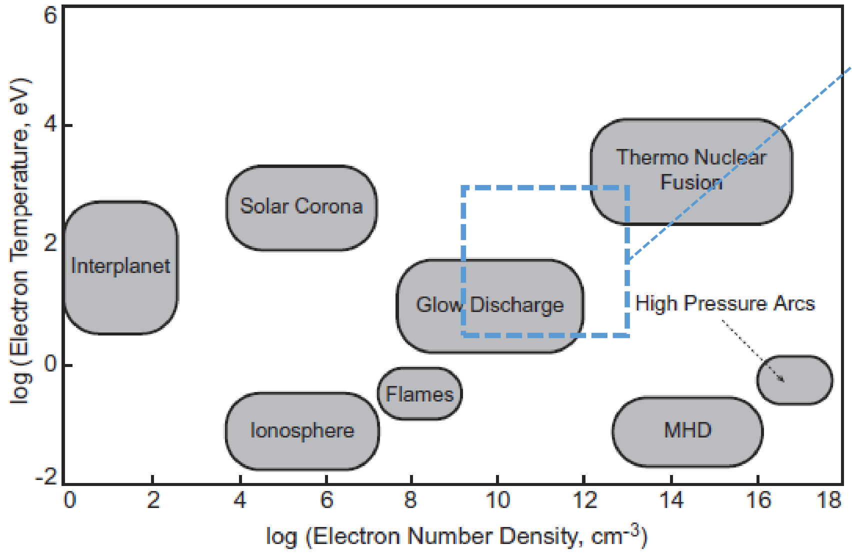
Biogas upgrading through Plasma

<u>What is Plasma?</u>

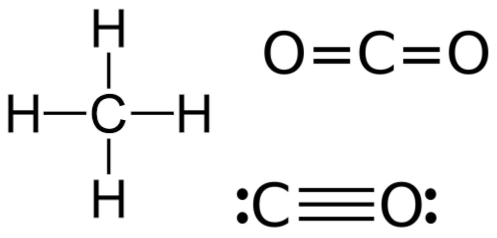




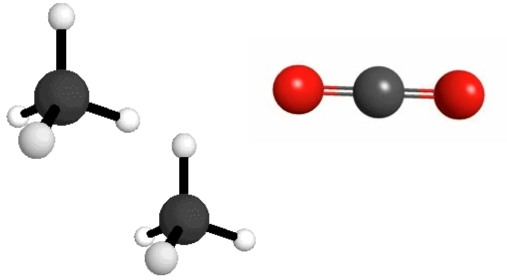
Variety of Plasmas : electrons temperature over electron density

Electron T >> Other particles T ➔ Non-Thermal plasma (NTP) or Non-equilibrium plasma

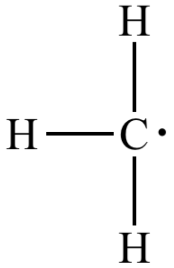
Various types of species in the plasma phase:



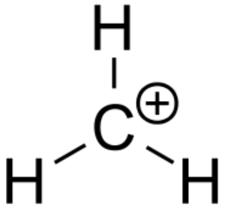
Molecules



Excited species

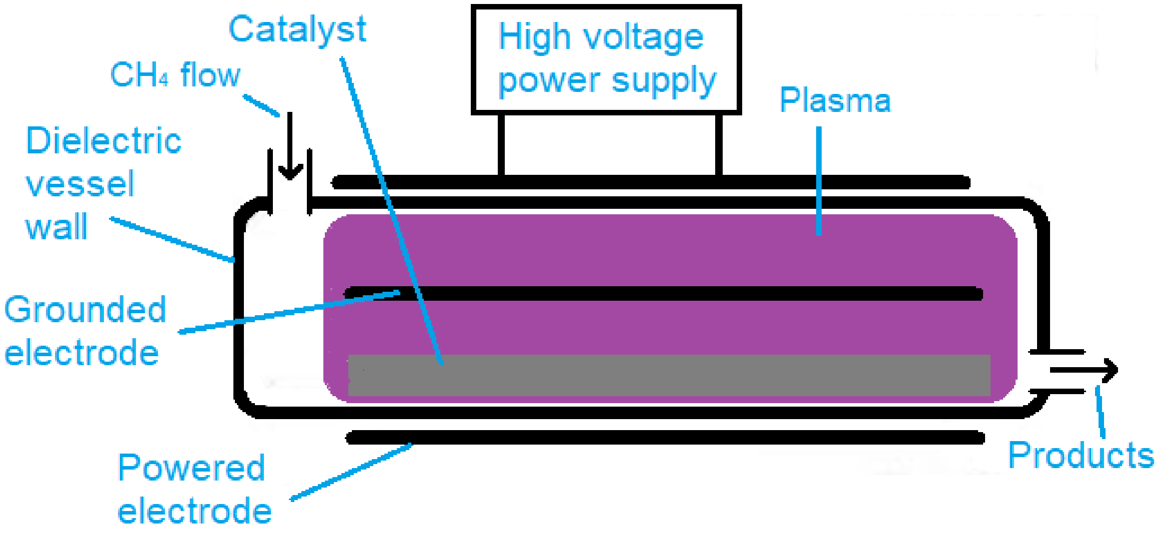


Radicals



Ions

Plasma – Catalysis as an alternative route



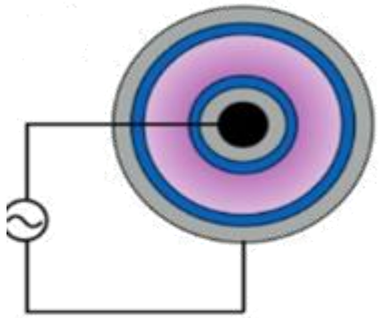
Schematic of regular dielectric barrier discharge plasma catalysis set-up

Combining plasma and catalysis for methane upgrading:

+ Plasmas allow the activation of strong chemical bonds in methane and carbon dioxide at even ambient temperature and atmospheric pressure

+ Hybrid plasma-catalytic systems exhibit synergetic effects and enhance selectivity

- Strongly coupled system, the mechanistic details are difficult to unravel.



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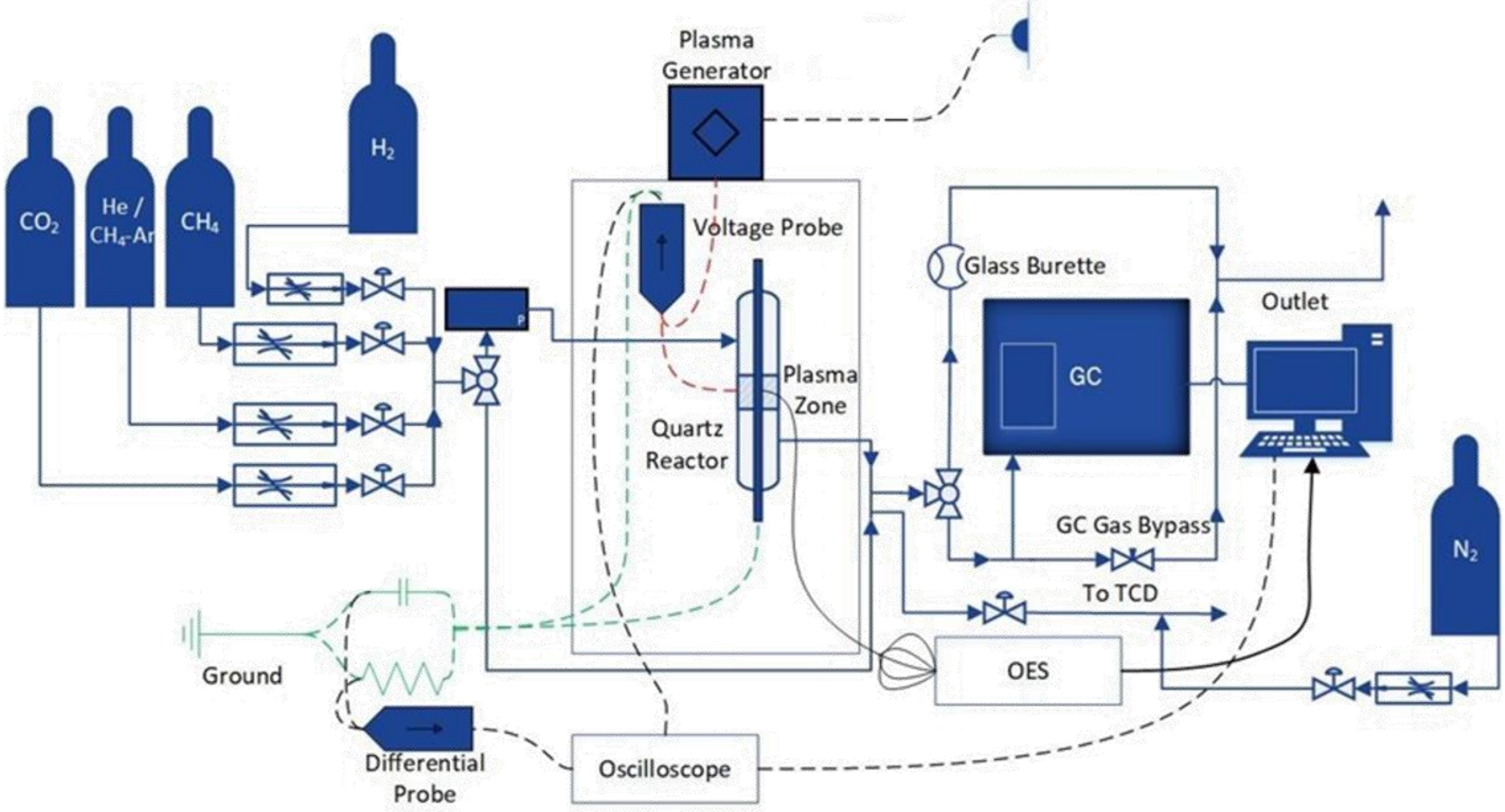
Experimental setup schematic



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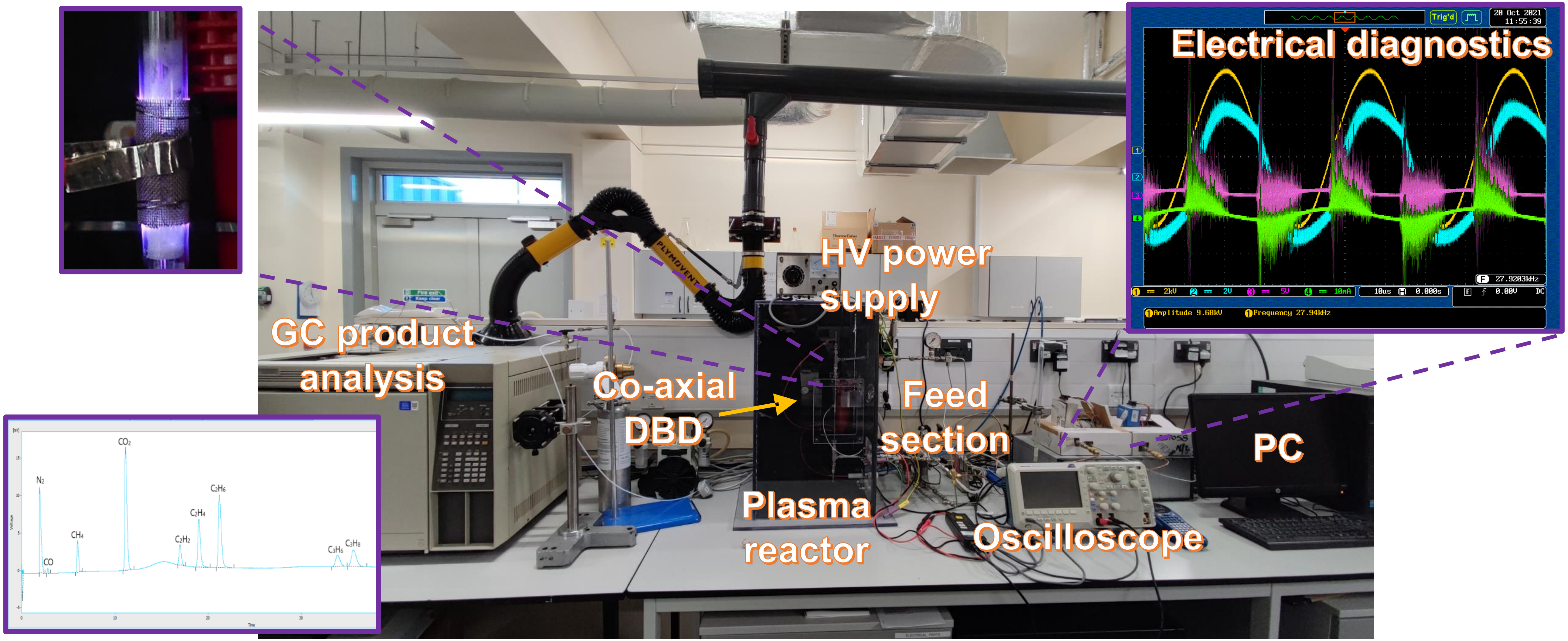
Experimental setup and procedures



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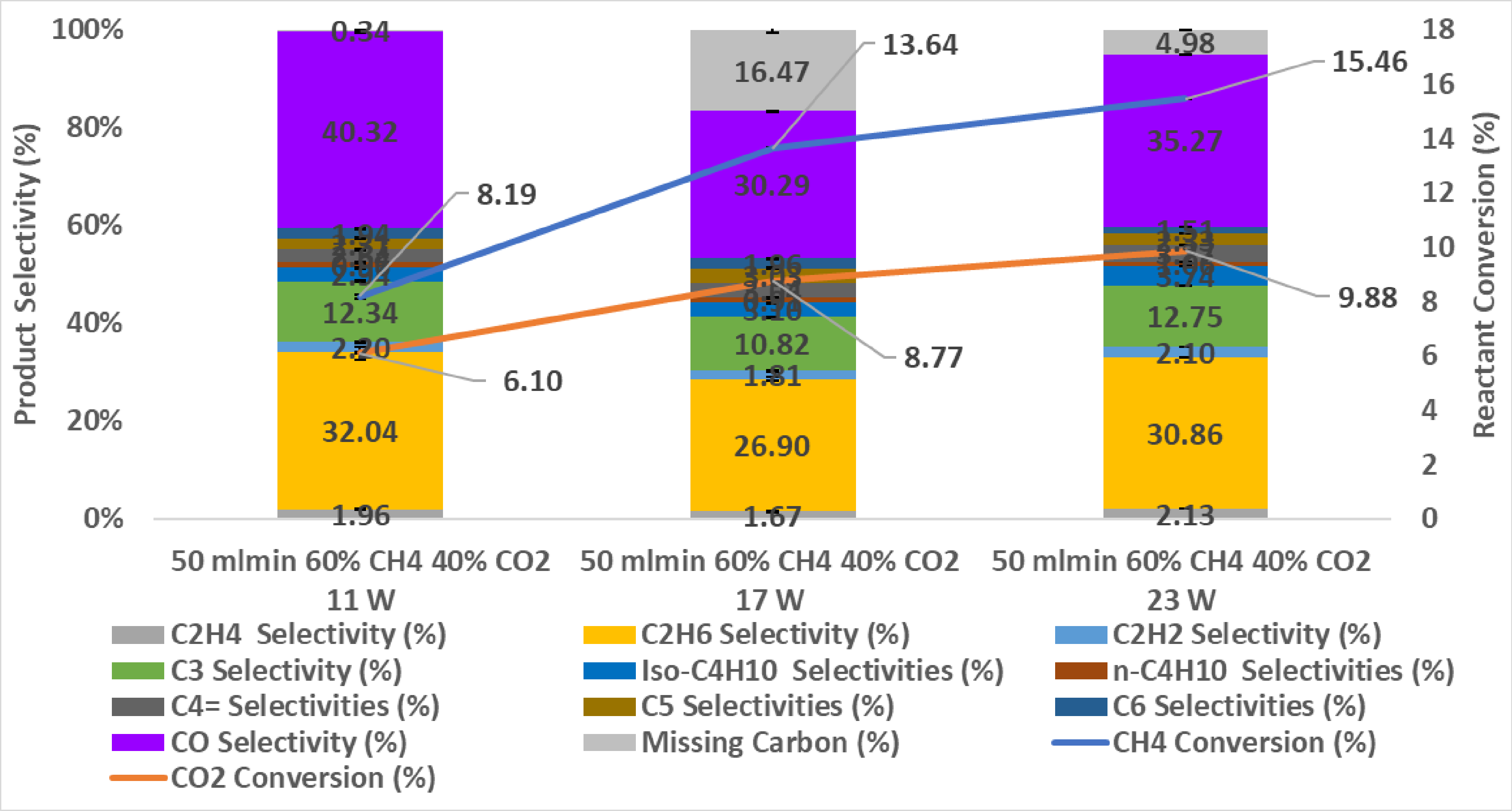
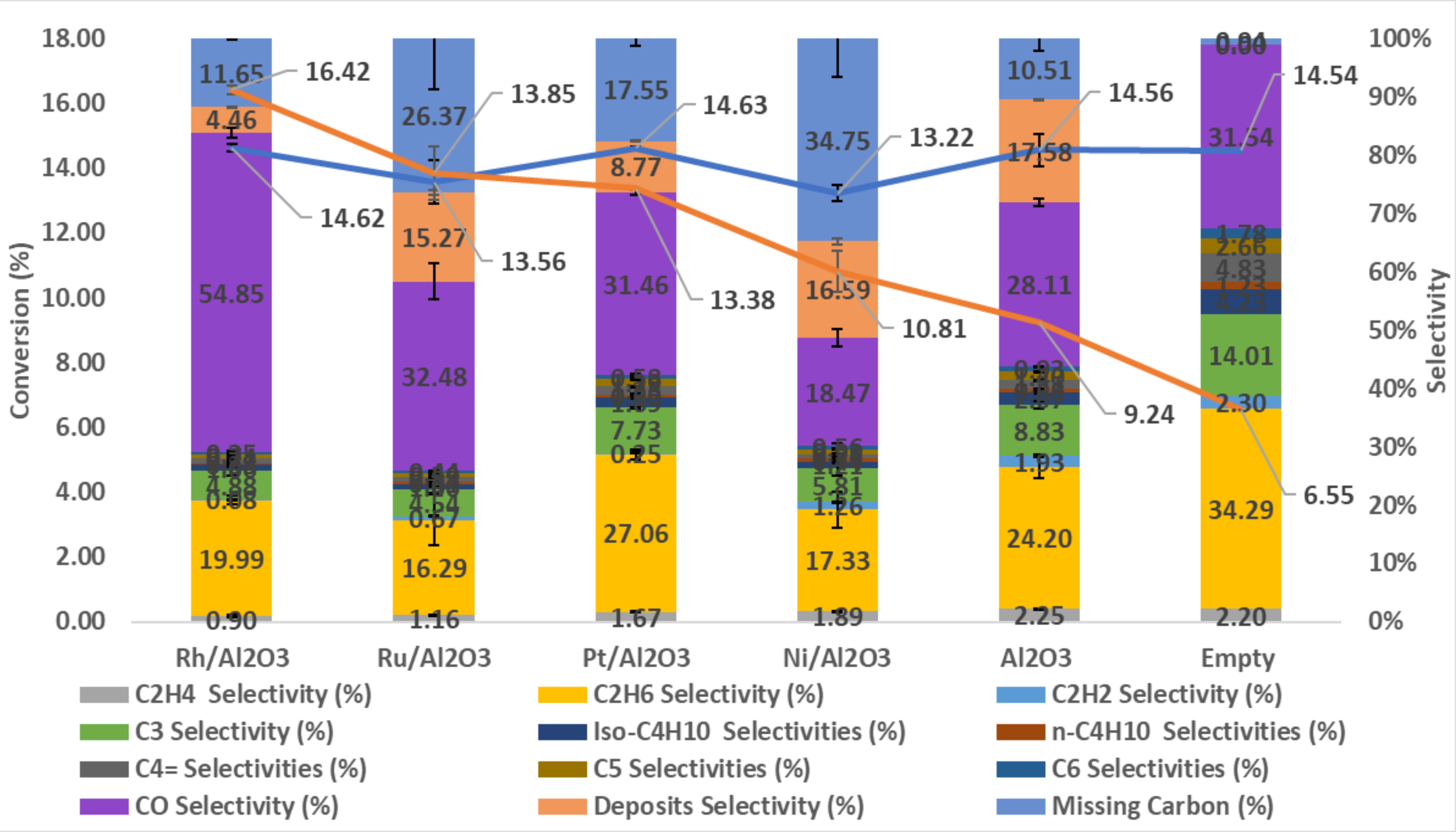
Biogas conversion in DBD plasma



Power: 17.6 W
Flowrate: 50 ml min^{-1}
CH_4/CO_2: 60/40

Effect of power on the noncatalytic plasma conversion of biogas

Biogas conversion via plasma-catalysis



Effect of catalyst on the plasma-catalytic conversion of biogas

Power: 17.6 W
Flowrate: 50 ml min^{-1}
CH_4/CO_2: 60/40

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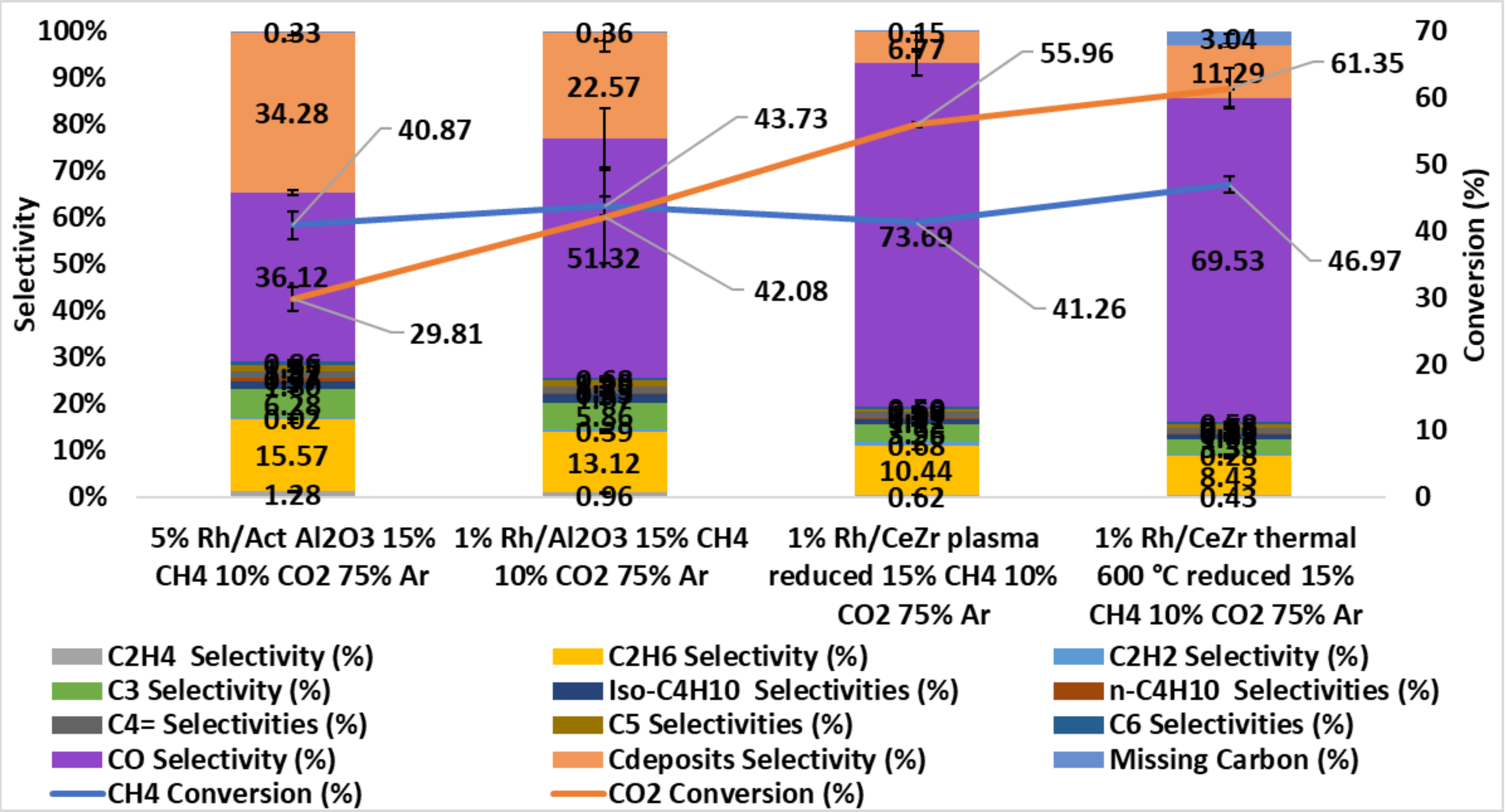
Biogas conversion via plasma-catalysis



Effect of catalyst support on the plasma-catalytic conversion of biogas under argon dilution

Power: 17.6 W
Flowrate: 50 ml min^{-1}
CH_4/CO_2: 60/40

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Thank you for your attention, any questions?

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optimat

Commercialisation Strategy Development

Dr Kayleigh Nelson, Optimat Ltd

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Commercialisation of the Technology

Methodology

Initial Briefing

Understand the technology, advancements, limitations & potential applications

Desk Research

Quantify the potential market, understand market dynamics, identify potential competitors & model the supply chain

Stakeholder Interviews

Potential customers, partners and stakeholders interviewed to gain feedback on the process capability and its potential

Analysis & Assessment

Evidence base interrogated to define target market, market potential, market access options & commercial requirements

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Commercialisation of the Technology

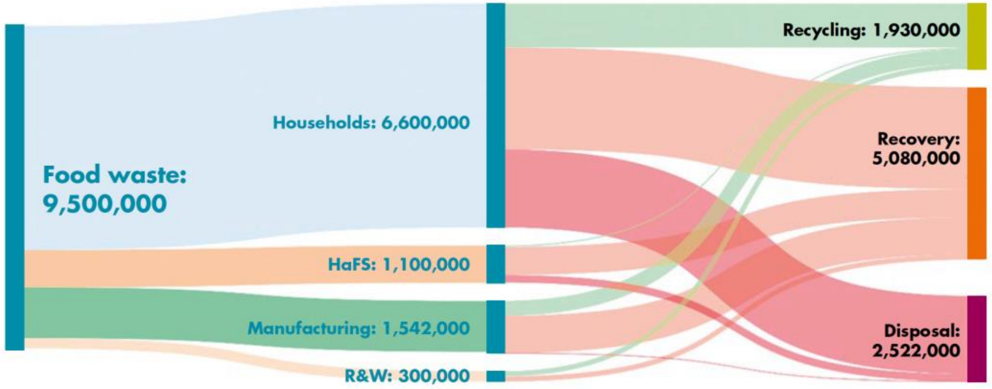
Markets – Valorisation of Waste

- Competition for waste
  - Existing arisings not really sufficient to support current AD plant capacity

Legislation to increase food waste collection in England from 2023 – Increase feedstock available, but transit concerns

Sewage sludge

- Around 4 million tonnes of produced in the UK every year.
- A significant proportion of the sewage sludge is processed via AD to generate biogas,
- The majority of digestate (87%, equivalent to 3.5 million tonnes) is spread on agricultural land
  - Concerns over long term viability of digestate as fertiliser



Just **20%** of food waste in the UK is recycled, which includes both AD (most favourable) and compost (less favourable)

The majority of food waste currently ends up going to recovery measures such as incineration (**>53%**)...

...with the remainder being disposed of in landfill (1Mt) or down the sewer (1.5Mt)

Commercialisation of the Technology

Markets – Valorisation of Waste

- Competition for waste
  - Existing arisings not really sufficient to support current AD plant capacity

Legislation to increase food waste collection in England from 2023 – Increase feedstock available, but transit concerns

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- A significant proportion of the sewage sludge is processed via AD to generate biogas,
- The majority of digestate (87%, equivalent to 3.5 million tonnes) is spread on agricultural land
  - Concerns over long term viability of digestate as fertiliser

> *“There is not a pile of organic waste available that people don’t know what to do with”*

> *“AD plants either have a CHP or produce bio-methane. Some CHPs burning natural gas to keep going – reflection on demand for materials”*

> *“There is a drive to reduce food waste – driven by bad weather (affecting crops), recession and environmental drivers – so less raw material, and AD plants are struggling to fill capacity.”*

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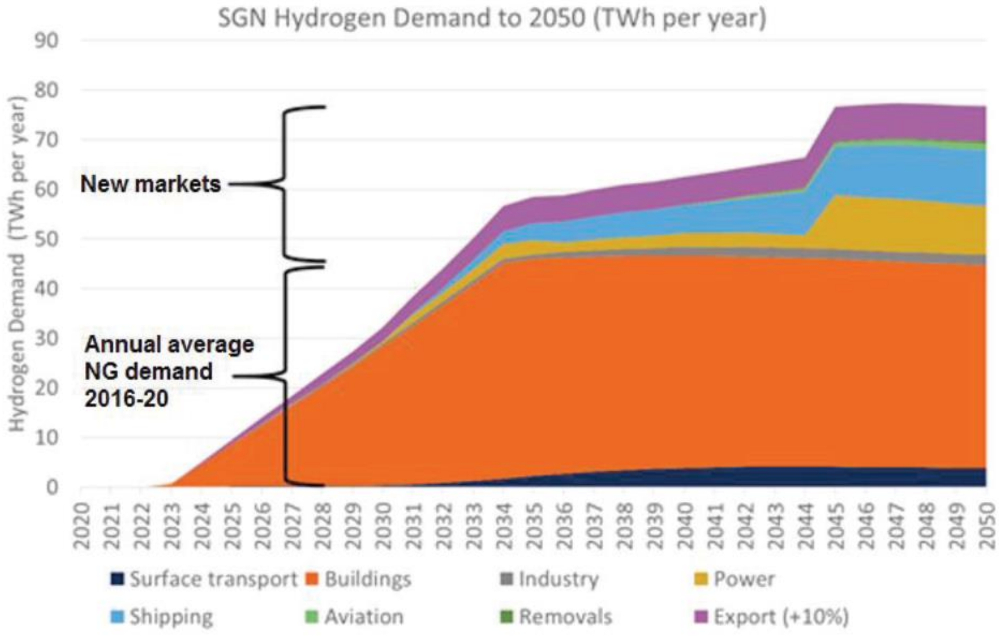
Commercialisation of the Technology

Markets – Hydrogen Production

- Fledgling Industry - Very early stages currently
- UK target of 10GW by 2030, with at least half of this being green hydrogen
- UK hydrogen demand in 2050 estimated at between 110 and 430TWh
    - Expected to be addressed, predominantly, by
        - Methane reformation
        - Electrolysis
- Local circular economy loops attractive
- Plans for business models to incentivise production



Hydrogen Applications

Existing	Likely	Transitional	New
Refining	Industrial heat - Steel	Co-firing - coal and gas plants	HDV
Chemicals - Ammonia	Shipping - Ammonia	Grid blending	Rail
Chemicals - Methanol	Aviation - Synfuels		Heating
	Power - Balancing		

Uncertainty →

Commercialisation of the Technology

Markets – Hydrogen Production

- Fledgling Industry - Very early stages currently
- UK target of 10GW by 2030, with at least half of this being green hydrogen
- UK hydrogen demand in 2050 estimated at between 110 and 430TWh
  - Expected to be addressed, predominantly, by
    - Methane reformation
    - Electrolysis
- Local circular economy loops attractive
- Plans for business models to incentivise production

“Selling hydrogen will be easy – it’s the least of your problems”

“Don’t worry about markets for hydrogen – when this plant gets up and running there will be a mature hydrogen market and lots of demand”

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Commercialisation of the Technology

Conclusions

- There is significant potential for this process to valorise organic waste, but it must be recognised that there is, already, an established route (i.e. anaerobic digestion) to valorisation. The current market dynamics need to be carefully considered when developing a market positioning strategy to show how the process can complement and add value to typical AD processes.

- The future markets for hydrogen are diverse and there are expected to be several different market applications available to target.

- Manufacture of cost competitive hydrogen will be a key requirement, with initial estimations suggesting this is achievable.

- The potential to develop process plants of several different scales to meet specific demand is an attractive asset of this process. It is expected that this flexibility will align with the strategies of key players in several different applications for the delivery of geographically distributed hydrogen.

Commercialisation of the Technology

Conclusions

- Partnership with appropriate engineering design and manufacturing companies will be required to commercialise the technology, irrespective of business model adopted
- Establishment of a development, design and engineering company (spin out venture) is considered the optimum vehicle to catalyse the development in industrial scale capability
- Hydrogen likely to be more attractive than biomethane in the future
- The process and its future potential are fully aligned with the UK Government’s legal commitment to achieve Net Zero greenhouse gas emissions by 2050 and with the Hydrogen BECCS process.

Thank You

Dr Kayleigh Nelson
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Commercialisation Plan – Hydrogen Production Process

Final Report

University of Aberdeen

19th October 2022

J3371/UoA

Executive Summary

An innovative hydrogen bioenergy with carbon capture and storage (BECCS) process[1] to convert organic matter into hydrogen is currently under development by a consortium consisting of the universities of Aberdeen, Cranfield and Verona, which combines dark fermentation, anaerobic digestion, plasma reforming, steam gasification and water gas shift processes. It offers an opportunity to generate cost competitive, purified hydrogen from a variety of organic waste sources (food waste, farm waste, sewage sludge, etc.), with the processes selected to achieve the maximum possible hydrogen output. Further, it is anticipated that this process will be scalable. This commercialisation plan provides early indication of the way forward to realise the commercial potential, given the process developed thus far.

The local and global demand for hydrogen is anticipated to increase significantly as it becomes a key energy vector in the future. The level of demand anticipated is such that there are no concerns over the ability to sell hydrogen produced by this process. Overall, the volume output of this process will likely be small compared to other hydrogen manufacturing technologies (primarily based on feedstock availability and collection), but still a significant contributor to meeting expected demand. A key target market for hydrogen is space heating, replacing natural gas. Accordingly, the market for biogas produced by anaerobic digestion (AD) plants is expected to diminish over time. Stakeholder engagement indicates that this technology is perceived as a direct competitor to AD, the established industrial process used to valorise organic waste. If the process technology under development can be positioned as an advancement to the traditional AD process, it will find an attractive market niche as it will enable retention and advancement of AD plant capabilities.

Identification of a reliable, consistent volume of organic feedstock presents a major challenge. Within the wider industry, there are significant volumes of collected waste, but this is already, on occasion, insufficient to meet demand. Uncertainty surrounding volumes of food waste generated has also been identified, with changing legislation in England likely to increase the volume of waste collected, but this is balanced by the expectation that less food waste will be generated as a result of changing behaviour, driven, in part, by the current ‘cost of living crisis’.

It is recommended that this process should be positioned as an added value option for AD with its potential carbon negative capabilities highlighted. In addition, the process technology is flexible and may be implemented as part of local circular economies, where hydrogen and carbon dioxide produced from waste can be re-used within the local economy.

Further development of the technology and demonstration at an industrial scale is advised. Partnership with design and engineering specialists is considered the optimum vehicle to catalyse the development of industrial scale capability. Establishing a ‘spin-out’ company from the academic institutes is deemed the most effective way to capitalise upon the technology developed in this, and subsequent, projects.

It is recommended that there is an emphasis on presenting the results of the project on an ongoing basis, both within academia, and within relevant industries to raise awareness of the technology. A combination of academic papers, presentations at relevant conferences, and event and news items in industry / trade press should be pursued to highlight future applications and commercial potential.

---

[1] Hydrogen BECCS is defined as the manufacture of “hydrogen from biogenic feedstocks via gasification or other bioenergy conversion routes, combined with carbon capture and storage” .

Table of Contents

Appendices:

Appendix A: List of Organisations Interviewed

Prepared By: Iain Weir and Kayleigh Nelson	**Date:** 20th October 2022
Approved By: Deborah Creamer	**Date:** 21st October 2022

1 Introduction

1.1 Context

The University of Aberdeen, in collaboration with the Universities of Cranfield and Verona, has received funding from the UK Department for Business, Energy and Industrial Strategy's Hydrogen bioenergy with carbon capture and storage (BECCS) Innovation Programme, Phase 1 to develop an integrated biological-thermal-electro-chemical process to manufacture hydrogen from organic waste. This commercialisation plan has been prepared as one of the project deliverables. It details potential target markets for the technology, the potential scale and deployment locations of future plants and potential deployment strategies, assuming a successful Phase 2 pilot project.

1.2 The Hydrogen Manufacturing Process

An innovative process to convert the organic matter present in many types of waste into hydrogen using a combination of biological, thermal and electrochemical process is being developed. The overall process consists of a sequence of several individual processes which, in combination, produce the maximum volume of hydrogen from the organic matter. The key individual processes are:

1. Dark fermentation
2. Anaerobic digestion
3. Plasma reforming
4. Steam gasification
5. Water gas shift

The outputs of each of these processes and their linkages can be shown, schematically, as follows:

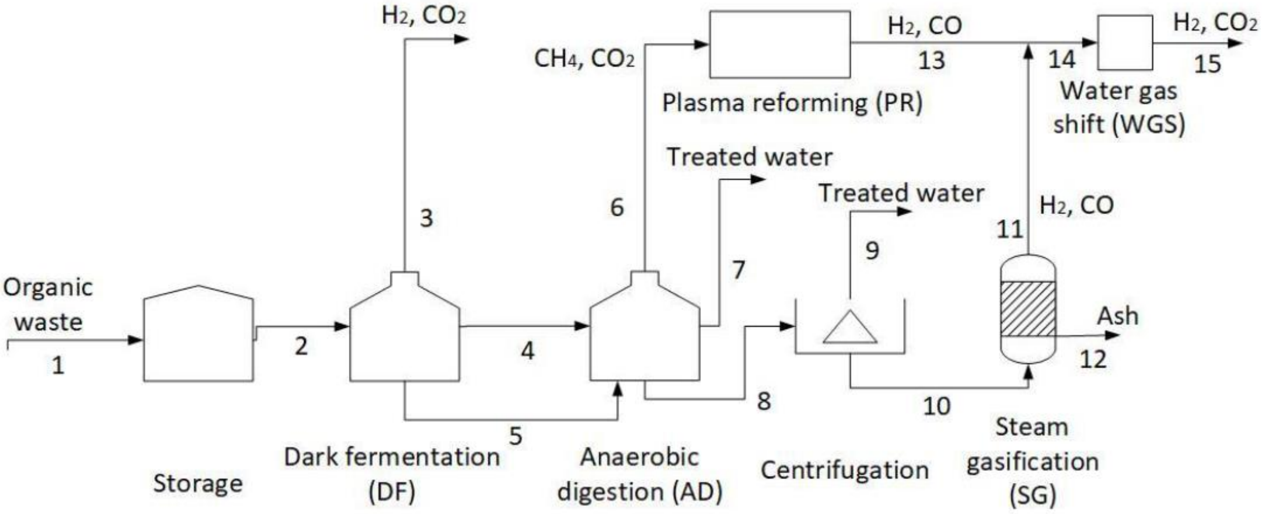

Figure 1: Process Overview

These core processes will be supplemented by feedstock preparation, hydrogen purification and carbon dioxide capture. It should be noted that existing carbon capture technologies are compatible, however, the capture of carbon dioxide output is outwith the scope of the pilot plant given the focus on innovation in the aforementioned processes.

Early estimates suggest that a conversion of 13% of the dry organic matter into hydrogen is practical and a levelised cost of hydrogen of £50/MWh can be achieved when the technology is fully developed and productionised. This cost is comparable to predicted future blue and green hydrogen manufacturing costs[2].

1.3 Methodology

This commercialisation plan is based on:

- An initial briefing to fully understand the technology and its potential applications.
- Independent desk research to quantify the potential market, understand market dynamics, identify potential competitors and model the supply chain.
- Interview programmes with potential customers, partners and stakeholders to gain feedback on the process capability and its potential. Ten interviews were carried out as listed in Appendix A, covering the organic waste management and embryonic hydrogen manufacturing sectors.
- Analysis and assessment of the evidence base collated to define the target market, market potential, scale of development, market access options and commercial requirements.

The research work was carried out in August and September 2022.

---

[2] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1011506/Hydrogen_Production_Costs_2021.pdf

2 Market Analysis

This market analysis is based on a combination of desk research and stakeholder consultation as described above.

2.1 Target Market Definition

The commercial development of this technology needs to be based on an understanding of two markets, namely the valorisation of organic waste and the future hydrogen market, and how they can be linked through the proposed process technology.

These markets are discussed in the following two sections.

2.2 Market Overview – Valorisation of Organic Waste

2.2.1 Market Size

There are a range of organic waste arisings that could potentially be used as feedstock for the production of hydrogen. These include:

- **Food waste**
  The level of food waste generated in the UK is uncertain. WRAP estimates that the UK generates 9.5 million tonnes a year of food waste, of which, only 1.9 million tonnes is recycled[3] at present, while other sources indicate that the level of food waste generated may be higher as a result of additional waste within supply chains[4]. Food waste for recycling is collected by specialist companies, such as Keenan Recycling and typically supplied to anaerobic digestion (AD) facilities.

  The remainder of food waste is recovered for energy generation (Energy from Waste (EfW)), is spread on the land or is landfilled. 6.1 million tonnes of biodegradable municipal waste (BMW) were sent to landfill in the UK in 2020.

  New regulations for local authorities in England in 2023, which will bring England in line with the other devolved nations, on the mandatory separation of food waste are likely to increase the volume available for valorisation. It is indicated that £290m of funding will be released from 2023/2024 which has the potential to be used for new, innovative anaerobic digestion plant designs.

  Whilst there are general moves to increase the volume of waste recycled, there are also known barriers to waste collection which are yet to be overcome, such as the underlying recycling infrastructure, local authority area boundaries and commitments (collection frequency, segregation methods), development of economically sustainable solutions, and individual participation in recycling efforts. Additional behavioural shifts towards reducing food waste are anticipated as a result of increasing environmental awareness and the current ‘cost of living

---

[3] https://wrap.org.uk/taking-action/collections-recycling/markets-materials/organics-collection-sorting-reprocessing

[4] https://www.sciencedirect.com/science/article/pii/S2352550920314202

crisis' within the UK but it remains unknown whether this will have short or long term impacts on supply.

Interview feedback suggests that these changes in England will result in the collection of an estimated additional 2 million tonnes of food waste for reprocessing.

- **Farm waste**

  90-100 million tonnes of agricultural by-products (such as manure and slurry), which are suitable for AD, are produced in the UK each year[5]. Over 7.3 million tonnes per annum are already collected for processing[6]. It is most commonly used as an input for AD plants, with over 440 farm waste fed AD plants in the UK.

- **Sewage sludge**

  Around 4 million tonnes of sewage sludge are produced in the UK every year. A significant proportion of this is processed via AD (currently the main valorisation route) to generate biogas, either for injection to the grid or to fuel combined heat and power (CHP) plants, and the processed digestate is also utilised. The majority of digestate (87%, equivalent to 3.5 million tonnes) is spread on agricultural land, 4% is incinerated, 3% is used in industry and 6% used for land reclamation/restoration[7].

  130,000 tonnes of arisings in Scotland were noted during the interview programme, distributed across the country in line with the population distribution.

- **Other**

  Other sources of organic feedstock include energy crops, distillery (and brewery) waste and fats and oils. Distillery and brewery waste is also used on agricultural land while waste fats and oils are, increasingly, used for the manufacture of low carbon fuels (for example, see https://www.argentenergy.com/).

2.2.2 Competition

The established current route for valorisation of organic waste is anaerobic digestion. The overall process devised is currently seen by the AD industry as direct competition. However, there is potential to change perceptions of the technology and position the process as an upgrade system or extension to established AD plants. This enables conversion of the methane produced via AD into hydrogen. If hydrogen becomes a key energy vector, as anticipated, this will enable the retention of AD while the demand for biogas for grid injection shrinks.

> *"This would be a competing market for the feedstock used by AD. Given the delays in separate organics waste collections, there is only a limited percentage of all the food waste produced in the UK currently presented for recycling and adding another route into the mix would place further pressure on those AD facilities that use food waste as a feedstock."*

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[5] https://www.biogas-info.co.uk/about/faqs/#:~:text=Beyond%20the%20water%20industry%20AD,plants%20on%20the%20Biogas%20Map.

[6] https://www.fwi.co.uk/business/diversification/farm-energy/is-there-still-a-future-in-ad-plants-for-uk-farmers

[7] https://assuredbiosolids.co.uk/about-biosolids/

There were 660 operational AD facilities in the UK earlier in 2022[8], an increase from 642 in 2021[6], following the opening of new 21 plants[9]. In 2021 the overall segmentation of AD plants is as follows:

- 536 combined heat and power (CHP) plants
- 107 biomethane to grid plants – directly supplying gas to the grid
- 12 plants with other outputs

Further, 446 of these plants were fed with farm waste outputs and 196 with other organic waste.

Figure 2: Map of operational AD plants in the UK, updated April 2022[10]

Currently, growth in the number of AD plants is unclear, due to a number of changes in government incentive schemes. It is expected, however, that the changes in food waste collection regulations in England will catalyse new investment in AD.

Other developing and emerging routes for valorisation of organic waste include the:

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[8] https://www.nnfcc.co.uk/press-release-ad-report-2022

[9] It is assumed 3 plants closed during 2021

[10] https://www.biogas-info.co.uk/resources/biogas-map/

- Manufacture of biodiesel from waste fats and oils. For example, Argent Energy has two plants in the UK and one in Holland with overall production of around 240,000 metric tonnes of biodiesel each year.
- Manufacture of hydrogen from biomethane generated from organic waste using steam methane reformers. For example, Bayo Tech is developing this capability in conjunction with UK partners.[11]

2.2.3 Market Dynamics

As indicated above, AD is well established in the UK with significant operating capacity and is considered an effective way to process organic waste. There are also attractive circular economy practices that have developed, such as trucks delivering food waste being fuelled with biomethane from the AD plant.

However, there are operational challenges for many plants as a result of the impacts of COVID and the current economic crisis. It is reported that many operators are unable to obtain sufficient waste to feed their plants and, as a result, gate fees are very low. Some CHP operators are apparently burning natural gas to keep facilities going. The competition for access to waste is, therefore, currently very strong. Further if initiatives to reduce food waste, a key priority for Zero Waste Scotland, are successful then food waste volumes will reduce further. This is not, therefore, an attractive market situation for the introduction of a new process that accesses the same types of raw material.

Future market changes may further impact the attractiveness of AD. For example, the ambition to transform the national gas network to a hydrogen network[12], if it proceeds at scale, will undermine the market for biomethane from AD plants.

There are also some concerns about the use of digestate from AD being used on agricultural land relating to micro plastics content and microbial resistance. These issues may result in the need for an alternative use for digestate.

2.2.4 Opportunities

The analysis carried out, based particularly on stakeholder feedback, suggests that it will be difficult to compete with an established process, such as AD. It is considered more likely that there is an opportunity to complement AD to, for example:

- Extend the AD process with steam reforming, steam gasification and water shift to produce hydrogen rather than biomethane
- Use steam gasification and water shift processes to product hydrogen from digestate.

However, significant demand growth for organic waste processing, when the new regulations are implemented in England in 2023, may offer the opportunity for the two processes to co-exist in the market. However, feedback from the interview programme suggests that AD companies are already mobilising to address this wider opportunity, suggesting demand may be satisfied by the time this technology has developed to a commercial stage.

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[11] For example, see https://www.bioenergy-news.com/news/uk-hydrogen-project-to-use-food-waste-derived-biomethane/

[12] https://www.sgn.co.uk/sites/default/files/media-entities/documents/2021-11/North%20East%20Network%20and%20Industrial%20Cluster%20Development%20Summary%20Report%20November%202021.pdf

Other opportunities may also be attractive, based on the manufacturing cost and sales price of hydrogen. For example, would it be attractive to extend the AD process to manufacture hydrogen rather than to produce electricity (via the CHP plant) or to process biogas to hydrogen, rather than injecting into the gas grid or feeding CHP plants? However, this would depend on the profit from hydrogen manufacture enabling purchase of sufficient electricity to replace the output of the CHP plant.

2.3 Market Overview – Hydrogen

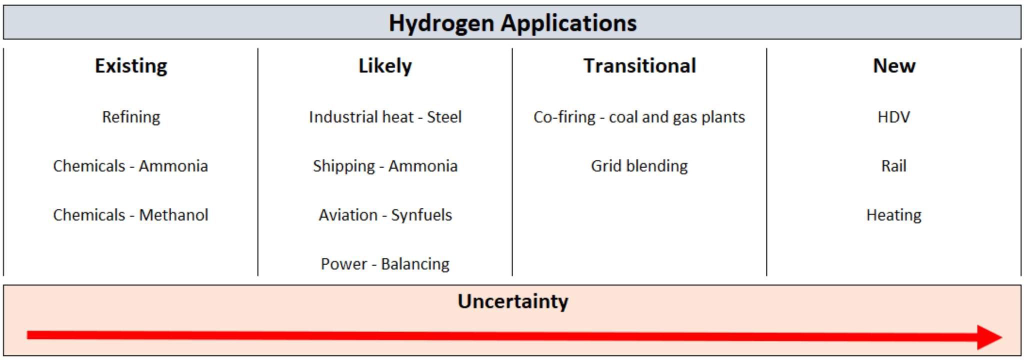
2.3.1 Market Size

Currently the market for hydrogen is in industrial sectors, with oil refining, chemical industries and steel making cumulatively using around 90 million tonnes per year, with very little significant hydrogen consumption in other sectors[13]. Refining utilises 40 million tonnes of hydrogen per year as a feedstock, reagent or as a source of energy. The chemicals industry consumes around 45 million tonnes of hydrogen per year with around 75% of this going to ammonia production and 25% to methanol production. A further 5 million tonnes of hydrogen is consumed for steel making using the direct reduced iron process. This distribution of hydrogen use has been broadly consistent since the year 2000. For context, the current annual global demand for hydrogen in transport is 20,000 tonnes (i.e. 0.02 million tonnes per year).

However, the range of potential applications for hydrogen are expected to grow significantly in the future. There are many proposed potential applications for low carbon hydrogen in a zero-carbon economy which can be categorised into four groups:

- Existing uses – these applications offer both short term and long-term opportunities for low carbon hydrogen
- Likely uses – where future demand is likely to be large, but development may take some time
- Transitional uses – offering translational opportunities for hydrogen over a limited time period
- New uses – which could include potentially large future applications but where the relative advantages of hydrogen over other options is very uncertain

An example list of potential application across these four groups is presented in the figure below.



Hydrogen Applications

Existing	Likely	Transitional	New
Refining	Industrial heat - Steel	Co-firing - coal and gas plants	HDV
Chemicals - Ammonia	Shipping - Ammonia	Grid blending	Rail
Chemicals - Methanol	Aviation - Synfuels		Heating
	Power - Balancing		

Figure 3: Potential Low Carbon Hydrogen Applications

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[13] Global Hydrogen Review 2021, International Energy Association, October 2021

The degree to which hydrogen penetrates various end use applications is dependent on many different factors. Currently the market is in the very early stages of development. Government policies and incentives are expected to be important drivers but so, too, are factors such as the cost of hydrogen compared to other low carbon alternatives and the investment required in new equipment to switch to hydrogen.

There is therefore considerable uncertainty over the potential future demand for hydrogen.

To date, there are numerous targets for the production of hydrogen, for example:

- the British Energy Security Strategy[14] states a 2030 production target of 10 GW, with at least half of this from electrolysis (green hydrogen)
- The European Union hydrogen strategy[15] has an objective to install at least 6 GW of renewable hydrogen electrolysers between 2020 and 2024 and 40 GW by 2030. More recently, an additional 15 million tonnes of renewable hydrogen production are proposed for 2030, consisting of 10 million tonnes of imports and 5 million tonnes of European production.

However, development of future demand for hydrogen is, as yet, unclear as it depends on the speed and scale of adoption of hydrogen in different applications. For example, the National Grid Future Energy Scenarios[16], like many others, have developed different scenarios for the transition to net zero with different demands for hydrogen identified in each. This is demonstrated in the figure below, which shows that there are significantly different demands for hydrogen in each scenario and in different applications, highlighting the lack of clarity on future hydrogen markets.

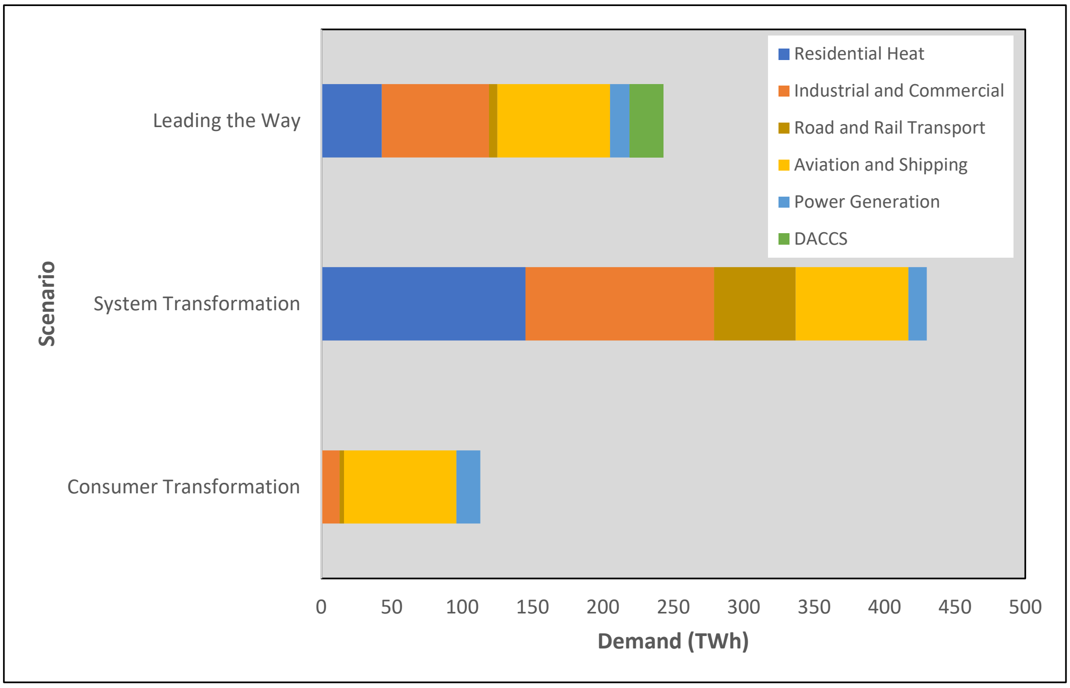

Figure 4: Potential UK Demand for Hydrogen

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[14] British Energy Security Strategy, HM Government, 7th April 2022, see https://www.gov.uk/government/publications/british-energy-security-strategy/british-energy-security-strategy

[15] A hydrogen strategy for a climate-neutral Europe, European Commission, July 2020

[16] Future Energy Scenarios, National Grid ESO, July 2022

Similarly at European level there are numerous analyses of the potential scale of the European hydrogen market over the period to 2050. As examples, those published by the Gas for Climate Initiative[17] and the European Project, Hydrogen4U[18] are as follows:

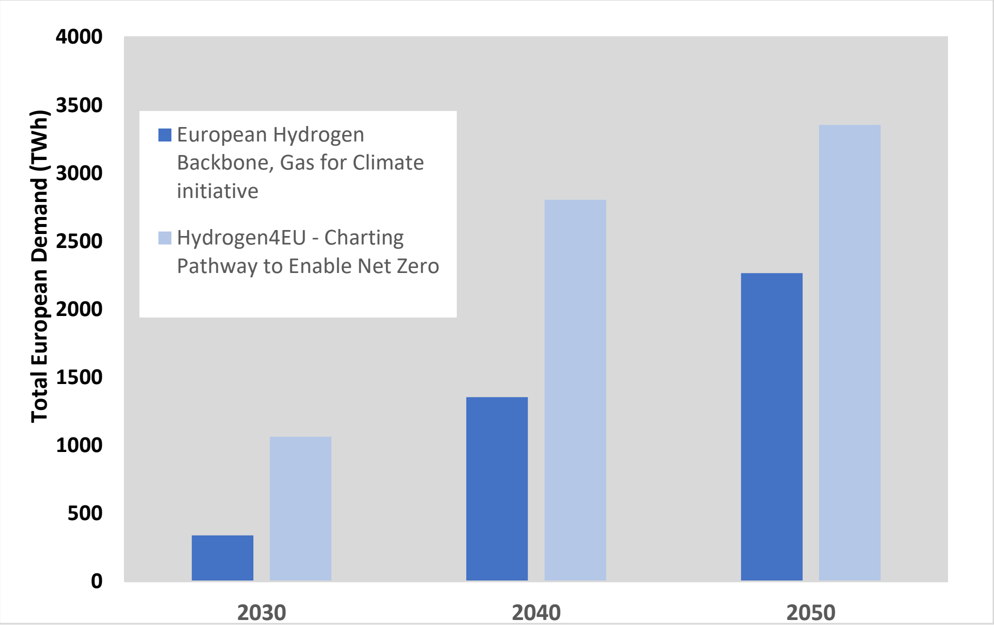

Figure 3: Potential Scale of European Hydrogen Demand (2030 to 2050)

On a global basis, the International Energy Agency[19] estimates global hydrogen demand in 2030 in two different scenarios[20] of 115 and 130 million tonnes of hydrogen, with the vast majority (over 95%) forecast to be used by existing industry applications. Demand from new applications is, therefore, relatively modest. It is expected that low/zero carbon hydrogen production will replace existing manufacturing methods in existing applications, but these are likely to be large plants co-located with large industrial facilities. Analysis of new applications under the two scenarios used in the report indicates demand in:

- Transport of 0.7 million tonnes, predominantly in heavy duty road transport, and 8 million tonnes, where 60% is for shipping (hydrogen and hydrogen derived fuels)
- Buildings of 0.15 and 2 million tonnes by 2030, based on hydrogen blended with natural gas
- Power generation of 0.3 and 5 million tonnes by 2030

So, it is predicted by many that there will be significant future demand for low/zero carbon hydrogen, but what is not clear at this time is what the actual future demand for hydrogen will be as all forecasts are based on a number of assumptions, which may, or may not be accurate. For example, SGN predicts a demand of almost 80 TWh per year by 2050 for Scotland, excluding the Western and Northern Highlands and the Islands[12], as shown below, but this is based on a number of assumptions regarding application areas and projected scale of demand.

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[17] European Hydrogen Backbone, Gas for Climate Initiative, June 2021

[18] Hydrogen4EU – Creating Pathways to Enable Net Zero, Deloitte, 2021

[19] Global Hydrogen Review, 2022, International Energy Agency, September 2022

[20] These two scenarios are stated policies and announced pledges

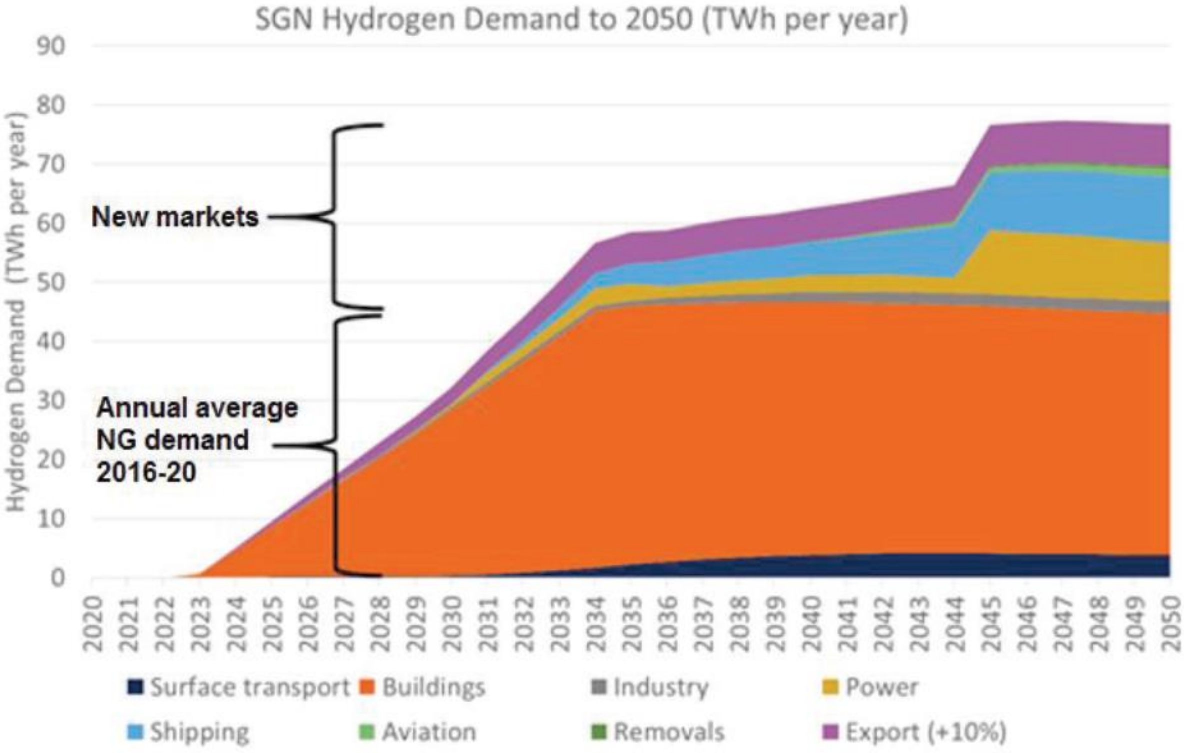

Figure 5: Project Future Hydrogen Demand

The scale of demand for hydrogen for heating, either as a blend with natural gas or as 100% hydrogen, is the largest market segment but is open to doubt. It is proposed by others, including the Scottish Government[21], that heat pumps are a much more attractive solution.

2.3.2 Market Potential – Hydrogen from Biological Waste

The potential production of hydrogen from organic waste via biological processes is considerable[22]. Potential global production of hydrogen from organic waste has been predicted to be comparable to current hydrogen production (110-130 million tonnes/year). However this is reliant on effective waste collection as assumptions are based on the total waste produced and, as highlighted earlier, the volumes collected are much lower and, currently, there is evidence that they are insufficient to support processing capacity.

“AD plants either have a CHP or produce bio-methane. Some CHPs burning natural gas to keep going – this is a reflection on demand for materials”

“There is a drive to reduce food waste – driven by bad weather (affecting crops), recession and environmental drivers – so less raw material, and AD plants are struggling to fill capacity.”

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[21] Heat and Buildings Strategy, Scottish Government, October 2021

[22] https://onlinelibrary.wiley.com/doi/full/10.1002/bbb.1884

2.3.3 Competition

There are plans across Scotland and the rest of the UK to establish hydrogen manufacturing capacity. Scottish Enterprise has identified 13 hydrogen hubs across Scotland[23] while other analyses[24] suggest significant blue hydrogen manufacture in Scotland in the late 2020's.

Initial large scale hydrogen production is expected to be blue hydrogen (e.g. the Acorn Project, Ineos at Grangemouth and, potentially, Exxon/Shell at Mossmorran) with green hydrogen being produced at scale over a longer timescale. Other options to manufacture hydrogen from a range of sources are being investigated. Examples include Advanced Plasma Power.

At a UK and European level, there are similar plans for blue and green hydrogen manufacture, but with a bias towards green hydrogen, as defined by UK and European strategy documents referred to above.

Overall, it is expected that the technology developed here will be a small player in terms of volume output (based on availability of feedstock material) compared to other hydrogen manufacturing technologies. For example, the output of a steam methane reformer (SMR) is, typically, 100,000 tonnes/year of hydrogen. There is naturally an opportunity to expand production through increasing the number of facilities operating with this technology, where a centralised facility covering a city the size of Aberdeen would produce approximately 1,000 tonnes/year of hydrogen.

2.3.4 Market Dynamics

The markets for hydrogen, apart from existing uses as shown in Figure 2, are still developing / emerging. It is, therefore, difficult to make robust predictions on future demand. Similarly, supply chains and market structures (inc. pricing) have not yet developed.

2.3.5 Opportunities

There are, however, a number of potential opportunities for hydrogen in Scotland, such as:

- Hydrogen for heating, as proposed by SGN[12]
- Fuel cell powered heavy duty vehicles – hydrogen fuel cells are identified as a key option for heavy duty vehicles, along with batteries[25]. Organisations such as Aberdeen City Council has already established a hydrogen fuel centre and a fleet of hydrogen powered buses are operating in the region
- Transport Scotland are proposing[26] "alternative traction" options for some of its rail network (Highland and other long-distance rural lines where electrification of the routes is not seen as cost-effective), with hydrogen powered trains offering a potential solution. It has recently been reported[27] that testing of a hydrogen powered train in Scotland is progressing well.
- The manufacture of sustainable aviation fuel[28], where the Fischer–Tropsch process is used to convert mixture of carbon monoxide and hydrogen into hydrocarbons.

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[23] https://www.investmentmonitor.ai/wp-content/uploads/sites/7/2022/09/Hydrogen-How-Scotland-is-developing-its-new-clean-energy-sector.pdf

[24] For example see https://theacornproject.uk/about/ and www.snzr.co.uk

[25] Skills for Low Carbon Heavy Duty Vehicles, Transport Scotland, October 2021, see https://www.transport.gov.scot/media/50464/skills-for-low-carbon-hdvs-pdf.pdf

[26] https://www.transport.gov.scot/media/47906/rail-services-decarbonisation-action-plan.pdf

[27] https://news.st-andrews.ac.uk/archive/scottish-hydrogen-train-project-on-track-to-deliver-climate-targets/

[28] Sustainable Aviation Fuels Roadmap, Sustainable Aviation, 2020

It is, therefore, realistic to assume that demand for hydrogen will develop as production output develops. In fact, according to some of the stakeholders interviewed:

"Selling hydrogen will be easy – it's the least of your problems"

"Don't worry about markets for hydrogen – when this plant gets up and running there will be a mature hydrogen market and lots of demand"

Of course, hydrogen will need to be purified to the specification required (96/97% purity for grid injection and 99.9999% for fuel cell use) and sold at a reasonable price.

Further, the scalability of the process under development, aligns well with these opportunities as facilities could be developed to address local demand across Scotland, e.g. local supply of hydrogen for heating, co-located with HDV fuelling stations or at key locations on rural train lines.

2.4 Discussion – the Market Opportunity

The market opportunity must be considered in two parts – accessing raw material and selling hydrogen.

2.4.1 Accessing Raw Material

The work carried out identifies that accessing raw material is likely to be the most significant challenge. Key stakeholders interviewed highlighted the relative maturity of the AD market, the tight market conditions at the moment and the changing incentive regime(s). It was also noted that there are large players operating a portfolio of AD plants that are committed to long term operation.

"There is not a pile of organic waste available that people don't know what to do with"

The situation is likely to change in the near future as regulations in England demand wider food waste collections and there are pressures to maximise food waste collection. These are expected to provide additional material available for AD. It is expected, however, that this tonnage will be aggressively pursued by AD operators to feed existing and new plants. Further, the timing of the collection of this additional food waste is likely to be prior to full development of this technology.

It should also be noted that efforts to reduce food waste are likely to reduce the volumes available.

The option to extend AD plants to produce hydrogen rather than biomethane and to develop an alternative, higher value market for digestate are key opportunities identified. The first of these is market driven (i.e. if the heating network is changed to hydrogen reducing the demand for biomethane) while the second offers the opportunity for digestate producers to address emerging environmental concerns in current markets.

More generally, there is a wish within the organic waste sector to maximise income and green credentials, with hydrogen manufacture being considered as very attractive. Operators would be keen to move to hydrogen production if it is financially attractive. However, it is too early to assess whether the costs of this process will be sufficiently attractive.

2.4.2 Hydrogen Markets

Hydrogen markets in the net zero space are embryonic and are expected to develop strongly over the next few years as hydrogen becomes accepted as a fuel in a range of applications.

These applications are likely to offer the potential for customised local hydrogen supply. For example, local manufacture of hydrogen to support:

- Hydrogen powered trains in rural areas
- Fuel stations for heavy duty vehicles
- Local heat networks

However, these opportunities are only now emerging and are very immature.

2.4.3 Other Issues and Caveats

In the wider industry context, it is evident that many critical processes will not be able to achieve net zero and some residual carbon will remain. Offsetting is, therefore, required and the ability to develop a wholly net negative carbon process at industry level will be necessary and attractive to achieve net zero targets.

It is, therefore, important to highlight that the future implementation of this technology should include carbon dioxide capture and storage/utilisation provision. This was strongly highlighted by all key stakeholders consulted, where the potential for decarbonisation solutions to achieve net zero across industry is contingent on net negative processes such as this one.

Whilst there is less of a requirement to calculate the carbon dioxide emitted from the valorisation of organic waste (as this organic waste has absorbed carbon through its lifecycle), it is anticipated that this could also be subject to change in the future.

It may be possible to address carbon dioxide emissions if a local circular economy could be developed where both hydrogen and carbon dioxide are used locally. There are general trends towards such local economies, for example renewable hydrogen powered farming community projects such as Glensaugh HydroGlen.

3 Commercialisation Plan

It is rather early in the technology development process to be preparing a commercialisation plan and there is insufficient evidence of the scale, performance and cost of the proposed process to enable definition of a clear way forward. Key commercialisation issues are, however, discussed below.

3.1 Target Market Segment(s)

It is considered too early to identify specific types of organic waste that should be targeted, as the performance of the process and its suitability for specific types of waste are not yet known.

The current structure of the organic waste processing sector, its expected growth over the next few years and the dominant position of anaerobic digestion suggest that it will be difficult to compete directly with this industry. Based on the evidence gathered during this work it is believed that it will be more attractive to engage with the AD sector and offer the opportunity of added value processing to access new market opportunities, which include:

- Manufacture of hydrogen for a range of applications
- Reduced dependence on biogas to grid, which will be a particular issue if hydrogen becomes the key domestic and commercial heating fuel in the future
- Alternative, higher value markets for digestate to address concerns in current agricultural markets

The potential opportunities for the supply of hydrogen are dependent on the way different markets develop over time.

It is expected that there will be a range of market opportunities for hydrogen in the future as it becomes a commodity product that is used in different of applications. The challenge will be the ability to manufacture hydrogen at the required purity and market price, with early price estimates[2] already available.

The scalability of this process technology means that it is likely to be suitable to address local, small scale hydrogen demand, whether this is for rail, road or domestic applications, where large volume processes, such as methane reforming and electrolysis will not be economically viable, and transport options from large central manufacturing facilities will be costly. In these local markets, slightly higher product costs may be tolerated.

3.2 Deployment

The process technology under development can be deployed at several different scales to deliver maximum biohydrogen production and biogenic carbon removal, with individual parts of the process designed accordingly. These scales range from production of hundreds of tonnes to at least 10,000 tonnes of hydrogen per annum, which would correspond to a very large facility, i.e., covering Scotland's central belt. As such, the process technology could be deployed at a wide range of locations, depending on how relevant markets develop and which specific opportunities are targeted. Deployment locations could include:

- Large cities, such as Aberdeen, Dundee or Newcastle to treat food waste arisings in the city

- Water treatment facilities across the UK to process large tonnages of digested sludge (e.g. 140,000 tonnes are processed per annum at seven plants in Scotland).
- Existing AD plants across the UK to produce hydrogen as an added value product. The locations for these are shown in Figure 2.
- Specific locations to address a specific hydrogen demand, such as key locations on rural train routes (e.g. West Highland Line and the Far North Line) to meet the fuel requirements of hydrogen powered trains.

The business model for commercial exploitation is proposed in Section 4, below.

3.3 Target Customers

There are two options to consider for the provision of hydrogen manufacturing capacity – either the supply of manufacturing systems to supply chain companies, such as AD plant operators, or the establishment of merchant facilities that manufacture hydrogen from particular raw materials, such as organic waste, biogas, etc.

There are numerous types of company operating AD plants ranging from specialist AD companies (e.g. Energen BioGas and Bio Capital), water companies to farmers and investment companies (e.g. Greencoat Capital).

Merchant manufacturers of hydrogen would be a new segment of the chemical industry.

3.4 Market Access

To access both types of target customer, we are assuming that the university partnership will wish to exploit the research through partnership with appropriate commercial organisations. Thus, partnership with an organisation with the capability to develop such equipment and, thereafter, an industrial manufacturer of process plant is required. The Wood Group, one of the stakeholders interviewed in this study, has already expressed interest in supporting commercial development, assuming an appropriate financial arrangement can be agreed. There are, of course, numerous other companies with similar capabilities. There are also numerous UK companies with capabilities in process plant manufacture, often integrating specialist equipment from third parties. Many such companies are considering opportunities that will result from development of the hydrogen economy and it is expected that it will be relatively easy to identify suitable partners, at the appropriate time, assuming the process developed offers an attractive business proposition. Many of these companies have been identified and assessed in a number of studies[29] to assess UK supply chain capability for hydrogen and carbon capture and storage industries.

3.5 Marketing and Sales Strategy

It is considered too early to develop a marketing and sales strategy for the process technology that will result from this, and subsequent, innovation projects. However, at this stage it is worthwhile to consider

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[29] For example, see https://www.gov.uk/government/publications/supply-chains-to-support-a-uk-hydrogen-economy, https://oeuk.org.uk/wp-content/uploads/2022/07/NSTD-CCS-Supply-Chain-Report-2022-OEUK.pdf and the Energy Industries Council supplier database (see https://www.the-eic.com/MarketIntelligence/EICSupplyMap)

the need to promote the early results of technology development to begin to develop a market profile and market interest.

It is recommended that there is an emphasis on presenting the results of the project on an ongoing basis, both within academia, and equally importantly, within relevant industries. A combination of academic papers, presentations at relevant conferences and events, and news items in industry / trade press should be pursued to raise awareness of the technology, its applications and its commercial potential.

The potential for the process technology to be part of a circular economy, where hydrogen and carbon dioxide produced from waste is used in the local economy, should be highlighted where possible within marketing activities.

Of course, it is assumed that relevant intellectual property / know-how is retained to ensure that there is value in the technology when the university partnership considers its transfer to appropriate exploitation partners.

4 Business Model

In considering an appropriate future business model to exploit this technology it is assumed that:

- Valuable (i.e. exploitable) process design and operational know-how will be developed in the current project (pilot) and subsequent developments.
- The university partnership will wish to exploit this design and process know-how at the appropriate time.
- Success in the current project, and the subsequent demonstration project, will showcase the potential of the technology but a larger scale demonstration will be required to support industrial exploitation[30].
- It will, therefore, be several years before a commercial proposition will be available and, over that time, the focus will change from process development to engineering design, application development and cost optimisation. This is considered to be a different skillset than the current capabilities of the academic project team.

At the appropriate time, the university partnership has two main options for developing and exploiting the technology – to continue to operate as a university partnership or to set-up a spin out company, which focuses on close to market process design and development. Setting up a spin-out company, with the shares held by, for example, the partner universities, relevant academic staff and other investors (e.g. Scottish Investment Bank and other venture capital organisations) is considered the preferred option as it offers the freedom and potential to develop and adapt its capabilities as required at any given time, as the technology matures and the exploitation challenges change. Establishing a spin-out company is also likely to be more suitable to access appropriate grant and investment support options.

The proposed spin-out company will focus on process development, design, engineering and exploitation, rather than research, and would be expected to have a strong relationship, potentially including some common staff members, with the current university partnership.

In the longer term, it is expected that income will be generated by the spin-out company through design and know-how licensing arrangements with process manufacturing companies and through further process development programmes, most likely to address specific waste streams.

It is suggested that an appropriate time to establish this spin-out company would be at the latter stages of the planned next stage demonstration project, when the process capability will be much more well defined, the organic waste supply chain / market will have matured and embryonic hydrogen markets will have developed further. It is considered too early to further define the spin-out business model, investment requirements, sources of income and its overall commercial potential as it will be established in a market environment that will be quite different from the way it is today.

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[30] A key example here is the development of carbon capture technology. It has been developed to high TRL levels but there is reluctance in industry to invest until it is proven in real industrial situations.

5 Alignment with Government Commitments and Programmes

5.1 Alignment with the UK Government's Legal Commitment to Achieve Net Zero by 2050

The key output from the process under development will be hydrogen. Further, the process could be developed with carbon capture and storage equipment[31], making it an overall carbon negative zero manufacturing process.

Hydrogen is clearly identified as being key to achieving net zero emissions[32] where it is expected to be used in:

- Industry, as feedstock for steel and chemical (e.g. ammonia and fertiliser) manufacture
- Transport applications including
    - Heavy-duty trucks, buses and off-road vehicles
    - Hydrogen powered trains
    - In the manufacture of synthetic/sustainable aviation fuels
    - In the maritime sector as a fuel and as a precursor for ammonia
- Domestic, commercial and industrial heating applications
- Power generation

The expected UK demand for hydrogen in each of these applications in three net zero scenarios has already been shown (in Figure 4). Further, the scale of demand for hydrogen in Scotland to support industrial decarbonisation has been estimated by the Scotland Net Zero Roadmap project. It is estimated that over 10,000 GWh of hydrogen will be required to support industrial decarbonisation by the mid-2030's in Scotland. SGN, however, project much larger volume requirements, as shown in Figure 5, when all applications, including commercial and domestic heating are considered.

This project, therefore, is fully aligned with the UK Government's legal commitment to achieve Net Zero greenhouse gas emissions by 2050, with the scale of the contribution dependent on the number of hydrogen production plants established over the period to 2050.

5.2 Integration with and Benefits to the Hydrogen BECCS process

Hydrogen BECCS is defined as the manufacture of "hydrogen from biogenic feedstocks via gasification or other bioenergy conversion routes, combined with carbon capture and storage"[33]. This is exactly what the proposed process will do. It will manufacture hydrogen and carbon dioxide from organic waste with appropriate technology(s) to capture the carbon dioxide. It is, therefore, totally aligned with Hydrogen BECCS and its development will demonstrate the value and potential of Hydrogen BECCS.

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[31] The captured carbon will be used in local applications where appropriate or transported offshore for long term storage.

[32] For example, see Hydrogen for Net Zero. A critical cost-competitive energy vector, The Hydrogen Council, November 2021 (https://hydrogencouncil.com/wp-content/uploads/2021/11/Hydrogen-for-Net-Zero_Full-Report.pdf)

[33] Hydrogen BECCS Innovation Programme: Phase 1 Competition Guidelines, 7th February 2022, see https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1052852/hydrogen-beccs-phase-1-competition-guidance-notes-version-2.pdf

6 Conclusions

This commercialisation plan has reviewed organic waste arisings and current valorisation methods and assessed the potential future markets for hydrogen. The key conclusions of this plan are:

- There is significant potential for this process to valorise organic waste, but it must be recognised that there is, already, an established route (i.e., AD processes) to valorisation. The current market dynamics need to be carefully considered when developing a market positioning strategy to show how the process can complement and add value to typical AD processes.
- The future markets for hydrogen are diverse and there are expected to be several different market applications available to target.
- Manufacture of cost competitive hydrogen will be a key requirement, with initial estimations suggesting this is achievable.
- The potential to develop process plants of several different scales to meet specific demand is an attractive asset of this process. It is expected that this flexibility will align with the strategies of key players in several different applications for the delivery of geographically distributed hydrogen.
- Partnership with appropriate engineering design and manufacturing companies will be required to commercialise the technology, irrespective of business model adopted.
- Establishment of a development, design and engineering company is considered the optimum vehicle to catalyse the development of industrial scale capability.
- The expected flexibility in terms of the scale of the process is considered an important competitive advantage.
- The process and its future potential are fully aligned with the UK Government’s legal commitment to achieve Net Zero greenhouse gas emissions by 2050 and with the Hydrogen BECCS process.

Appendices

Appendix A: List of Organisations Interviewed

Representatives of the following organisations were interviewed as part of this study:

- Anaerobic Digestion and Bioresources Association
- Binn Eco Innovation Park
- Keenan Recycling
- Net Zero Technology Centre
- SGN
- Scottish Hydrogen and Fuel Cell Association
- Scottish Water
- Wood Group
- Yorkshire Water
- Zero Waste Scotland

We acknowledge and would like to thank the individual interviewees for their contribution to this study.

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