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ENERGY FROM BIOMASS

Examining Real-World Scenarios through Thermodynamic, Societal, & Economic Lenses

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Executive Summary

In order to achieve the time-bound climate goals, it is pertinent that only relevant energy solutions are developed which can rapidly reduce greenhouse gas emissions at acceptable costs and risks. Here, biomass emerges as a pivotal element in this shift due to its potential for net-neutral or net-negative emissions. With this idea in mind, the 'Powering Agrifood' consortium was established to investigate emerging technologies that present opportunities for the biomass value-chain. The main activity within the consortium was developing various case studies/ scenarios for implementing biomass-based systems to facilitate the energy transition while generating supplementary revenue, and diminishing both energy expenses and carbon footprint. This white paper is a synopsis of the most important case studies developed within the activities of the Powering Agrifood consortium.

Initially in chapter 2, the basic technology treatment of the various biomass-to-energy process concepts is provided. An example of Pugh Matrix comparison is provided, which was extensively used across many case studies. In chapter 3, a case study pertaining the re-purpose of biomass feedstocks for energy is discussed. Solid-oxide fuel cells and their applications using biomass-derived fuels are presented in Chapter 4. In chapter 5, the novel idea of producing biomass derived hydrogen or bio-hydrogen is analyzed.

Various case studies highlight that biomass can play a crucial role in overall decarbonization and energy transition of various sectors. However, the optimum biomass-to-energy conversion technology is highly dependent on the context of the case. Moreover, the optimum technology will depend on specific priorities of the stakeholder, as different technologies exhibit advantages in various areas, including thermodynamic efficiency, economic metrics, and sustainability parameters. It was also concluded that bio-energy cannot compensate for the entire demands for a region, but it will likely play a larger role in decarbonizing and contributing to local regions. It was also observed that implementing biomass-to-energy technologies could also boost social indicators of a region particularly in areas of employment, access to clean energy, and reduced inequalities.

Since the consortium was formed by predominantly Dutch stakeholders, an outlook for biomass in the Dutch energy context is provided in final chapter. It was identified that developing green-gas trigeneration systems based on solid oxide fuel cells (SOFC's) for sustainable space heating could play a key role in reducing the natural gas imports for the country.

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1. Introduction

The Paris Agreement for the first time brought all the nations into a common cause of restricting the global temperature rise below 2°C. In order to achieve these time-bound climate goals, it is pertinent that only relevant energy solutions are developed which can rapidly reduce greenhouse gas emissions at acceptable costs and risks. Here, biomass emerges as a pivotal element in this shift. A key advantage of biomass lies in its potential for carbon neutrality. Since biomass is derived from organic materials, which is directly or indirectly produced via photosynthesis, the CO_2 emissions released during biomass combustion are offset by the CO_2 absorbed by the organic material during their growth cycle. This could potentially make biomass as a net-neutral or negative emissions fuel (if the CO_2 is captured and stored), thereby contributing in the overall energy transition. Furthermore, incorporating biomass into the energy mix could also enhance the energy security by diversifying energy sources, thereby mitigating reliance on fossil fuels. This will compensate against supply disruptions and market volatility. With effective policies, technological innovation, and sustainable practices, the benefits of biomass can be fully harnessed, paving the way for a sustainable energy future.

With this in mind, the 'Powering Agrifood' consortium was developed to establish collaboration between three distinct pillars—1) companies in the agri-food sector, 2) energy companies, and 3) research institutions. The objective of the consortium was to investigate emerging technologies that present opportunities for the biomass value-chain, aiming to facilitate the energy transition while generating supplementary revenue, and diminishing both energy expenses and carbon footprint.

The main activity within the consortium was developing various case studies/ scenarios for implementing biomass-based systems. Such system perspective studies focussed on how farmers, cooperatives and processing plants can positively impact local or regional energy systems by offering flexibility, reversible conversion or electrification. This activity included making an inventory of energy-efficient, green and flexible technologies that can most cost-effectively help reach the sector's sustainability goals with regards to energy usage and waste minimization, towards 2025 and onwards.

This white paper is a synopsis of the most important case studies developed within the activities of the Powering Agrifood consortium. For every case study a technology process model was developed on Aspen Plus. For some case studies the model was then used for techno-economic analysis and sustainability analysis. This approach is depicted in Figure 1.

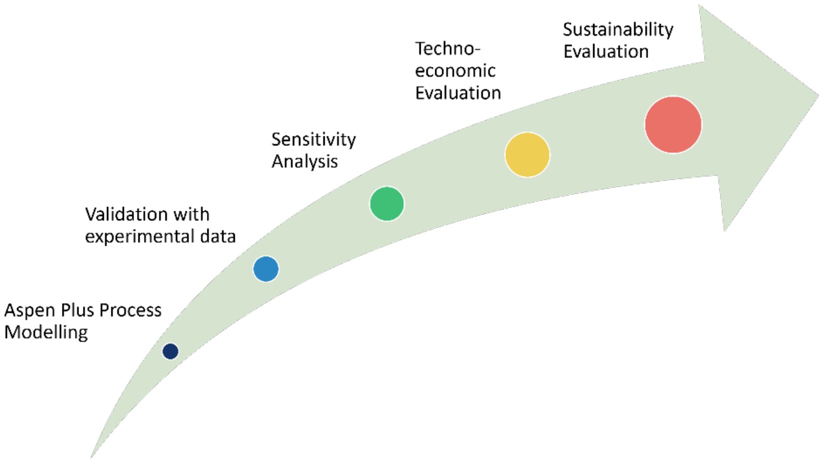


Figure 1: General Approach for the evaluation of all the case studies.

Initially in chapter 2, an introductory overview of the various biomass-to-fuel process concepts has been provided. It also introduces the 'Pugh Matrix' methodology, which is a powerful tool to compare and identify optimum choices. Chapter 3 describes the case study results related to re-purposing biomass feedstocks for energy purposes for the agri-food industry. Solid-oxide fuel cells and their applications using biomass-derived fuels are presented in Chapter 4. In chapter 5, the novel idea of producing biomass derived hydrogen or bio-hydrogen is analyzed. Finally, the major conclusions of the case studies are summarized in Chapter 6. Since the consortium was formed by predominantly Dutch stakeholders, an outlook for biomass in the Dutch energy context also provided within the same chapter.

2. Overview of biomass-to-fuel process concepts

There are two main biomass conversion pathways, which are categorized on the process attributes and parameters. The categories are thermochemical and biochemical. Apart from this various physical treatment processes are also employed.

1. Physical treatments include mechanical processes such as milling, grinding, or size reduction, aimed at enhancing the accessibility of biomass for subsequent conversion stages. In most cases, these processes are employed as pre-treatment steps to increase the energy density of the biomass.
2. Thermochemical conversion, on the other hand, leverages heat to transform biomass into energy-rich products, where high temperatures induce chemical changes, leading to the production of biofuels, gases, and biochar.
3. Lastly, the biochemical conversion pathway employs biological agents, such as enzymes or microorganisms, to break down complex biomass molecules into simpler compounds. This pathway emphasizes the role of biological catalysts in facilitating the conversion of biomass constituents into biofuels or biogas.

The operating principles of the various technologies considered in the case studies are explained below.

Combustion

Combustion is the most established technology out of all biomass processing methods. In biomass combustion, the organic material is dried and then it is burnt to release heat energy. This heat energy can be used for space/water heating, steam production, or for generating power. Biomass combustion must be managed carefully to minimize emissions of pollutants such as particulate matter, nitrogen oxides (NO_x), and volatile organic compounds (VOCs).

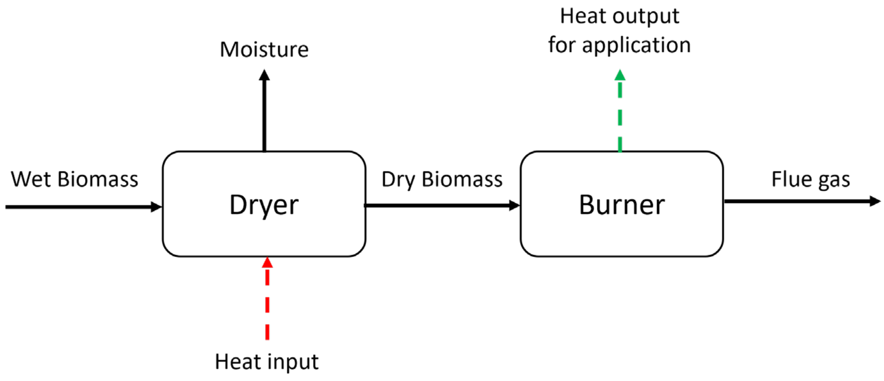


Figure 2: Simplified process block diagram for combustion. Herein, solid lines represent mass flows while dashed lines indicate energy flows. Red arrows indicate utility inputs while green arrows indicate the products of the process.

Anaerobic Digestion (AD)

AD is a developed technology that has been widely used in full-scale plants across the world, since it can convert a diverse range of feedstocks into biogas. The process involves micro-organisms, which break down biodegradable materials (biomass) in absence of oxygen in a digestor, resulting in the production of biogas and digestate (unreacted biomass and inert). During anaerobic digestion, organic compounds within biomass are first hydrolysed into simpler molecules by hydrolytic bacteria. These simpler molecules are then fermented into volatile fatty acids and alcohols by acidogenic bacteria. Finally, the methanogenic bacteria convert these products into mainly CH_{4} and CO_2, which is called as biogas. This gas can be used as a renewable energy source for generating electricity, heat or biofuel. The remaining digested material, known as digestate, is rich in nutrients and can be used as a soil conditioner or fertilizer.

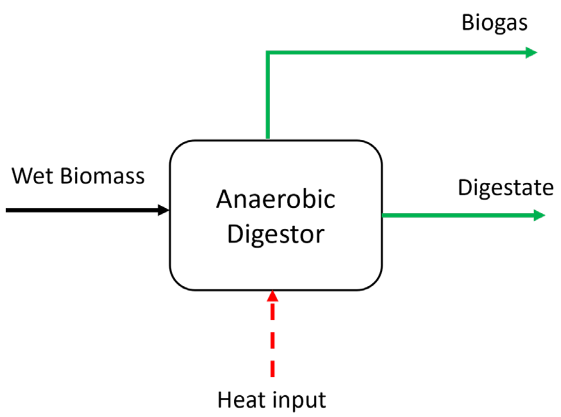


Figure 3: Simplified process block diagram for anaerobic digestion.

These digestors are operated at low temperatures (25–65°C) and have high retention times (~ days). Besides the temperature and duration of the process, AD is simple since it can operate at atmospheric conditions. Typically, this technology is used to convert feedstocks such as industrial wastewater, animal manure, and food waste. However, in recent years there has been a growing interest in applying this process to lignocellulosic materials. This can be done via an additional enzymatic pre-treatment step, which can break down the more complex lignocellulosic materials. Another possible pre-treatment steps are hydrothermal and alkali pre-treatment. In the former, water is added at elevated temperatures and pressures, which breaks down cell membranes and releases the intracellular materials. In alkali pre-treatment, certain chemicals are added to increase overall pH thereby making it easier to break down the lignin in the biomass.

Pyrolysis

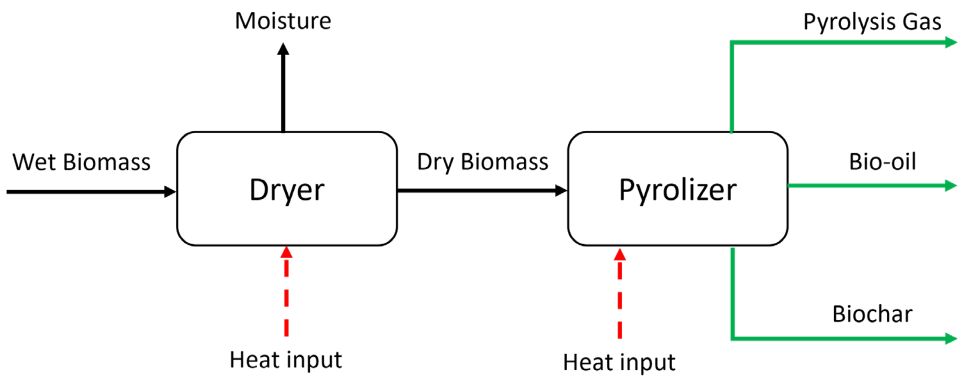


Figure 4: Simplified process Block Diagram for pyrolysis.

Biomass pyrolysis is a thermochemical conversion process involving the decomposition of organic matter at elevated temperatures in the absence of oxygen. Three types of products are formed because of pyrolysis – pyrolysis gas (CH_4, CO_2, CO, H_2, lower order hydrocarbons etc), bio-oil (higher order hydrocarbons), and bio-char (ash and carbon). Pyrolysis is done at high temperatures (500–900°C) and short residence times (1-20 seconds). The relative proportions of the three products depends on the process parameters namely the temperature and residence time. By adjusting these parameters, it is possible to optimize the process and achieve the desired product composition and properties.

The pyrolysis gas and bio-oil can be used as fuel for heat or power production or can be further processed into valuable chemicals. Biochar has applications as a soil amendment to improve soil fertility, water retention, and carbon sequestration in agricultural soils. It should be noted that the process of pyrolysis is under development, and there are only a few pilot plants available currently. This means that the commercialization of this process will probably take a few more years.

Gasification

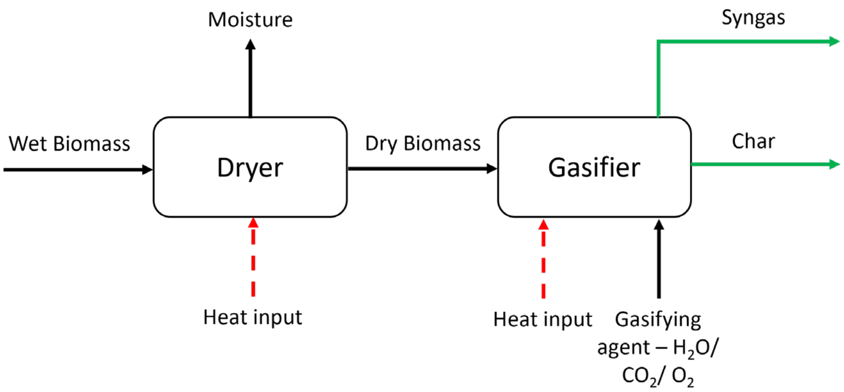


Figure 5: Simplified process block diagram for gasification.

Gasification of biomass is a thermochemical process that converts organic materials into a gas mixture called syngas, which is primarily composed of hydrogen (H_2), carbon-monoxide (CO), carbon-dioxide (CO_2), water vapor (H_2O), and lower order hydrocarbons. Unlike combustion, gasification occurs in a controlled environment with limited oxygen supply through a gasification agent like CO_2, H_2O or non-stoichiometric amounts of O_2. Gasification is done at very high temperatures (700–1200°C) with low residence time (~seconds) depending on the specific gasifier design. Gasification offers several advantages, including high energy efficiency and flexibility in biomass feedstock. The syngas produced from gasification can be used for various applications – as a fuel to generate heat and power or upgrading it to produce other chemicals. The other bio-product char (mixture of ash and carbon) can be used for soil amendment or as fuel for indirect gasifiers. Biomass gasification also requires careful control of operating conditions and gas cleaning processes to optimize syngas quality and minimize environmental impacts.

Supercritical Water Gasification (SCWG)

SCWG is a thermochemical decomposition of biomass employing water in supercritical conditions as a reaction medium. Supercritical water refers to conditions beyond the critical point of water which is 374°C and 22.1 MPa. The elevated temperatures and pressures required for supercritical conditions make it possible for the reactions to happen quickly and evenly. One of the major advantages of SCWG technology is its ability to effectively handle biomass with high moisture content, without the need for drying. Typically, SCWG is conducted at very high temperatures (400–800°C) and pressures of (23–25 MPa). Under these conditions, the biomass undergoes decomposition and gasification reactions resulting in the production of syngas comprising of hydrogen (H_2), carbon monoxide (CO), water vapor (H_2O) and small amounts of methane (CH_4). However, SCWG is still a developing technology and there are very few pilot plants operating worldwide.

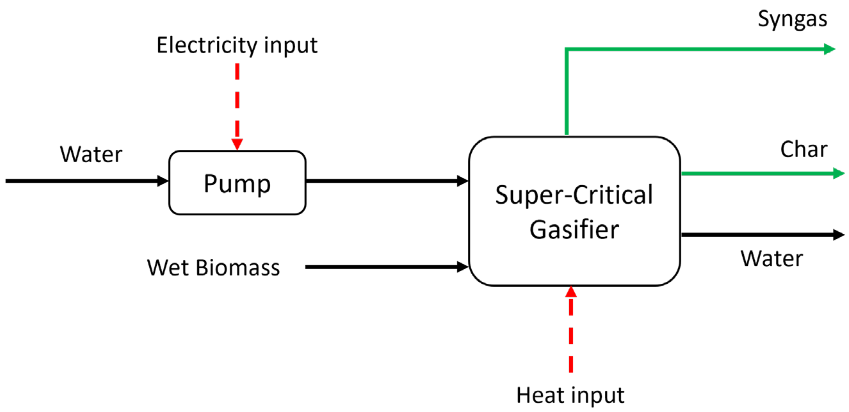


Figure 6: Simplified process block diagram for SCWG.

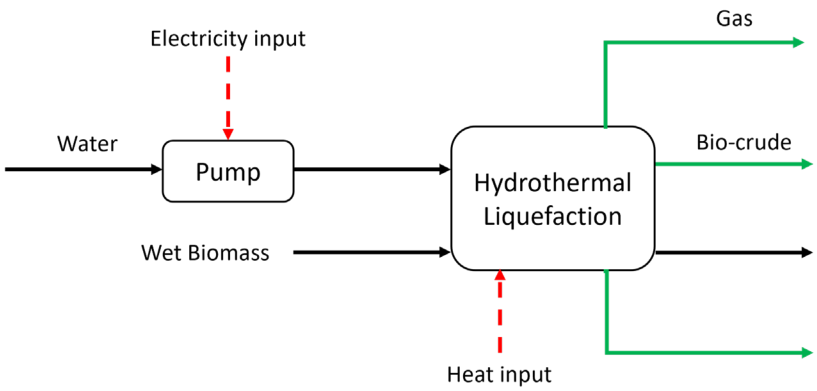


Figure 7: Simplified process flow diagram for HTL.

Hydrothermal Liquefaction (HTL)

Hydrothermal liquefaction (HTL) is another thermo-chemical process that occurs at moderate temperatures (250-500°C), and with high pressure (5–20 MPa). However, the pressure required is still lower than the one used for SCWG since water in these conditions is still subcritical. This conversion method provides the advantage that there is no need to dry the feedstock, thereby reducing the energy input. In general, this process can be completed within a relatively brief timeframe (5–120 min), and it can yield a diverse range of outcomes. The primary products obtained from HTL are gas, char, bio-crude, and an aqueous phase extract. In HTL, biomass undergoes depolymerization and decomposition in a subcritical water environment, breaking down complex organic polymers such as cellulose, hemicellulose, and lignin into smaller, more energy-dense molecules.

Pugh Matrix Comparison of Technologies

The Pugh Matrix, also known as the decision Matrix, is a systematic tool employed in engineering and project management to evaluate and compare multiple alternatives against a set of criteria. This structured decision-making technique provides a quantitative and visual framework for objectively assessing the relative merits of various options [2]. Table 1 provides a simplified comparison of the various biomass-to-energy conversion concepts.

Table 1: Pugh Matrix for comparison of the various biomass to energy conversion technologies.

Criteria	Combustion	AD	Pyrolysis	Gasification	SCWG	HTL
Process Conditions		+		-	-	-
Residence Time	+	-	+	+	+	
Efficiency	-	-			+	+
CAPEX	+				-	-
TRL	+	+		+	-	-

- <u>Process Conditions:</u> AD process requires very low temperatures, liquefaction occurs at moderate temperatures (250°C to 500°C), while SCWG, pyrolysis, gasification, and combustion can require temperatures from 500–1300°C. Most of these processes can take place at normal atmospheric pressure except for SCWG (>22 MPa) and liquefaction (5-20 MPa).

- Residence Time: All processes can occur quickly, unlike AD, which takes at least few weeks.

- Efficiency: The percentage of biomass feedstock that can be converted to energy was used to classify these processes. Combustion and AD have low efficiency compared to SCWG, pyrolysis, and gasification, which are highly efficient. This was determined from literature.

- CAPEX: Typically, building a plant involves significant costs. SCWG and liquefaction processes are considered to be more expensive as compared to other technologies since they require extreme conditions (elevated temperatures and pressures) as compared to other processes which operate at atmospheric conditions.

This is a simplified example for comparing the various technologies as explained in the earlier sections. Such a matrix was developed for most of the case studies based on the needs and specifications of the various stakeholders. The most interesting technologies were then identified for modelling in ASPEN and further evaluation.

3. Powering the agri-food value chain

Energy and food systems are closely connected, with around 30% of the world's energy being used in food production and distribution. This energy use accounts for a third of the greenhouse gas emissions from food systems. In these case studies, we aimed to propose sustainable solutions to meet the increasing demands of various agrifood processes. We discovered that these processes typically generate a biomass by-product, often used for non-energetic purposes such as fertilizer or animal feed. We identified an opportunity to repurpose this biomass by-product for internal energy production and use, potentially reducing energy expenses and enhancing the overall sustainability of the process.

Case Background and Motivation

This research was made in collaboration with Royal Cosun, a Dutch agro-industrial cooperative that stands as a prominent player in the global food and natural ingredients sector, with a commitment to sustainability and innovation. This research aims to determine how to offset the energy demand of the Royal Cosun using one of their current by-products, while considering the associated costs, the technology readiness level, and the overall environmental impact of the various biomass-to energy process concepts (as elucidated in chapter 2).

Due to reasons of confidentiality, not all results for the case study have been disclosed. However, they can be made available upon reasonable request. Please contact the corresponding author for further information.

Research Methodology

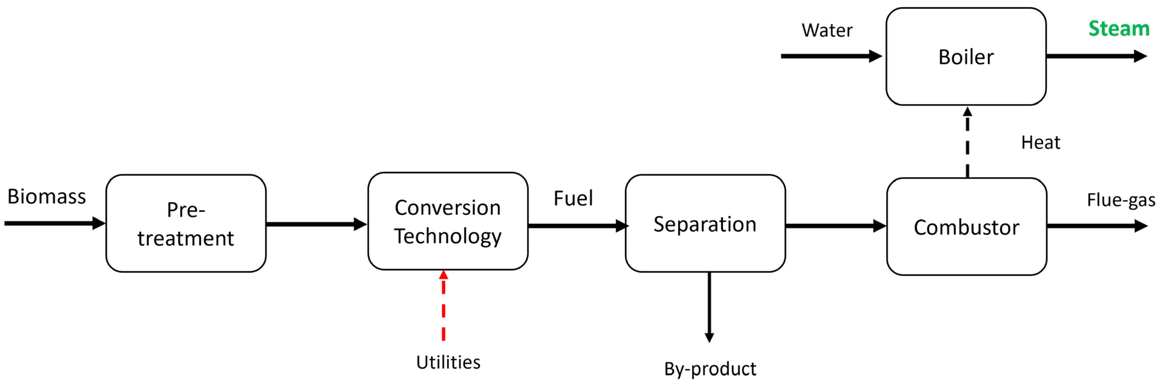


Figure 8: A generalised process block diagram (PBD) for the considered technologies for the Cosun case study.

The first step of this research was to conduct a literature survey to identify various biomass-to-energy conversion technologies. This resulted in 9 different technologies, which were then compared through a Pugh matrix, based on Cosun's needs and requirements (similar to one provided in section 2.6). Four technologies; namely steam gasification, super-critical water gasification, anaerobic digestion, and combustion; were identified from the Pugh matrix to be interest to Cosun. To compare the efficacy of the models, the produced fuel is burnt to produce steam to be used internally within the Cosun process. A generalised PBD for all the technologies is provided in Figure 8. For combustion, instead of the conversion technology block the biomass is directly sent to the combustor from the pre-treatment block (cf. Figure 8).

For every technology, a process flow diagram (PFD) was developed depicting the various stages of process (handling, pre-treatment, conversion, and utilisation). Aspen Plus was used to model the technology specific PFD. All the input parameters used in this model such as temperatures, pressures, and reaction kinetics were based on literature values. The individual models were then validated by literature data and then run for the Cosun feedstock. This was followed by heat integration and optimization studies, to maximize the energy yields and process efficiency. A sensitivity analysis was undertaken to evaluate the impact of variation in key parameters. The fuel produced from the biomass was utilised to produce steam. The technologies were compared to each other based on two parameters: system efficiency (η_{eff}) and steam-to-biomass ratio (STBR), which are defined as follows.

$$\eta_{eff} = \frac{Q_{steam}}{W_{in} + Q_{in} + (m_{BM} * HHV_{BM})}$$

$$STBR = \frac{m_{steam}}{m_{BM}}$$

Here, the heat duty (Q_{steam}) refers to the heat obtained from the produced steam; W_{in} and Q_{in} are work and heat input for the process and m_{BM} and HHV_{BM} are the mass flow rate and higher heating value of the biomass feedstock. m_{steam} is the amount of steam produced from the biomass feedstock at the required conditions.

Following the process modelling, a techno-economic analysis was undertaken to evaluate the economic feasibility of the technologies. Since, the fuel produced from biomass by-product the feedstock costs were assumed to be zero.

Furthermore, since the fuel was used internally to produce steam; the revenue was assumed to be savings in natural gas cost required for equivalent steam production. The life-time for the plant was considered to be 10 years.

A simplified sustainability comparison was also performed for all the models. It was assumed that the emissions from the combustion of feedstock-based fuels are net-zero, since the CO_2 captured via photo-synthesis is cycled back to the environment. The CO_2 emissions are primarily due to the utilities (assumed to be electricity) required for each model, the CO_2 emission savings are due to the natural gas saved for producing equivalent amount of steam.

Results

The results of the technical and economic performance of the four modelled processes are provided in Figure 9 and Figure 10 respectively. From the technical performance it can be seen that SCWG has the highest energy efficiency and STBR ratio, while combustion has the lowest STBR ratio. The efficiencies of SCWG and gasification are quite similar but there is a large difference in the corresponding STBR ratios. Conversely, anaerobic digestion and combustion have similar efficiencies and STBR ratios.

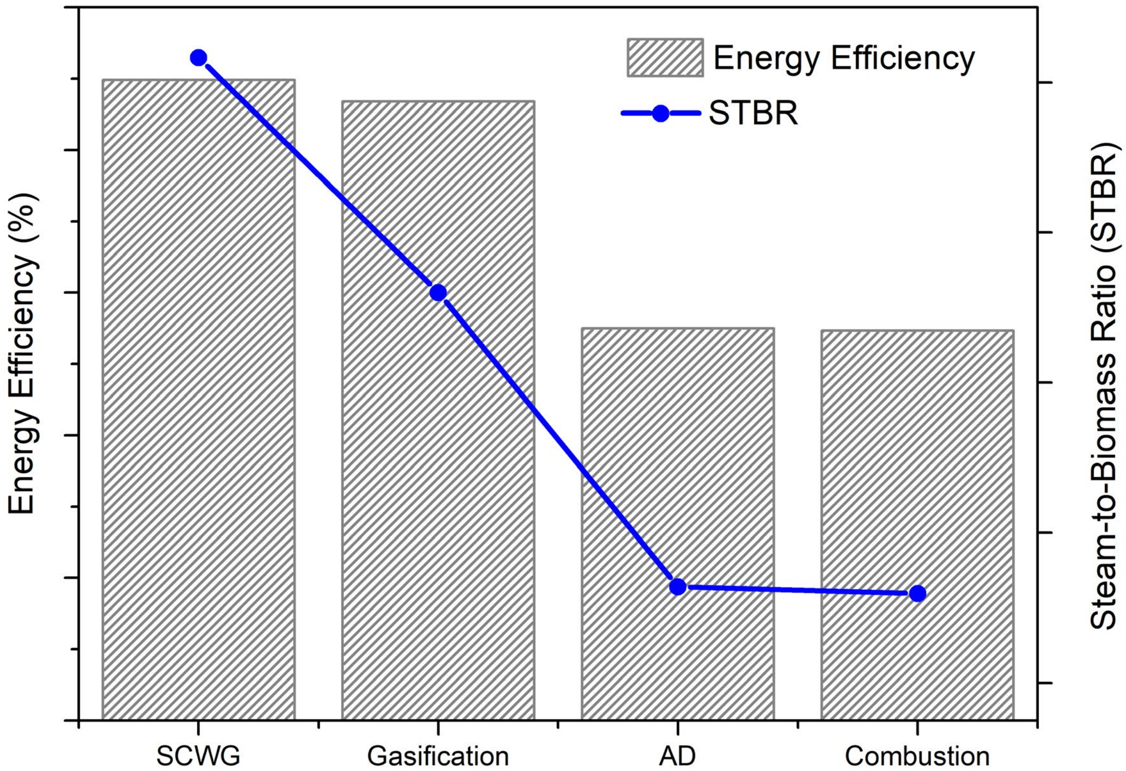


Figure 9: Comparison of the four modelled process technologies on technical parameters namely energy efficiency and steam-to-biomass ratio (STBR).

The economic comparison however tells a different story. Albeit SCWG does well on technical parameters; it has the highest CAPEX and OPEX costs amongst the four models. On the other hand, combustion had the lowest technical indicators (STBR), but it also has the lowest OPEX among the four with considerable CAPEX. Hence, it has the lowest NPV among the four. In the four models, gasification has the highest NPV and the best combined technical and economic parameters. This is predominantly because of having a low CAPEX in comparison to a high STBR ratio. Hence, it also has the highest IRR.

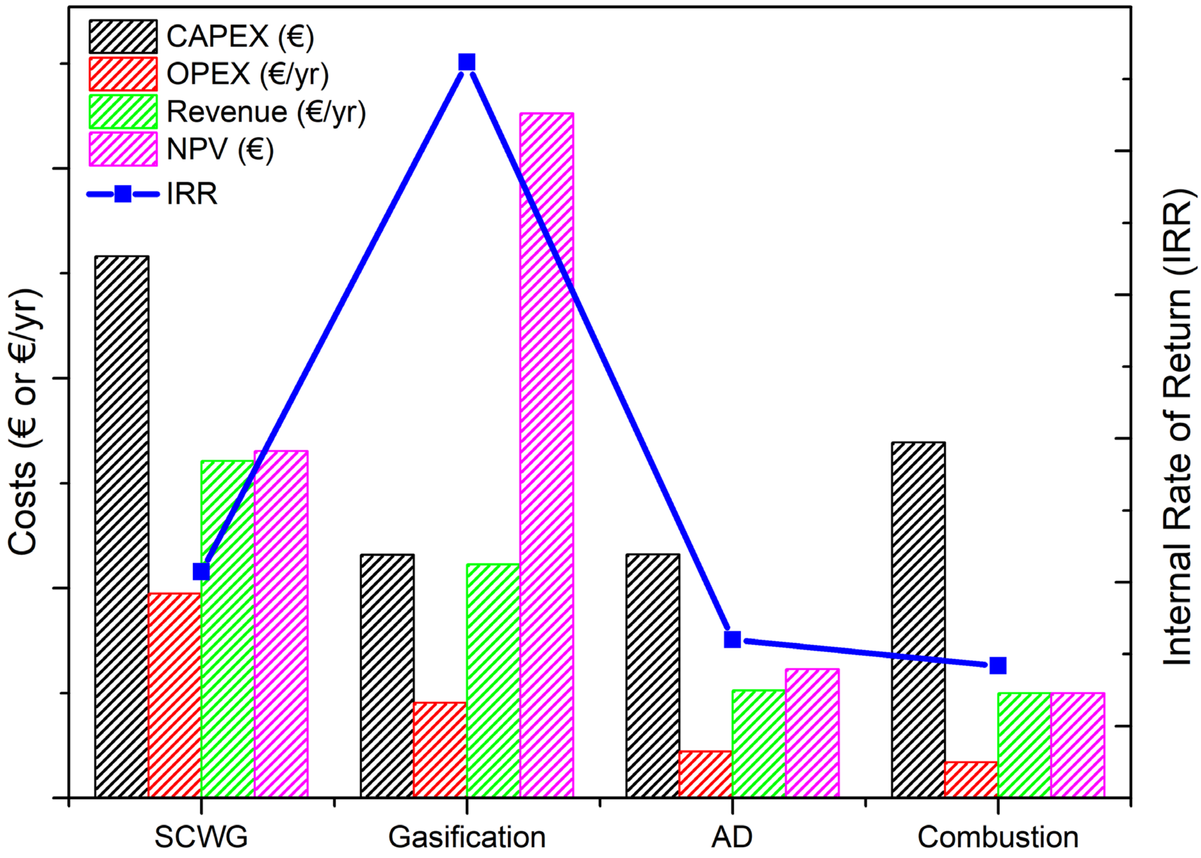


Figure 10: Comparison of the four modelled process technologies on economic parameters namely CAPEX, OPEX, revenue, net-present value (NPV), and internal rate of return (IRR).

The sustainability comparison tells a different story. It can be seen that the net emissions saved is the lowest for the SCWG and the highest is for the combustion. This is predominantly because of the variation in the utilities required. Gasification has the next best emission savings predominantly due to a high STBR ratio (leading to high natural gas savings).

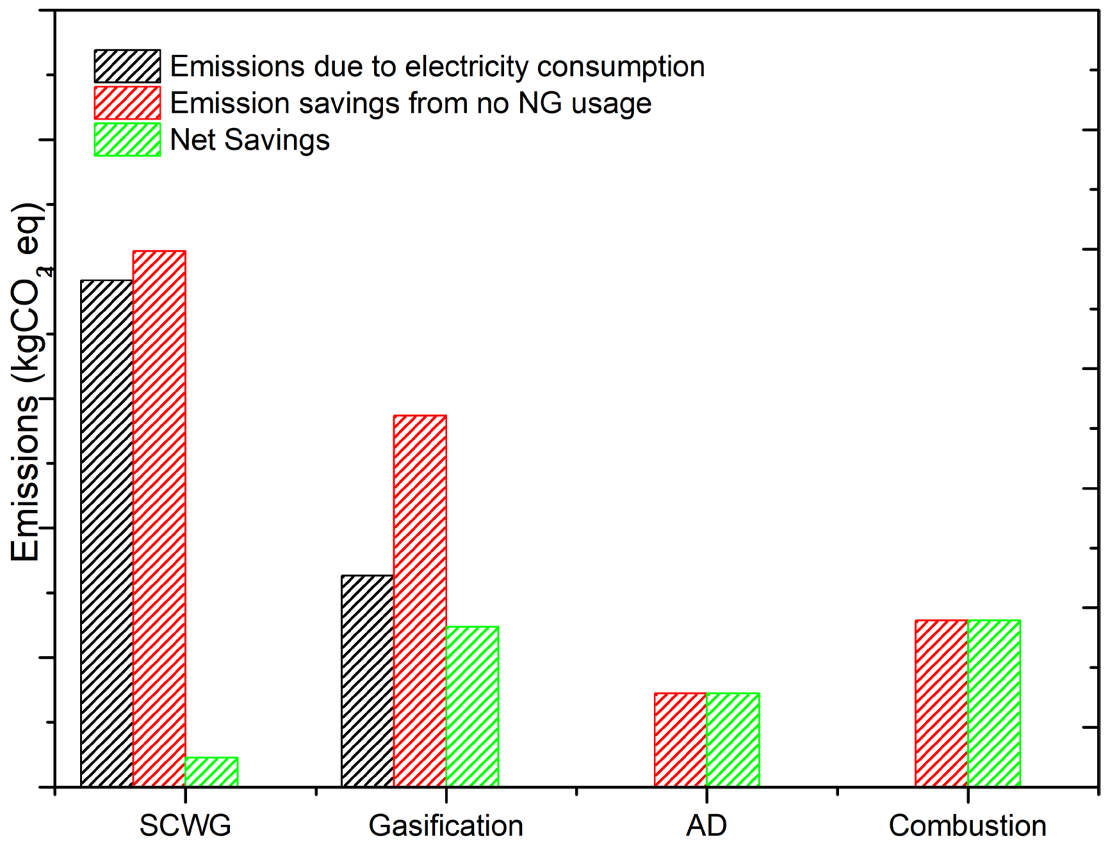


Figure 11: Comparison of the four modelled process technologies on sustainability parameters.

Key Take-aways

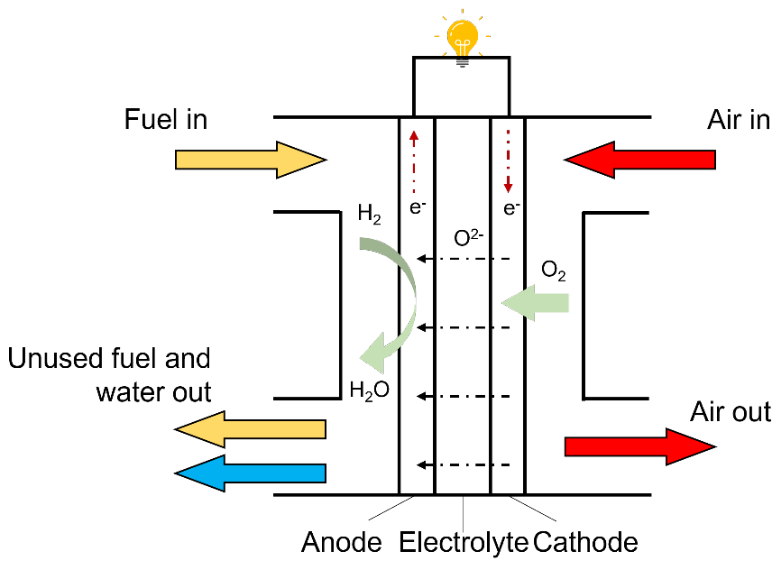
- *Among the four technologies, only two have high efficiency namely SCWG and gasification.*
- *However, from techno-economic analysis it was identified that all the four technologies modelled are economically viable in the current scenario of high natural gas prices.*
- *Gasification has the highest IRR among the four models, which is predominantly due to its low CAPEX.*
- *Combustion and AD have low NPV due to the low STBR.*
- *Combustion depicted a higher CO_2 emission saving compared to the other models.*

4. AD-SOFC as stand-alone utility generation systems

Biogas–produced by the anaerobic digestion of biomass–is a clean, renewable, and under-utilized source of energy. The gas produced is similar to natural gas, with a composition of 50-70% methane, which can be converted using conventional energy conversion devices, often CHP (convention heat & power systems), to provide energy-efficient waste management solutions [1]. Typically, the electrical efficiency of these devices is 30-40%. Solid-oxide fuel cells (SOFCs) are alternative devices that offer higher electrical efficiency (50-60%) and high temperature residual heat [2]. This work analyses the application of such AD-SOFC systems as stand-alone utility providing systems. A brief explanation of the working principle of SOFCs is provided below.

Two separate cases were analysed to understand the efficacy of such AD-SOFC systems [3], [4]. The results of these case studies are currently being reviewed for a peer-reviewed publication. Hence, not all details have been shared in this white paper. However, they can be made available upon reasonable request. Please contact the corresponding author for further information.

Solid Oxide Fuel Cells (SOFCs)



Cathode: $O_2 + 4e^- \rightarrow 2O^{2-}$

Anode: $2H_2 + 2O^{2-} \rightarrow 2H_2O + 4e^-$

Overall: $2H_2 + O_2 \rightarrow 2H_2O$

Figure 12: Schematic overview of SOFC with half reactions.

SOFCs are electrochemical devices that convert the chemical energy of fuels to electricity and heat. They can achieve higher efficiencies than combustion-based systems constrained by Carnot cycle. A solid oxide cell comprises of – a porous anode, a solid ceramic electrolyte membrane, and a porous cathode electrode. The half-cell electrochemical reactions occurring at electrodes are provided in Figure 12. These cells typically operate at high temperatures (700-1000°C). Contrary to other fuel cells which only operate on H_2; solid oxide cells can handle different fuels. This is due to two reasons – 1) the high operating temperature of SOFC allow reforming reactions of complex hydrocarbons (e.g., biogas) to occur, and 2) SOFC's conduct oxide ions (O^{2-}); which enable the oxidation of both H_2 and CO. This makes SOFC an apt candidate to be paired with an AD for gamut of applications.

Tri-generation system for hospitals in South Africa

Case Background and Motivation

The power grid in South Africa is experiencing severe disruptions, with power outages lasting up to 12 hours a day. This situation is particularly dire for public buildings such as hospitals; which require a continuous supply of cooling, heat and power (CCHP) for various life-saving equipment. Presently, fossil fuel-based generators are being used to overcome these power disruptions. However, these systems have huge financial and ecological repercussions. In order to achieve the climate goals, it is pertinent that stand-alone generation solutions are developed that can rapidly reduce greenhouse gas emissions at acceptable costs and risks. An opportunity was identified wherein biomass, waste water, and other organic waste sources, can be used to produce biogas using an anaerobic digestor provided by iRCB Biogas. The produced biogas can then be used to provide the CCHP requirements of a hospital using a SOFC. Consequently, the research aims to model a tri-generation biogas-SOFC system for hospitals in South Africa and optimize this system based on its thermodynamic properties.

Research Methodology

Most hospitals in the South African public sector are categorized as district-level institutions. These types of hospitals have an average capacity of 131 beds and 20 surgical beds. The energy requirements for tri-generation were estimated to be (peak demand): electricity 390 kW, space cooling 245 kW, water heating 70 kW, and space heating 45 kW [5].

Initially, an SOFC model was developed in Aspen Plus software, based on the parameters provided by Hauck et al. [6]. This SOFC model was first validated with experimental data provided by Kazempoor et al. [7], for a fuel comprising of equimolar amounts of H_2, CO, CO_2, and H_2O. The validation is provided in Figure 13. The model follows the same trendline as experimental data, however it overestimated the voltages at higher current densities.

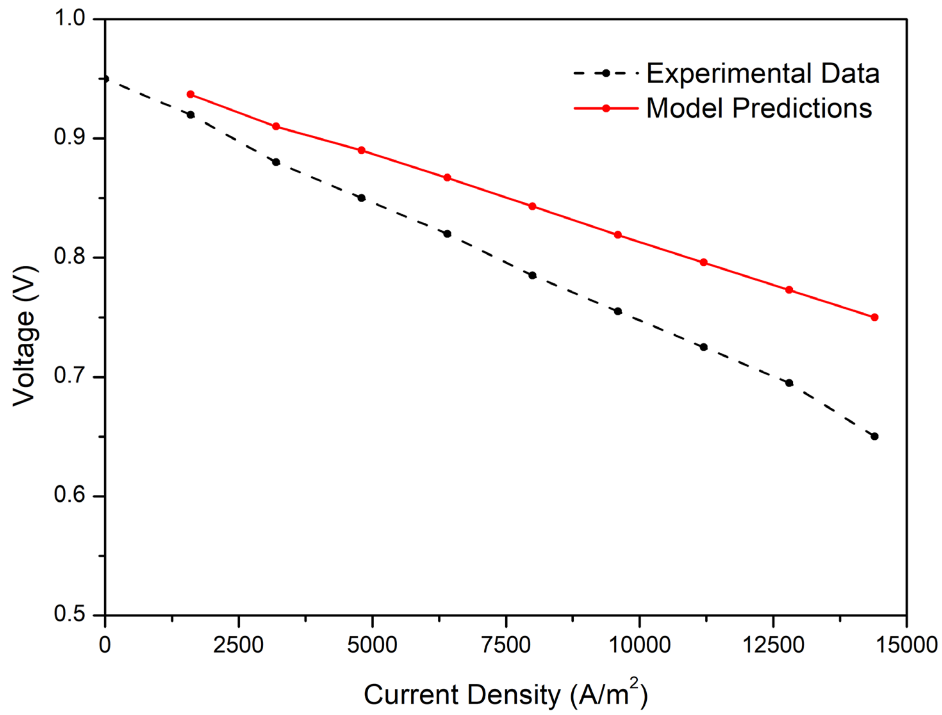


Figure 13: SOFC I-V curve for validation.

Following this a system model for a biogas fueled SOFC tri-generation system was simulated in Aspen Plus software to estimate the material and energy balances. The composition of biogas was provided by iRCB Biogas– a company currently developing a novel digestor design for various applications. Since the SOFC operates on biogas, it needs to be cleaned of pollutants such as H_2S; which is done in a cleaning unit. Also, a reformer in some amount of the biogas is pre-reformed are required. This is done to avoid high thermal gradients in the SOFC and thus extend the life of the SOFC.

Various process options are available to facilitate the three types of demand as indicated in Figure 14. Hence, four different process models were developed which varied in the downstream process line-up after the SOFC, as indicated in Figure 14. These models were compared on the basis of the system energy efficiency and exergy efficiency to identify the superior configuration. The definitions for energy and exergy efficiency are provided below.

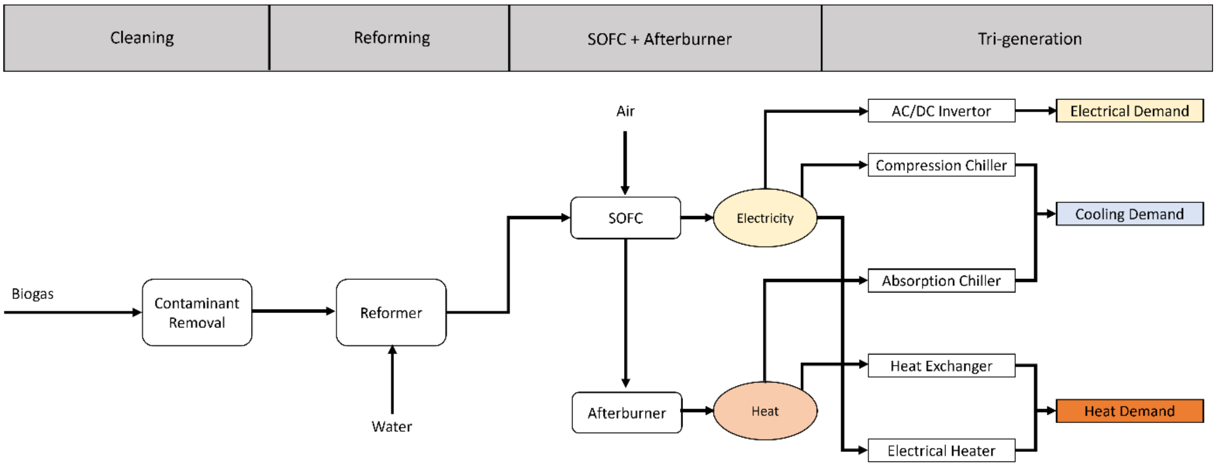


Figure 14: Various process options for a biogas-fueled SOFC tri-generation system.

$$\eta_{energy} = \frac{P_{net} + Q_{cooling\ cycle} + Q_{hot\ water}}{(LHV_{BG} * \dot{m}_{BG}) + W_{in}}$$

$$\eta_{exergy} = \frac{P_{net} + Ex_{cooling\ cycle} + Ex_{hot\ water}}{\Sigma Ex_{BG} + W_{in}}$$

Here P_{net} refers to the net electric power delivered by the SOFC, $Q_{cooling}$ and $Ex_{cooling}$ is the cooling duty and exergy provided by the cooling cycle; $Q_{hot\ water}$ and $Ex_{hot\ water}$ is defined similarly for the hot water. LHV_{BG} and $\dot{m}_{BG}$ are the lower heating value and inlet flow rate of the biogas. ΣEx_{BG} is the sum of chemical and physical exergy of the inlet biogas; while W_{in} is the supply of additional utilities after heat integration.

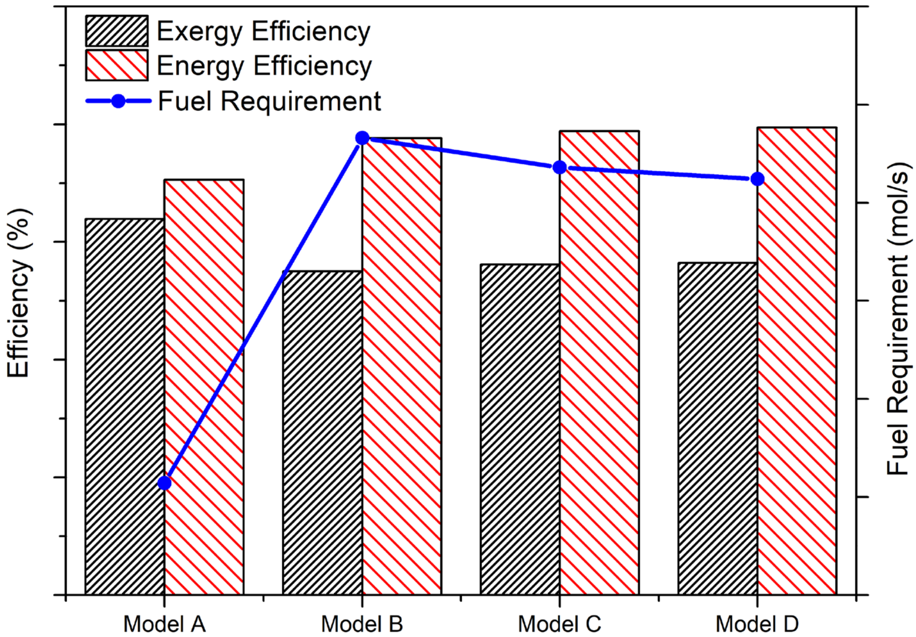


Figure 15: Comparison of energy efficiency, exergy efficiency and fuel requirements for the models.

Results

The results for the four configurations are summarized in Figure 15. It can be seen that model A has a higher exergy efficiency than compared to the other three models, which have a similar exergy efficiency. On the other hand, model A has a lower energy efficiency compared to the other three models. Model A requires the least amount of biogas to provide the same tri-generation capacities as compared to the other models.

Key Take-aways

- *The designed AD-SOFC system can adequately cater to the various utility requirements for a hospital.*
- *Multiple system configurations with different down-stream processes were modelled in Aspen Plus. All models depicted a high energy and exergy efficiency.*
- *Among all models, model A has the highest exergy efficiency by 9 pp (percentage points) as compared to other models and a lower biogas requirement by 11%. Hence model A was identified to be the best configuration.*
- *On the other hand, model A had a lower energy efficiency by 5 pp. This depicts that exergy efficiency is better metric than energy efficiency for the evaluation of tri-generation systems.*
- *A techno-economic study is planned to further evaluate the economic viability of such systems.*

Stand-alone electricity generation system for Africa

Case Background and Motivation

In 2021, around 43% of the population of Africa – ~600 million people, still lacked access to electricity. Of these around 80% of the people live in rural areas. Currently, settlements along existing main grids are often connected to them; while stand-alone systems provide electricity access in low demand rural areas. These stand-alone systems are based either on diesel or gasoline generators, which make them environmentally unsustainable [8]. A study estimated that the total methane production potential from available feedstocks in sub-Saharan Africa is 26 billion m^3 (~270 TWh). This underscores the importance of encouraging communities in Africa to harness this organic waste resource to improve local energy supply [9]. The present case study analyses the application of an AD-SOFC off-grid electricity production system for rural Africa.

Research Methodology

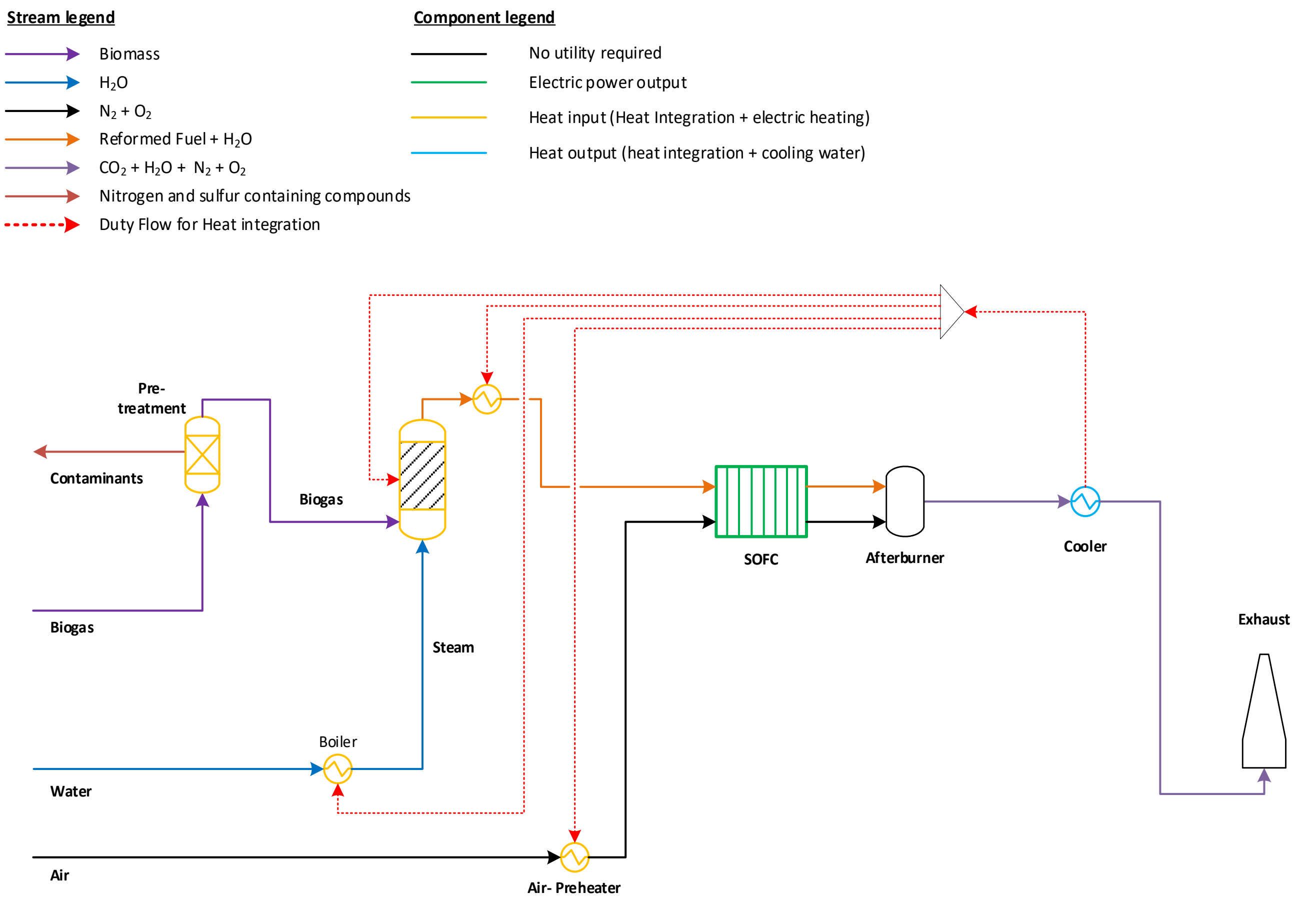


Figure 16: Process flow diagram (PFD) of the proposed biogas fueled SOFC system.

A system model for a biogas fueled SOFC system was simulated in Aspen Plus software to estimate the material and energy balances. The same SOFC model was used as explained in the previous case study. Figure 16 depicts the PFD of the biogas fueled SOFC model as developed on Aspen Plus. For simplified operation the overall system was developed to operate at atmospheric pressure. The biogas is first cleaned to remove pollutants such as H_2S, after which the biogas enters a reformer. Here, steam was used as the reforming medium to avoid coke deposition. The amount of steam supplied to the reformed was determined by a parameter called as steam-to-carbon ratio (STCR). The temperature of the reformer was varied as per the external reforming ratio (RR). The definitions of these ratios are provided below. Here, $\dot{m}_{carbon-in}$ refers to the flow rate of carbon in the biogas, while $\dot{m}_{steam}$ refers to the flow rate of steam in the reformer. $\dot{m}_{CH4}^{in}$ and $\dot{m}_{CH4}^{out}$ are the input and output molar flow rates of methane to and from the reformer.

$$STCR = \frac{\dot{m}_{steam}}{\dot{m}_{carbon-in}}$$

$$RR = 1 - \frac{\dot{m}_{CH4}^{out}}{\dot{m}_{CH4}^{in}}$$

After the external reformer, the fuel enters the SOFC. The fuel utilization in the SOFC is typically < 90%. Hence, the balance fuel and hot air exiting the SOFC were sent to an afterburner. The heat from the flue gas was used for heat integration. A sensitivity analysis was conducted on various parameters such as fuel utilization, temperature, steam-to-carbon ratio (STCR), and external reforming ratio. This was done to identify the most optimum operating points based on energy and exergy efficiency with respect to various parameters. Following this, a techno-economic estimation was done and compared to a diesel based combined heat and power (CHP) system to ascertain the economic viability of the system.

Results

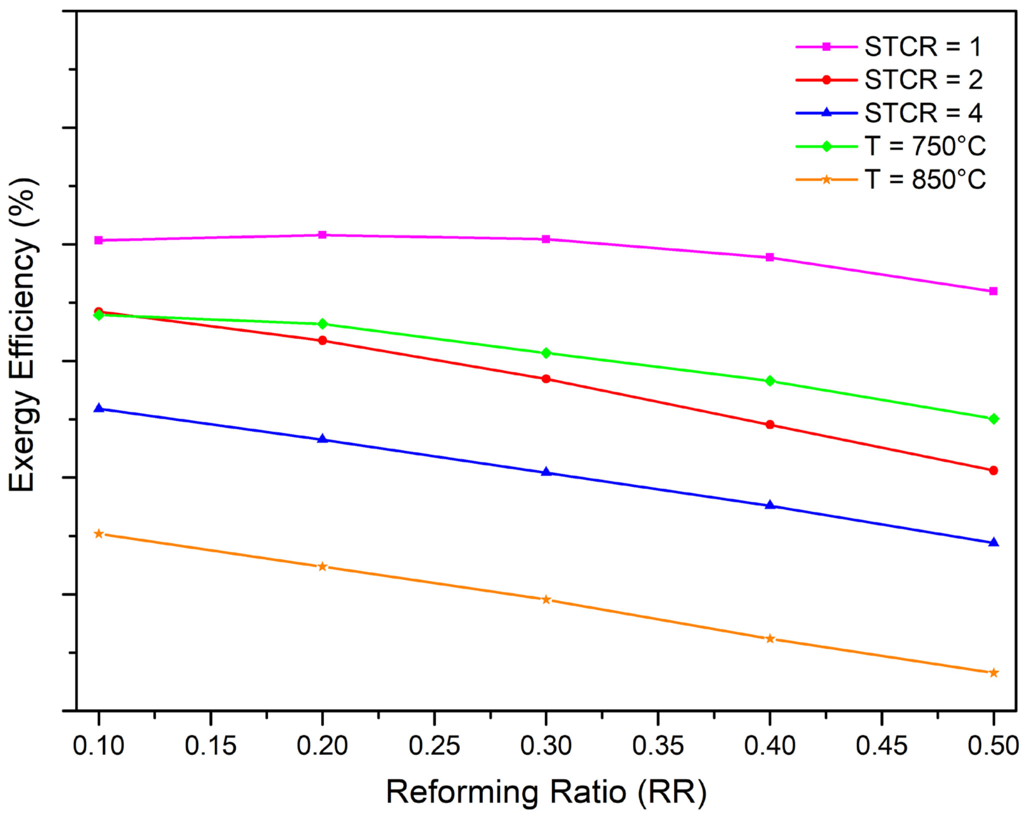


Figure 17: Influence of STCR, RR, and temperature on the exergy efficiency of the system. The STCR is varied at the SOFC temperature of 700°C.

The sensitivity analysis was undertaken to analyze the effect of various parameters on the exergy efficiency. Here, the exergy efficiency was defined as;

$$\eta_{exergy} = \frac{P_{net}}{\Sigma Ex_{BG} + W_{in}}$$

where ΣEx_{BG} is the sum of chemical and physical exergy of the inlet biogas, W_{in} is the supply of additional utilities after heat integration, and P_{net} is the net power delivered by the SOFC. Some results of the sensitivity analysis are provided in the figure below Figure 17.The figure depicts the influence of three parameters – RR, STCR, and SOFC temperature on the exergy efficiency. It can be seen that and increase in RR, STCR and temperature leads to a reduction in exergy efficiency. Among these, as seen from the figure the temperature of operation and STCR has the highest effect on the overall efficiency.

After optimization and heat integration of the process, the SOFC system had an efficiency of 22 pp (percentage points) higher than a CHP system. It was estimated that from the same amount of biogas, an SOFC system can deliver 52.8% more electricity compared to a conventional CHP system.

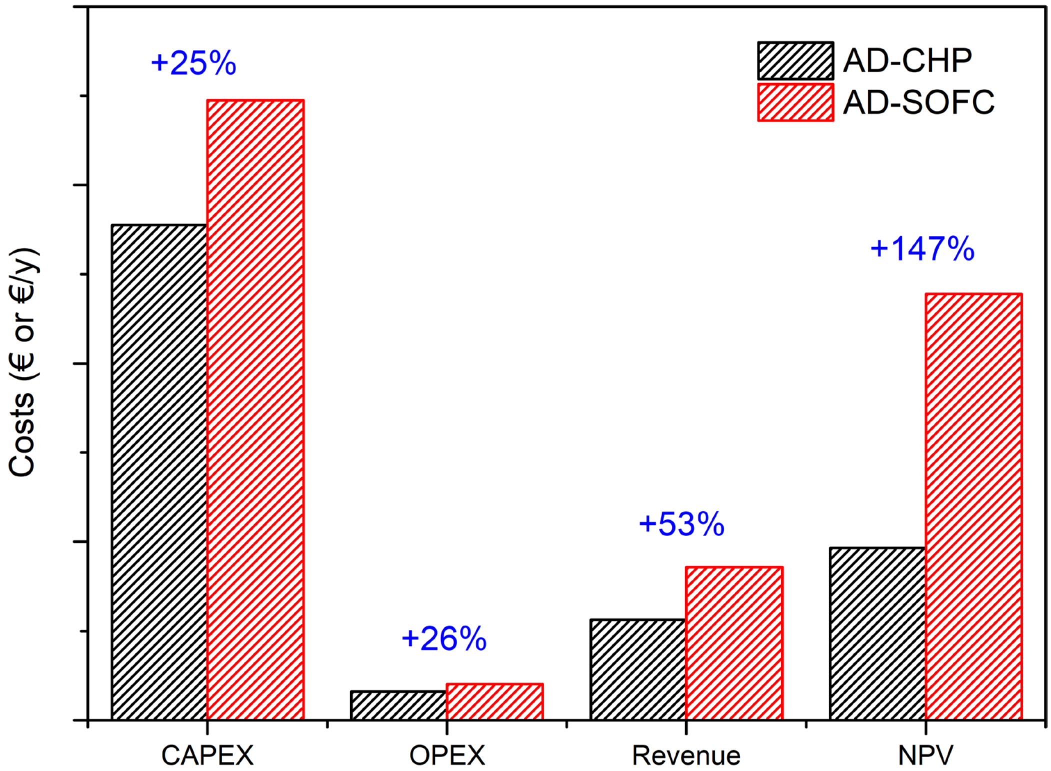


Figure 18: Comparison of techno-economic results for AD-CHP and AD-SOFC systems.

A techno-economic evaluation was developed for an AD-CHP system and an AD-SOFC system based on the results of the Aspen model. The lifetime of the plant was considered to be 10 years and the discount rate was assumed to be 3%. The SOFC stack lifetime was considered to be 5 years. Considering a biomass feedstock price of 40 $/ton; the Levelized Cost of Electricity (LCOE) for the CHP system was 40% higher than the SOFC system. The summarized results are provided in Figure 18. Sensitivity analysis of all parameters indicated that feedstock price of biomass and the selling price of electricity has the highest effect on the economic indicators of the process. The AD-SOFC system had a payback period of 6 years compared to 8 years for the AD-CHP system.

Key Take-aways

- *The AD-SOFC model had a higher energy efficiency compared to the AD-CHP model by around 30%.*
- *It was estimated that the smallest bio-reactor coupled with the SOFC is capable of producing enough electricity to cater to the needs of a village of 100 households.*
- *An AD-SOFC system had a higher NPV and lower payback period than an AD-CHP system. The payback period is still more than 5 years, but it is assuming significant feedstock costs.*
- *Thus, it can be concluded that an AD-SOFC system is a viable option to produce off-grid in Africa.*

5. Hydrogen production from biomass

Worldwide, agriculture is responsible for 17% of all greenhouse gas emissions. These emissions come from land-use change through deforestation, enteric fermentation from ruminant animals, fertilizer use, and crop residue, among others. Together, the agricultural emissions of Indonesia, Brazil, and India make up 30% of worldwide agricultural emissions. India, in particular, is the single largest emitter of non-CO_2 emissions associated with crops and livestock [10].

India is the world's third-largest consumer of energy [11]. Moreover, among the world's biggest markets, India has the fastest-growing renewable power capacity [12]. To complement the growth in renewable energy, the country launched a National Hydrogen Mission in 2020 with the ambition of making India a hydrogen hub. Producing hydrogen from the residual biomass would help India meet its goal of becoming a hydrogen hub by harnessing the energy in this waste, avoiding its inappropriate disposal, and replacing dirtier energy sources with more environmentally friendly ones.

Case Background and Motivation

Kerala is a state of India, which is situated on the south-west coast of India. Kerala has a large water network comprising of backwaters, and small rivers originating from the mountain terrains (Western Ghats). The presence of a large number of rivers has made Kerala rich in water resources, which are being harnessed for power generation (dams) and irrigation. Since the past few years' incidence of floods in the state is becoming more frequent and severe making the operation of these dams very difficult. Hence, predominantly the state has a large reliance on fossil fuels.

An opportunity was identified wherein the biomass sources within the state can be used to generate hydrogen use thermochemical conversion methods (as elucidated in chapter 2). This will help in reducing the reliance of the state on fossil fuels and improve the flooding problems. This research seeks to investigate the viability of using biomass for hydrogen production in Kerala, India [13]. This study was developed in cooperation of the Kerala Re-imagined initiative by Biosfera foundation, which seeks to mitigate the near-yearly floods in Kerala. The results of this are currently being reviewed for a peer-reviewed publication. Hence, not all details have been shared in this white paper.

However, they can be made available upon reasonable request. Please contact the corresponding author for further information.

Research Methodology

Initially a societal analysis was conducted which included – compiling the biomass availability in the district of Kottayam. This was followed by undertaking a PESTEL analysis which contextualized the environment in which the technologies are planned to be implemented. Finally, an analysis of the relationship between the project and the UN Sustainable Development Goals (SDG’s) was carried out.

Part II of the analysis consisted of process modelling to estimate hydrogen production efficiency and emissions. Two conversion processes – pyrolysis and gasification were modelled in Aspen Plus. The feedstock for these processes was based on the biomass available in Kerala – a mixture of rubberwood, coffee trimmings and coconut leaves. A generalized PBD is represented in Figure 19. For every individual model configuration, heat integration was undertaken, and four calculations were conducted: the stream results and sensitivity analysis, the efficiency of hydrogen production, the potential production of electricity from SOFC, and the emissions reduced. For both pyrolysis and gasification, the effect of addition of water gas shift reaction was also identified.

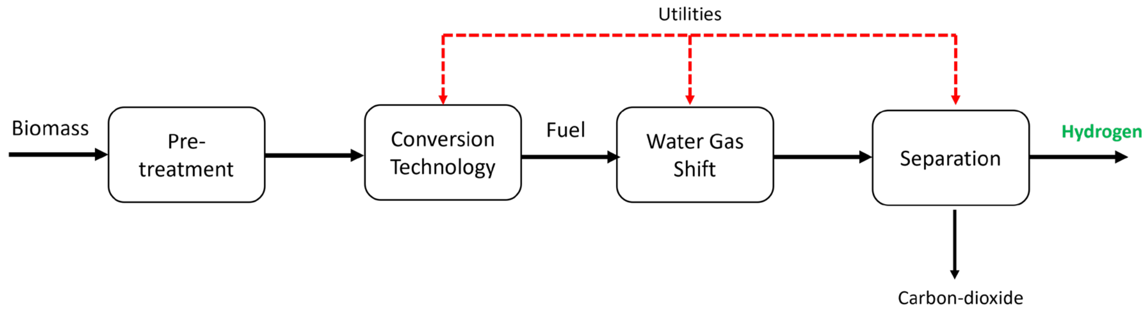


Figure 19: A generalised process block diagram for hydrogen generation from biomass in Kerala.

A simplified sustainability comparison was also performed for all the models. The CO_2 emissions are primarily due to the utilities (assumed to be electricity) required for each model, while the CO_2 emission savings are due to the replacement of grey-hydrogen with bio-hydrogen and the solid coke formed during the process.

Societal Analysis Results

The total biomass availability in Kerala was estimated to be 2.25 Mton/yr., with major crops being rice, coconut fronds and rubberwood. The societal analysis highlighted that the development of biomass-based hydrogen had the potential to be highly beneficial for Kerala, since it could provide additional green energy and flexibility to the system while decreasing unemployment. Notably, Kerala's unemployment is especially marked among the educated. Many biomass conversion technologies, including those investigated in this study, require high-skilled labor.

However, it was identified that the implementation of this initiative was largely threatened by the non-participation of people. This was primarily because farmers are less flexible to experimentation and under the stress of debts and loans resort to burning of biomass [14]. In order to combat non-participation from lack of time or resources, to implement such technologies, farmers need support and reassurance, including logistical, technological, and financial assistance. Therefore, any plan proposed must be context-specific, innovative, and inclusive.

Figure 20: Identified co-relations between the PESTEL analysis aspects and the Sustainable Development Goals (SDGs) by the UN [13].

Through the PESTEL analysis (cf. Figure 20), several bilateral relationships were found between this case study and UN sustainable development goals (SDG's). This case study was found to correlate most strongly with goal 7 (affordable and clean energy) and 10 (reduced inequalities). Inequality is a major threat to implementation, as it could lead to distrust and jeopardize participation.

Increasing income for farmers and increased status by employment could reduce social inequalities.

Technical Analysis Results

The main results of the process modelling are provided in Figure 21. Here the efficiency is defined as:

$$\eta_{en} = \frac{LHV_{H2} * \dot{m}_{H2}}{(LHV_{BM} * \dot{m}_{BM}) + W_{in}}$$

where LHV_{H2} and LHV_{BM} are the lower heating value of hydrogen and biomass, $\dot{m}_{H2}$ the hydrogen mass flow, $\dot{m}_{BM}$ the biomass mass flow after drying, and W_{in} the energy consumed per hour by the process.

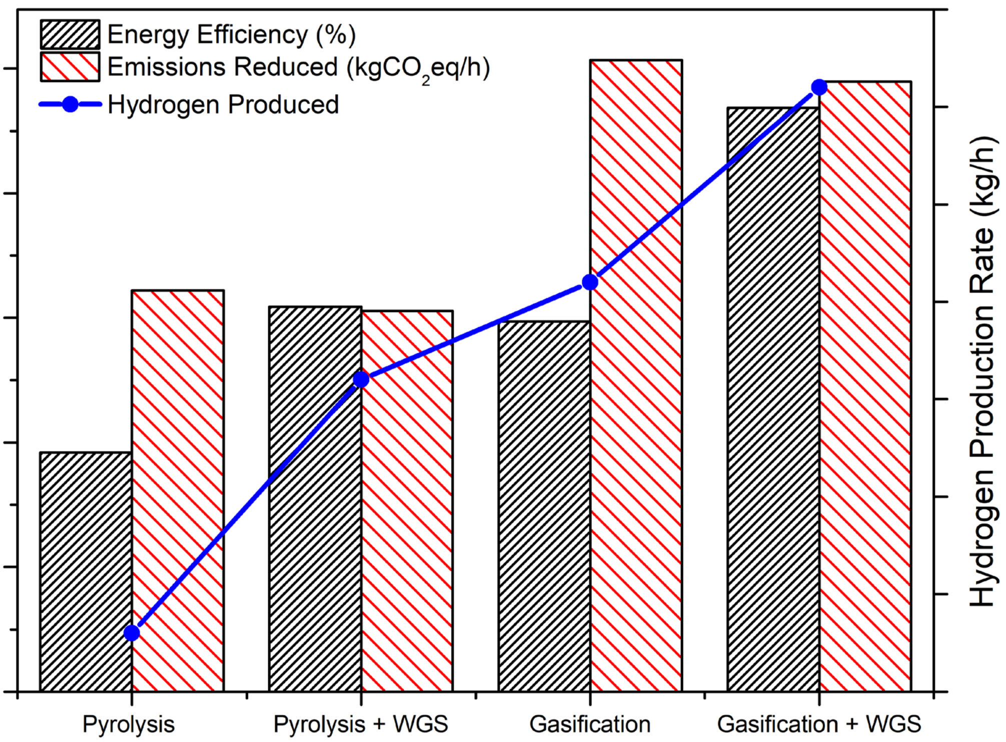


Figure 21: Comparison of energy efficiency, emission reduction and the hydrogen production rate for the four modelled configurations.

Gasification + WGS has the highest process efficiency for hydrogen production; while only gasification has the highest emission reduction possible. Hence, considering both the parameters gasification is better than pyrolysis. Inclusion of WGS leads to a higher efficiency and hydrogen production rate for both the models. However, the opposite can be said with respect to the emission reductions. This is primarily because inclusion of WGS requires additional utilities which have an emission.

Hydrogen can be used for electricity production. Fuel cells are an attractive option for hydrogen production due to the high achievable efficiency of around 60% (as seen in chapter 4). The produced hydrogen can be used for electricity production through a fuel cell. The back-of-envelope calculations show that if all of Kerala's biomass availability is used for hydrogen-to-electricity production, it can compensate up to 30% of the state's own hydropower production.

Key Take-aways

- *The societal approach highlighted that the production of hydrogen from biomass will lead to overall benefit to the state of Kerala particularly in reducing the reliance on fossil fuels and decreasing the unemployment in the region.*
- *The technological approach sought to compare two mature technologies – pyrolysis and gasification, in terms of their hydrogen production efficiencies and emissions reduction. Upon comparing the optimised models for both the technologies it was seen that gasification had a better efficiency, hydrogen production rate and emission reductions compared to pyrolysis.*
- *Inclusion of WGS for every model depicted displayed higher efficiency and hydrogen flow rate. However, including no WGS showed higher emissions reductions.*
- *From back-of-the-envelope calculations it was identified that if all the biomass from Kerala was converted to hydrogen and then used for electricity production, it can compensate ~30% of the total electricity demand of Kerala.*

6. Learnings from the case studies

The following chapter summarizes the essential learning for the various case studies analyzed in this project. These are provided in the section below. Since the consortium was formed by predominantly Dutch stakeholders, an outlook for biomass in the Dutch energy context is provided further.

Conclusions

- *Process modelling is a powerful tool for evaluating emerging biomass-related technologies. These process models can also be used as a stepping stone for conducting techno-economic assessments or life cycle studies; providing insights into the economic viability and sustainability of these technologies.*

- *Although various organic feedstocks are generally classified as biomass; the technologies, converting them to energy, are sensitive to the type and component of the feedstock (e.g., moisture content). Furthermore, the optimum biomass-to-energy conversion technology is highly dependent on the particular case and application (cf. chapter 3 and chapter 5).*

- *The optimum technology will depend on the specific priorities of the stakeholders relevant to the case. For example, as seen in chapter 5, gasification+ WGS, had better thermodynamic results; but without WGS the process depicted higher emission reductions. Similarly, in chapter 3 gasification had better thermodynamic indicators and net-present value, but combustion had a significantly low CAPEX and a high emission reduction potential.*

- *Various case studies highlight that biomass can play a crucial role in overall decarbonization and energy transition of various sectors. However, to put it into practice will require further initiatives spanning across all stakeholders in the value chain, with the local governments taking a leading role. Efforts need to be directed in educating farmers, ensuring proper collection of feedstocks, and developing proper competing markets for the use of biomass.*

- *As evidenced in chapter 5, harnessing all of the biomass could contribute ~30% of the electricity demands of Kerala. It can be concluded that bio-energy cannot compensate for the entire demands for a region, but it will likely play a larger role in decarbonizing and contributing to local regions.*

- *It was also seen that implementing these technologies can also improve social indicators (e.g., SDGs as initiated by UN) for the region such as employment, access to clean energy, and reduced inequalities. Chapter 3 addressed this by demonstrating the feasibility of converting local organic feedstocks to electricity in a cost-effective manner. Hence, deployment of such systems can provide electricity to previously underserved areas, thereby contributing to the development of these communities.*

Possible role of biomass in the Dutch scenario

Current Scenario

The Netherlands is aiming for a rapid transition to carbon-neutral economy; with the government aiming for reducing green-house gas emissions by 49% by 2030 and 95% by 2050. The Netherlands has made notable progress on its transition with renewable energy sources having doubled from 2008. Albeit, around 36% of the current power generation is via renewables [15]; the Netherlands is also facing new energy security challenges. In the previous decade, natural gas was the largest source of domestic energy production, with the field in Groningen being the main source. However, it was soon identified that the natural gas production activities in the Groningen field caused earthquakes. In response, the Dutch Cabinet issued decisions that aimed to end gas production from Groningen. This led to an increase in energy import, thereby making the Netherlands as a net gas importer. Thus, it was identified that phasing out the use of natural gas is necessary to meet the goals as set by the government.

Consequently, the Netherland has set itself the goal of producing 2 billion m^3 (bcm) of green gas annually by 2030 as a part of the green gas deal. Green gas is the gas derived from organic waste material (e.g., manure and sewer sludge) via anaerobic digestion and gasification.

Green gas-based tri-generation systems– a possible solution?

A large part of the current natural gas use is associated to residential heating requirements. Over 90% of the residential and commercial buildings pre-dominantly use natural gas for heating and cooking. The feasibility aspect of the Dutch energy transition is in turn to ensure the transition towards sustainable heating systems [16].

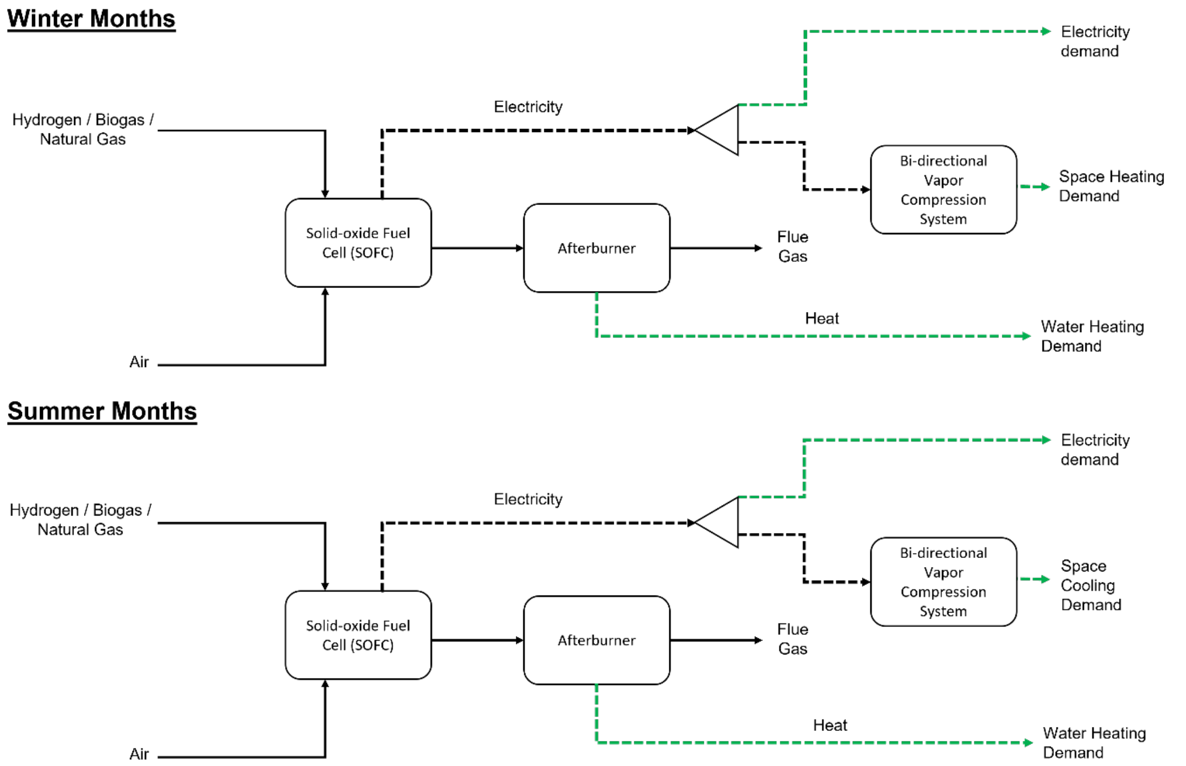


Figure 22: Tri-generation system employing the bi-directional vapor compression system for the Dutch case. The system will be operated in heat-pump mode during winter months, and in vapor compression mode during the summer months.

In chapter 4 of this white paper, tri-generation SOFC systems which employ vapor compression systems were described. Contrary to the South Africa case, which requires cooling year-round, the Dutch case has fluctuating requirements based on the season (heating requirements in winter, while cooling requirements during summer). It was identified that the vapor compression systems can be operated bi-directionally – as a heat pump or refrigerator. This can be done by employing a reversing valve to reverse the flow of the refrigerant within the loop.

For the Dutch case, the heat pump configuration of the system can be utilized to provide for the heat demand required during winter months. Conversely, the normal refrigeration mode can be utilized to provide cooling in the summer months. This is pictorially depicted in Figure 22.

Such devices can be powered by biogas, produced locally in digesters, and be used to cater to the energy demands – namely heat and power, for small villages. Furthermore, an advantage of the previously mentioned domestic gas production is that Netherlands has a well-established natural gas transport architecture. It is quite possible to upgrade the aforementioned green gas to natural gas specification and thus transport it through this grid connection. This grid connection can be used to fuel such devices for small residential complexes, to business parks and shopping complexes.

Potential benefits

- *Large-scale production of green gas, will reduce the energy storage requirements for renewables (wind or solar), which currently is the most expensive part across the value chain. Furthermore, it will help in the utilization of biomass which is otherwise incinerated.*
- *SOFC's have a higher energy efficiency compared to other CHP devices and hence present the opportunity to replace larger amounts of natural gas.*
- *If this system is fueled by green gas, it could lead to net-neutral emissions as compared to positive emissions from fossil fuels. It can also potentially lead to net-negative emissions, provided some of the carbon from biomass is sequestered in the form of fertilizers (digestate from AD). However, to confirm this an in-depth LCA analysis is required.*
- *Developing self-sufficient micro-grids, like utilizing such technologies for small villages, could reduce the grid congestion in the Netherlands. However, it could also potentially lead to blackouts if the system is shut-down. Hence, to confirm this a thorough evaluation of the system is required.*
- *There could be economic benefits from using such systems, locally produced biogas could be cheaper than imported natural gas (with associated carbon tax). However, this would require a more detailed evaluation.*
- *There is an increasing interest in looking at green hydrogen as a future energy carrier in the Netherlands. The development of the Groningen hydrogen valley and significant investments in offshore wind turbines in the North Sea corroborate this observation. Indeed, these trigeneration devices can also be fueled with hydrogen on account of fuel-flexible behaviour of SOFC's.*

7. References

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