Technical and Environmental Analysis of Methanol Synthesis from Solid Recovered Fuel and Lignite

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Abstract

The purpose of this work was to perform a technical and environmental analysis of methanol production from solid recovered fuel (SRF) and lignite feedstocks. The main driver was to ensure that while pursuing the dual goal of improving security of supply within the EU and reducing carbon dioxide emissions from the power and transport sector, other environmental issues were not engineered into the system, and to provide recommendations to improve the process sustainability.

The technical analysis was carried out using the inhouse ECLIPSE software and SimaPro was used for the environmental assessment. Data for the modelling was supplied by project partners, supply companies, databases, and literature where necessary.

The results showed that increased SRF in the feedstock mix, decreased the environmental impact of methanol production, however, the environmental impact was greater than the natural gas reformer used for benchmarking. The sensitivity study considered off-gas thermal recovery and carbon capture, which for the 80% SRF, the impact was less than the natural gas reformer.

It was concluded that SRF mixed with lignite to produce methanol could achieve the dual goal, providing off-gas recovery and carbon capture was employed. Other recommendations include considering onsite renewable electricity generation for process electricity.

Keywords: solid recovered fuel (SRF), lignite, process modelling, life cycle assessment (LCA), methanol production.

1   Introduction

Reducing imports of primary energy carriers as well as reducing CO_2 emissions from the power and transport sector are among the main goals of the European Union (EU). One promising option to address the dual goal is to take advantage of energy sources native to the EU and transform them into fuels and substances using processes that remove unwanted pollutants from emissions and waste streams.

Methanol is a high value substance that can be used as an energy storage vector, an easily transported and dispensed fuel, and a feedstock for synthetic hydrocarbons and their products. It can also be blended with gasoline [1]. As far back as 1998, George A. Olah proposed the methanol economy as an alternative to the hydrocarbon economy to reduce dependency of fossil fuels [2]. The end goal is to produce methanol from renewable sources, eliminating fossil fuels from methanol production. Currently, the three main fossil fuels used for methanol production are coal, coke oven gas and natural gas.

One of the cleanest methods to produce methanol is by a natural gas reformer [1, 3], however, there are other issues with using it as a feedstock in Europe and elsewhere. Europe is a net importer of natural gas with a high dependence on Norway, Ukraine, and Russia for natural gas supply [4]. In china, which is a leader the methanol economy, there are restrictions on the use of natural gas for some applications, one such, is using natural gas for methanol production. Although, this may change once shale gas becomes more widely available. For now, other feedstocks such as hard coal and coke oven gas are used to produce methanol [1]. There is no such restriction in the EU, however, due to the limited native resources of natural gas and the relatively large volumes of lignite in the territories of some EU member states [5], using lignite as a feedstock for methanol production, would lend itself to increasing security of supply. Furthermore, landfilling waste is expensive and creates environmental problems such as toxins, greenhouse gases and leachate. Minimising the use of landfill is a key aim of the EU. The EU Waste Framework [6], subsequently amended [7] outlines a priority order for waste management or 'waste hierarchy'. It is a five-step order of priority 1) prevention, 2) preparing for re-use, 3) recycling, 4) other recovery, e.g., energy recovery, and 5) disposal including landfilling. Utilising waste materials for fuel is step four of the hierarchy and solves the problem with what to do with waste that has no other usable function and is destined for landfill.

While increasing security of supply within the EU is an important goal, it must be done in a way that is not detrimental to the other goal of reducing CO_2 and other environmental burdens associated with power and fuel production. To this end, Life Cycle Assessment (LCA) is a tool that is used to model the material, energy, and emission flows at each stage of production to understand where environmental burdens occur, and to assess actions to negate said burdens.

In [1], four methanol production pathways were considered, and a comparison of their environmental consequences explored. Coal based methanol had greater environmental burdens compared to gasoline, while natural gas-based methanol had the lowest burdens across all indicators. Coke oven gas had fewer emissions than coal but larger burdens than gasoline. It was noted that the end-goal should be towards renewable based methanol, however, in the short-term, due to technical and economic considerations, reducing energy, water consumption and emissions of current methanol pathways would increase the sustainability of the methanol economy.

Similar results were found in [3], where coal, coke oven gas and natural gas to methanol were compared. It was found the single impact score of coal was 2-3.4 times greater than that of coke oven and natural gas. It was also suggested that using 100% renewable or nuclear electricity, the impact of coal to methanol could be reduced. Furthermore, flue gas process recycling and treatments, carbon capture and storage (CCS) and other emission and waste purifiers could reduce the burden from coal to methanol production.

Other routes to methanol production, such as electricity and methanol co-production from coal were studied in [8]. This was benchmarked against methanol production via a natural gas reformer.

In this study methanol production is based on gasifying solid fuels to carbon monoxide and hydrogen and then reacting to produce methanol under pressure using the methanol synthesis process. The High Temperature Winkler (HTW) gasification system has been selected for converting both solid recovered fuel (SRF) and lignite to synthetic gas. The gasification uses oxygen and steam as gasification agents, which are not only admitted to the fluidized-bed, but also into the free board to decompose undesirable reaction by-products (i.e., tar, hydrocarbons). Figure 1 shows the simplified block diagram of the process configuration. To determine the impact of varying feedstock ratios on the technical performance and environmental sustainability of the processes, varying SRF and lignite feedstock ratios are examined and compared.
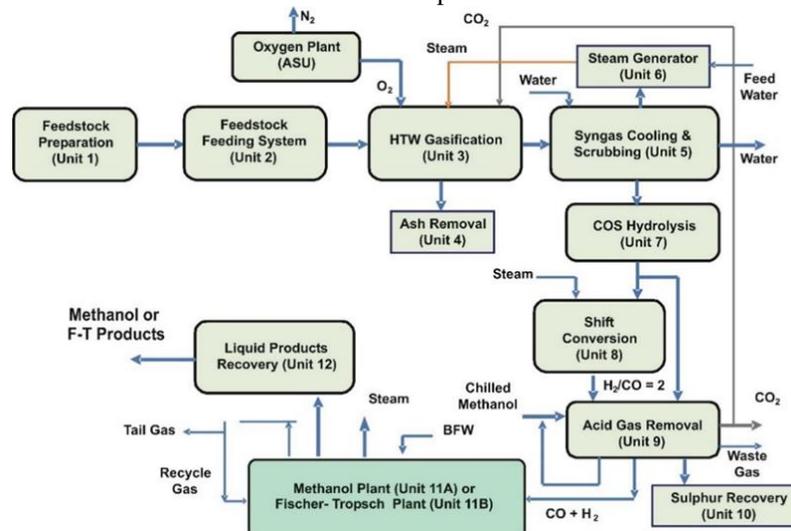
Figure 1: Simplified block diagram of process configuration

The novelty of the wider project is the development and testing of the innovative gas-cleaning concept for the removal of hydrogen sulphide and carbon dioxide from the syngas, which has the potential to reduce the capital and operational expenses compared to current state of the art technologies for syngas cleaning. Furthermore, the project develops the HTW technology for gasification of new types of feedstock, in this case the SRF and lignite mixtures. The novelty of the current paper, is that it is a whole system analysis of the proposed system, using feedstocks native to the EU and including the novel gas cleaning system. The work presented here is concerned with the technical and environmental analysis of the whole system. Ensuring that new environmental concerns are not engineered into the concept and highlighting any areas that should be addressed to improve the overall sustainability, a natural gas reformer is used to benchmark the process.

2   Methods

2.1   Feedstock

The two feedstocks considered in this work are SRF and lignite. In many countries, low rank coal, such as lignite, is an important energy source [8]. SRF is a high-quality product made from waste, which has a low moisture content and a high calorific value [9, 10]. Producing SRF from general waste not only helps to minimise landfill and reduces the associated environmental issues, but also reclaims it for use as an alternative energy source and can offset variable operating costs by avoiding any landfill fees.

SRF are highly heterogeneous mixtures that are generated from high calorific fractions of non-hazardous waste materials, which gives rise to fluctuations in quality and composition. The use of lignite could help to provide stable gasification conditions and could prevent problems caused by SRF quality [11]. However, both lignite and SRF have a rather low ash fusion temperature, resulting in severe slugging and fouling problems during fuel combustion or gasification processes. The co-gasification of SRF and lignite using the fluidized bed technology with operating temperatures below the ash melting point is an attractive alternative. In line with the EU waste hierarchy, the waste used to produce SRF must not be suitable for recycling, or any other functional use.
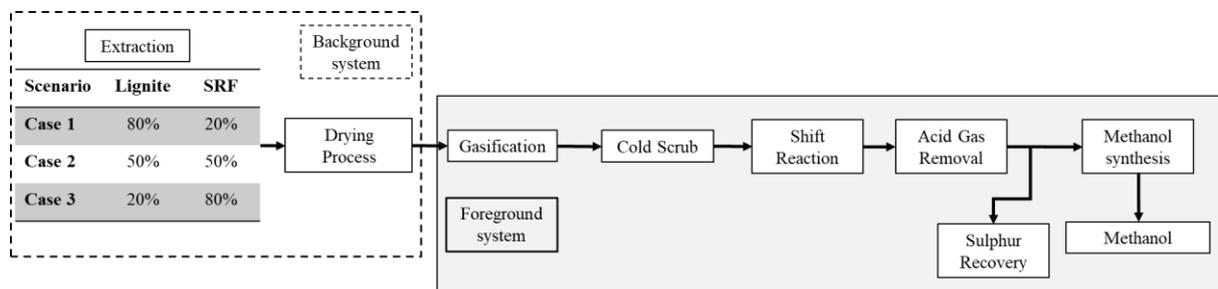
Figure 2: Solid fuel to methanol block diagram

2.2   Assessment methods

The in-house personal computer-based process simulation package, ECLIPSE, was used to perform process modelling and the technical assessment of the methanol production [12]. The data obtained from the partners was then used to adapt this study for the liquid fuel synthesis application. The SimaPro© software package was used to carry out the Life Cycle Assessment (LCA).

2.3   Goal and Scope

The goal of this study is to evaluate the environmental impact and sustainability of the synthetic fuels produced from lignite and/or waste for the process scenarios.

This study is a comparative study that focuses on the environmental impact of increasing the SRF in the feedstock. The functional unit (FU) allows systems to be compared on an equal basis. As the same final products are compared, the mass can be used in the FU. Therefore, the FU is *1kg of methanol produced at plant*. This is similar to [13], where the FU was 1kg of synthetic biodiesel produced at plant, [3] where the FU was defined as 1t methanol produced by the selected technical route, and [14] that used: one gasoline gallon equivalent of drop-in diesel which is compared against the conventional petroleum-derived diesel. In the comparison of the SRF and Dried Lignite, as they are not the same product but have the same function; to provide energy, the functional unit of 1000MJ of feedstock is used.

Allocation is used to determine the proportion of the environmental burden of products when multiple products are produced. However, the ISO 14044 states that allocation should be avoided wherever possible. It is suggested that this is done via dividing the unit process or expanding the product system [15, 16]. In SimaPro "avoided products" is the method used to expand the system. The impacts of the avoided products are subtracted from the total impacts [17]. In the case of the SRF a complication arises. Waste is an input to the process, however, within the software waste cannot be modelled as an input to the process. Some literature, such as [18], have avoided the issue due to the input; municipal solid waste (MSW), being the same and comparing the different technologies for waste to energy recovery. The chosen FU was one ton of MSW as received at the plant. Thus, any benefits in avoiding waste going to landfill is common across the technologies.

In [19], different allocation methods are explored, albeit for waste being recycled into different products within the cement and construction industries. If recycled material is used then virgin material does not need to be extracted and manufactured and thus, this is a straightforward avoided product, however, the environmental

impact of material recovery will still need to be accounted for. Similarly, in [20], electricity generated as a by-product of the process displaces electricity generated elsewhere. This approach is used in Sensitivity Study: the heat generated via the off-gas recovery displaces heat generated by natural gas elsewhere. The waste used to produce SRF has no other usable function in accordance with the European Waste Framework and would be disposed. This study only considers landfill disposal. The concentration of pollutants in landfill gas (LFG) are a function of the organics, paper and other combustible waste or biodegradable fractions. Leachate composition is dependent on metals, glass, plastics, and other non-combustible waste as well as the organic fractions [21]. Therefore, to capture the benefits of avoiding landfill, a high level LCA for the SRF process has been constructed using waste as an avoided product. There are no other incidences within the scope of this study where allocation is to be considered.

An LCA of the climate effect of co-firing a megajoule of SRF in a coal-fired electricity plant is considered in [22]. Here, the use of SRF avoids the use of coal. While this method is valid, it does not capture the environmental benefit of not sending the waste landfill.

This evaluation uses the endpoint environmental indicators, human health, ecosystems and resources. The ReCiPe method [23] is used for the Life Cycle Impact Assessment (LCIA). The LCIA translates emissions and resource extractions into a limited number of environmental impact scores using characterisation factors. It must be noted that comparison across different studies should be done with caution. This is due to the number of decisions available including inclusion and exclusion decisions made in the goal and scope of each study, LCA methods and database selections, and other considerations unique to each individual study. However, trends found in this study can be compared to other studies.

The background processes are modelled using data from databases where possible. Within the project, the lignite is received pre-dried, and therefore, for the LCA purpose, the drying process is modelled using ECLIPSE to attain the relevant utility inputs and flowrates. The SRF data is not contained within the databases and therefore, the LCA for this process has been constructed with data from the supply company and where appropriate, literature data.

The data for the foreground processes has been supplied from the Technical modelling analysis models using ECLIPSE software, which was fed from data reported elsewhere within the project. The results obtained were validated against other results from the project. There was a high degree of agreement found between the two.

A summary of the main assumptions is given here; the SRF assumes the environmental credit for diverting waste from landfill but takes on the environmental burden for waste collection, transport, and sorting.

Average distances for waste collection have been sourced from literature. Transport distances from the waste sorting facility to the SRF process and the SRF process to landfill have been estimated and agreed with the manufacturing company. The lignite transport distances have been estimated from literature. The waste collection vehicle is assumed to be a 21 metric ton municipal waste collection lorry. For the freight transport of lignite, SRF and waste a 32 metric ton lorry is assumed. The transport distances and vehicles are common to all scenarios. The waste is sorted at a municipal sorting facility (MSF), in [24], typical diesel and electricity values for sorting mixed stream waste are given. It should be noted that some of the paper waste is directly sent from the paper industry to the SRF process. However, to simplify the process, it is assumed that all input waste comes from the MSF.

After the MSF, waste would normally flow into its final steams (reuse, recycle, landfill). Due to the EU Waste Framework [7], waste must be reused or recycled before it can be used for other recovery, in this case energy recovery. Therefore, it is assumed that the waste that is used in the SRF process is waste that was destined for landfill. Waste components that are diverted from landfill and subsequently rejected from the SRF process, are sent back to landfill and therefore, except for transportation, are considered neutral.

The calorific value for natural gas is assumed to be $39.5MJ/m^3$. Oxygen usage within the process is produced by an air separation unit, technical modelling only considered the oxygen flow and so, for the LCA a conversion factor of 1.36MJ of electricity per kg of oxygen is used. Utility data such as electricity and wastewater treatment are taken from the database and assume as average data from Europe excluding Switzerland.

The primary limitations of this work are due to averaged and assumed data used for unknown elements, which are outside the control of this study.

3   Results

3.1 Technical

The overall performance for the process sections of the methanol plant is illustrated in Table 1. The feedstock input of the three options is maintained by 150 tonne/hr on an As-Received basis. Equivalently the total thermal inputs for Options 1-2-3 are 800, 867 and 935 MW (thermal). The results indicate that the methanol yields for Options 1-2-3, are 70.4, 75.2 and 82.9 tonne/hr, respectively. Adding by-product (i.e., off-gas) to the methanol product represents about 73.5%, 74.5% and 75.8% of the thermal conversion efficiencies.

Table 1: Mass Balance for the process, for the three feedstock ratios

Feedstock	Option 1	Option 2	Option 3
Lignite (tonne/hr)	120	75	30
SRF (tonne/hr)	30	75	120
Total thermal input (MWth)	800	867	935
Oxygen consumption (tonne/hr)	41	50	60
Electricity consumption (MWe)	53.0	56.3	60.2
Water consumption (tonne/hr)	124	137	151
Off gas (MWth)	202	235	255
Raw methanol production (tonne/hr)	70.4	75.2	82.9

3.2 Life Cycle Inventory (LCI)

The LCI is an incomplete mass energy balance, where only environmental relevant flows are considered. Table 2 and Table 3 contain the LCI for each feedstock preparation and process stage, and the natural gas reformer, respectively.

Table 2: Feedstock and Process LCI

	Process	Input Name	Input Value	Input Unit	Wastes & Emissions Name	Wastes & Emissions Value	Wastes & Emissions Unit	Product Name	Product Value	Product Unit
Feedstock	SRF	Paper waste	-623.90	kg	CO2	79.76	kg	SRF	1000	kg
		Plastic waste	-623.90	kg						
		Electricity	154.40	kWh						
		Diesel	2.70	kg						
		Gas	37.09	m3						
		Collection	29.70	tkm						
		Transport	195.22	tkm						
	Dried Lignite	Lignite	80.30	kg/s	Water	0.04	m3	Dried Lignite	41.69	kg/s
		Electricity	4.04	MWe						
		Transport	10.11	tkm						
Option 1 80% Lignite 20% SRF	Gasifier	Electricity	20.36	MJ	Ash	6.02	kg	Raw syngas	71.16	kg
	Cold Scrub	Water	36.00	kg	ASH	1.15	kg	Clean syngas	58.25	kg
		Electricity	0.78	MJ	Water H2O (L)	0.02	m3			
					HCL	0.003	kg			
					Ammonia	0.45	kg			
	Shift Reaction	Electricity	0.41	MJ	Water (L)	0.005	m3	Syngas	64.73	kg
	Acid Gas Removal	Methanol	2.25	kg	Methane	0.01	kg	H2, CO Gas	25.00	kg
		Electricity	19.06	MJ	Carbon Monoxide	0.01	kg			
					Carbon Dioxide	31.56	kg			
					Hydrogen	0.004	kg			
					Hydrogen Sulphide	0.03	kg			
					Methanol	2.51	kg			
					Ammonia	0.002	kg			
					Nitrogen Dioxide	0.27	kg			
	Methanol Synthesis	Electricity	6.18	MJ	Methane	3.23	kg	Methanol Product	19.61	kg
					Carbon Monoxide	2.47	kg			
					Carbon Dioxide	0.06	kg			
					Hydrogen	0.33	kg			
					Hydrogen Sulphide	0.002	kg			
					Methanol	0.01	kg			
					Nitrogen Dioxide	0.0001	kg			

	Process	Input	Value	Unit	Emission/Waste	Value	Unit	Product	Value	Unit
	Gasifier	Electricity	23.77	MJ	Ash	5.41	kg	Raw syngas	75.48	kg
		Water	38.00	kg	ASH	1.09	kg	Clean syngas	60.95	kg
	Cold Scrub	Electricity	0.78	MJ	Water H2O (L)	0.02	m3			
					HCL	0.002	kg			
					Ammonia	0.51	kg			
	Shift Reaction	Electricity	0.41	MJ	Water (L)	0.01	m3	Syngas	67.51	kg
		Methanol	2.25	kg	Methane	0.01	kg	H2, CO Gas	27.77	kg
		Electricity	19.06	MJ	Carbon Monoxide	0.02	kg			
					Carbon Dioxide	31.56	kg			
Option 2 50% Lignite 50% SRF	Acid Gas Removal				Hydrogen	0.004	kg			
					Hydrogen Sulphide	0.02	kg			
					Methanol	2.51	kg			
					Ammonia	0.003	kg			
					Nitrogen Dioxide	0.31	kg			
		Electricity	6.18	MJ	Methane	3.41	kg	Methanol Product	20.89	kg
					Carbon Monoxide	2.80	kg			
					Carbon Dioxide	0.06	kg			
	Methanol Synthesis				Hydrogen	0.37	kg			
					Hydrogen Sulphide	0.001	kg			
					Methanol	0.01	kg			
					Nitrogen Dioxide	0.0001	kg			
	Gasifier	Electricity	27.55	MJ	Ash	5.30	kg	Raw syngas	79.62	kg
		Water	41.00	kg	ASH	1.06	kg	Clean syngas	63.99	kg
	Cold Scrub	Electricity	0.78	MJ	Water H2O (L)	0.02	m3			
					HCL	0.001	kg			
					Ammonia	0.59	kg			
	Shift Reaction	Electricity	0.41	MJ	Water (L)	0.01	m3	Syngas	70.49	kg
		Methanol	2.25	kg	Methane	0.01	kg	H2, CO Gas	30.39	kg
		Electricity	19.06	MJ	Carbon Monoxide	0.01	kg			
					Carbon Dioxide	31.93	kg			
Option 3 20% Lignite 80% SRF	Acid Gas Removal				Hydrogen	0.004	kg			
					Hydrogen Sulphide	0.01	kg			
					Methanol	2.51	kg			
					Ammonia	0.003	kg			
					Nitrogen Dioxide	0.35	kg			
		Electricity	6.18	MJ	Methane	3.65	kg	Methanol Product	23.03	kg
					Carbon Monoxide	3.11	kg			
					Carbon Dioxide	0.06	kg			
	Methanol Synthesis				Hydrogen	0.41	kg			
					Hydrogen Sulphide	0.001	kg			
					Methanol	0.01	kg			
					Nitrogen Dioxide	0.0001	kg			

Table 3: LCI Natural Gas Reformer

	Inputs			Emissions & Wastes			Products		
	Air	113.4	kg	Argon	1.4514	kg	Clean Gas	25.809	kg
Reformer	Water	15.9	kg	Carbone Dioxide	16.2982	kg			
	Electricity	1.7	MJ	Water	0.7143	kg			
	Natural Gas	18.1	kg						
	Electricity	9.52	MJ	Water (L)	0.0022921	m3	Methanol	21.302	kg
				Carbon Monoxide	2.6078	kg			
Methanol Synthesis				Carbon Dioxide	0.1112	kg			
				Hydrogen	1.6847	kg			
				Methanol	0.009	kg			

3.3   Life Cycle Inventory Analysis (LCIA)

Figure 3 shows the single score comparison of SRF and Lignite on a 1000MJ basis. At this stage, producing SRF has an environmental benefit in the ecosystem and human health categories. This is due to avoiding sending paper and plastic to landfill. However, there are some environmental burdens, mainly, electricity usage, waste collection and freight transport. SRF has a higher Resource impact than the dried lignite. This is due to the three processes already mentioned and the natural gas usage in the SRF process. At this stage these are outweighed by the environmental benefits.

Bringing the lignite to market, along with the freight transport and electricity use have the highest impact on all three indicators for the lignite drying.
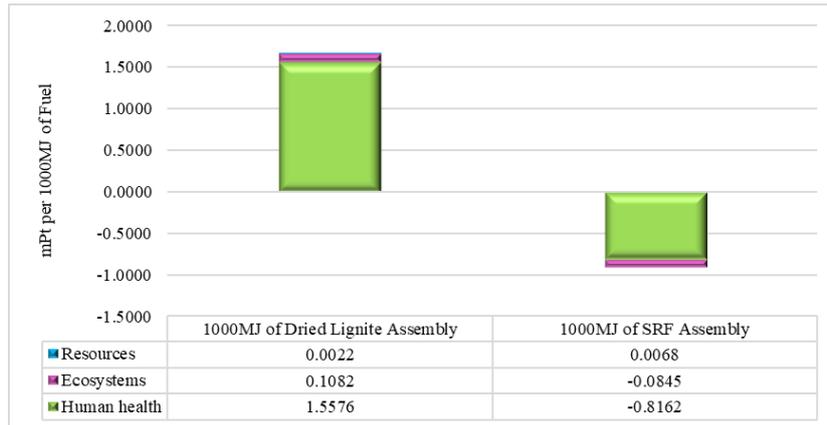
Figure 3: Comparison of SRF and Dried Lignite 1000MJ

Figure 4 shows the endpoint damage assessment for the three options and the natural gas reference case. As the SRF is increased in the feedstock mix, the impact on the Human Health and ecosystems is reduced, however, they have a higher impact than the natural gas reformer. The Resource indicator increases slightly with increased SRF; however, they are lower than that of the natural gas reformer.
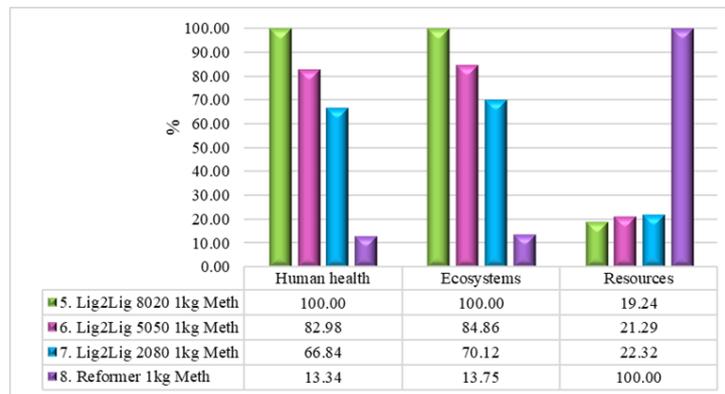
Figure 4: Damage assessment (ReCiPe 2016 Endpoint (H) V1.04 / World (2010) H/A) 1kg Methanol

3.4 Sensitivity

Two studies have been considered to lower the impact of the Human Health and Ecosystems indicator of the three feedstock options. The first is to utilise the methanol and other hydrogen components for heat generation. The assumptions for this analysis are,

1. All hydrogen containing gasses in the off-gas are combusted, therefore, they are set to zero emissions.
2. The combustion produces carbon dioxide and so there is an increase of carbon dioxide in the off-gas.
3. The heat generated from combustion is usable in another application such as district heating, process heating or water heating. However, the final use for the heat has not been specified, however, it has been assumed that the heat generated in this combustion offsets the requirement for heat to be produced elsewhere. In the studied case, equivalent heat from a central or small-scale natural gas boiler has been avoided.
4. All other flows remain unchanged and the LCI for the modified synthesis stage shown in Table 4

Table 4: Sensitivity Study 1 – Off-gas recovery for heat generation.

	Input			Wastes & Emissions			Product		
Methanol Synthesis Option 1 80% Lignite 20% Methanol	Electricity	6.175	MJ	Methane	0	kg	Methanol Product	19.61	kg
				Carbon Monoxide	2.4693	kg	Avoided Heat by NG	202	MJ
				Carbon Dioxide	12.8	kg			
				Hydrogen	0	kg			
				Hydrogen Sulphide	0	kg			
				Methanol	0.0057	kg			
				Nitrogen Dioxide	0.0001	kg			
Methanol Synthesis Option 2 50% Lignite 50% Methanol	Electricity	6.175	MJ	Methane	0	kg	Methanol Product	20.89	kg
				Carbon Monoxide	2.802	kg	Avoided Heat by NG	235	MJ
				Carbon Dioxide	13.8	kg			
				Hydrogen	0	kg			

	Input			Wastes & Emissions			Product		
				Hydrogen Sulphide	0	kg			
				Methanol	0.0062	kg			
				Nitrogen Dioxide	0.0001	kg			
Methanol Synthesis Option 3 20% Lignite 80% Methanol	Electricity	6.175	MJ	Methane	0	kg	Methanol Product	22.761	kg
				Carbon Monoxide	3.108	kg	Avoided Heat by NG	255	MJ
				Carbon Dioxide	15.96	kg			
				Hydrogen	0	kg			
				Hydrogen Sulphide	0	kg			
				Nitrogen	0.3827	kg			
				Nitrogen Dioxide	0.0001	kg			
Methanol Synthesis Natural Gas Reformer	Electricity	9.52	MJ	Carbon Monoxide	2.6078	kg	Methanol	21.3	kg
				Carbon Dioxide	4.21	kg	Avoided Heat by NG	226	MJ
				Hydrogen	0	kg			
				Methanol	0.009	kg			

The second study considers carbon capture after the acid gas removal stage. The purge gas at this stage is 92% CO_2, making the stream suitable for carbon storage. In this study, it is assumed that all the CO_2 in this stage is captured to later be compressed and stored. The compressor and storage stage are outside the boundary of this study; however, the CO_2 has been set to zero to indicate that CO_2 is not emitted from this stage of the process. The natural gas reformer does not have any carbon capture. The LCI for the Acid gas removal stage is shown in Table 5. This study includes the off-gas recovery at the methanol synthesis stage and all other flows remain unchanged.

Table 5: Sensitivity Study 2 – Carbon capture

	Input			Wastes & Emissions			Product		
Acid Gas Removal Option 1 80% Lignite 20% SRF	Methanol	2.25	kg	Methane	0.006	kg	4. H2, CO Gas	25.004	kg
	Electricity	19.06	MJ	Carbon Monoxide	0.0144	kg			
				Carbon Dioxide	0	kg			
				Hydrogen	0.0039	kg			
				Hydrogen Sulphide	0.0297	kg			
				Methanol	2.5083	kg			
				Ammonia	0.0022	kg			
				Nitrogen Dioxide	0.2696	kg			
Acid Gas Removal Option 2 50% Lignite 50% SRF	Methanol	2.25	kg	Methane	0.0061	kg	4. H2, CO Gas	27.771	kg
	Electricity	19.06	MJ	Carbon Monoxide	0.0151	kg			
				Carbon Dioxide	0	kg			
				Hydrogen	0.004	kg			
				Hydrogen Sulphide	0.022	kg			
				Methanol	2.5082	kg			
				Ammonia	0.0026	kg			
				Nitrogen Dioxide	0.3095	kg			
Acid Gas Removal Option 3 20% Lignite 80% SRF	Methanol	2.25	kg	Methane	0.0058	kg	4. H2, CO Gas	30.388	kg
	Electricity	19.06	MJ	Carbon Monoxide	0.0148	kg			
				Carbon Dioxide	0	kg			
				Hydrogen	0.004	kg			
				Hydrogen Sulphide	0.0144	kg			
				Methanol	2.5085	kg			
				Ammonia	0.0025	kg			
				Nitrogen Dioxide	0.3543	kg			

Figure 5 shows the single score results for the three feedstock options and the natural gas reformer, without any recovery, with off-gas recovery, and with off-gas recovery and carbon capture. Option 3, which has 80% SRF, with both off-gas recovery and carbon capture is environmentally better the natural gas reformer and has the added advantage of utilising energy sources native to the EU and valorising landfill material.

	Option 1	Option 2	Option 3	NG Reformer
■ Process w/o recovery	211.83	176.24	142.39	30.65
■ Process w recovery	115.24	74.59	36.08	16.28
■ Process w recovery & CO2 Cap	81.48	47.42	11.59	16.28
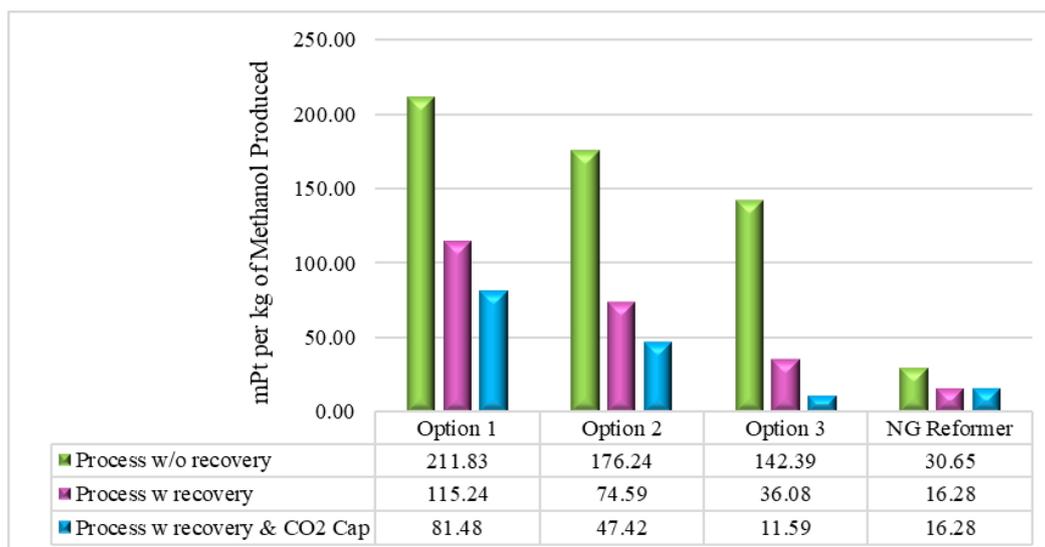
Figure 5: Single score analysis of the impact of off-gas recovery and carbon capture on the full process

4   Discussion

The technical analysis, Table 1, showed that increasing the SRF in the feedstock mix, increased the oxygen, electricity, and water usage, however, the methanol output also increased. LCA utilises a functional unit to compare all options on an equal basis. The functional unit used is 1kg of methanol produced.

The goal of this study was to evaluate the environmental impact and sustainability of the synthetic fuels produced from different SRF and lignite feedstock ratios for the synthetic production of Methanol. The first step was to attain LCI and resulting LCA data for the studied feedstock. The process data for the SRF was attained via communication with the manufacturing company. Waste collection, sorting, and transport LCI data was taken from literature. The lignite data LCI was populated from database data with the drying process being modelled in the ECLIPSE simulation software.

The endpoint analysis in Figure 4 has shown that increasing the SRF in the feed stock mix has less of an environmental impact than higher quantities of lignite. However, and except for the resource indicator, all options are more environmentally damaging than the natural gas reformer.

Although natural gas is a cleaner fuel for methanol production, there are other issues with using it as a feedstock in Europe and elsewhere. Europe is a net importer of natural gas and using lignite as a feedstock for methanol, would lend itself to increasing security of supply. Furthermore, the use of SRF solves a problem with what to do with waste that has no other usable function and is destined for landfill.

Nonetheless, improving the process, to become less environmentally damaging should be a goal. The methanol synthesis stage and the acid gas removal stage both have high off-gas emissions, as seen in Table 2 and both stages have a significant impact on the LCIA. The off-gas at the methanol synthesis stage contains large quantities of methane and other hydrogen components that can be combusted to generate heat. The acid gas removal stage has a high concentration of carbon dioxide that is suitable for carbon capture and storage.

Sensitivity Study 1: off-gas recovery for heat generation, examines the impact of recovering methane and other hydrogen containing gasses from the off-gas of the methanol synthesis process stage. Useful heat is generated that avoids natural gas generated heat elsewhere.

Sensitivity Study 2: Carbon capture from the acid gas cleaning stage, considered capturing the CO_2 from purge stream, along with the off-gas recovery for heat generation. The results of both studies were shown in Figure 5. Once these studies are taken into consideration, Option 3, which has 80 SRF performs environmentally better than the natural gas reformer. As a caveat, a more comprehensive study on these two tested systems should be carried out that includes a detailed analysis of the relevant flows of the recovery/capture systems, to confirm their environmental benefits.

Other processes that have a high impact on the indicators, such as electricity and lignite mining are outside the control of the process, however, they should also be addressed. The impact of lignite from the market including mining operations, is reduced naturally by reducing the proportion of lignite in the in the feedstock mix. Nevertheless, suppliers should be encouraged to adhere to environmental best practice to minimise their environmental impact. The same applies to the methanol from the market.

As electricity is decarbonised and renewables make up a larger percentage of the electricity fuel mix, the impact on the process from electricity should reduce. However, onsite renewable electricity generation could also be considered to reduce the overall impact of the process. Cleaner vehicles for freight transport and waste collection would lower their impact on the process.

5   <u>Conclusion</u>

Using waste and lignite to produce methanol enables Europe to produce this high value substance from abundant native resources, thus increasing security of supply and valorising waste material that was destined for landfill. However, the process has environmental consequences that should be addressed.

Higher SRF and lower lignite in the process feedstock has a lower environmental impact. Close consideration should be given to the off-gas emissions in the acid gas cleaning and synthesis stages. Burning the off-gas to produce useful heat, will eliminate methane emissions but increase carbon dioxide emissions. Nonetheless, due to the potency of methane as a greenhouse gas, this produces a reduction in the single score. Integrating carbon capture and storage to capture carbon dioxide from the acid gas cleaning stream would reduce the carbon dioxide emissions. Locating near other industries, may enable participation in a carbon capture shared network. Consideration should be given to the location of the plant to ensure that the heat generated can be utilised. Locating near suppliers would reduce transport emissions.

Duty of care considerations should be applied when selecting suppliers of products to the process. Suppliers of materials and haulage firms should comply with best practice and should actively be working to reduce their environmental impact. This will have a knock-on impact on the LCA of the products produced via the process.

Finally, due to the high electricity usage, onsite generation from renewable source should also be considered.

6   <u>Acknowledgments</u>

7   <u>References</u>

[1] Y. Yao, Y. Chang, R. Huang, L. Zhang and E. Masanet, "Environmental implications of the methanol economy in China: well-to-wheel comparison of energy and environmental emissions for different methanol fuel production pathways," *Journal of Cleaner Production,* vol. 172, pp. 1381-1390, 2018.

[2] G. Olah, "Beyond Oil and Gas: The Methanol Economy," *Angewandte Chemie International Edition,* vol. 44, pp. 2636-2639, 2005.

[3] z. Chen, Q. Shen, N. Sun and W. Wei, "Life cycle assessment of typical methanol production routes: The environmental impacts analysis and power optimization," *Journal of Cleaner Production,* vol. 220, pp. 408-416, 2019.

[4] Statistics Explained, "Natural gas supply statistics," Eurostat, 29 October 2020. [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?oldid=401136#Consumption_trends. [Accessed 15 January 2021].

[5] A. Errard, N. Stylanidou and M. Goll, "Production of lignite in the EU - statistics," Eurostat, 17 September 2020. [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?oldid=498589#What_is_lignite_and_how_significant_is_this_fossil_fuel_in_the_EU.3F. [Accessed 15 January 2021].

[6] European Commission, "Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives," European Commission, 19 November 2008. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32008L0098. [Accessed 16 October 2018].

[7] European Commission , "Consolidated text: Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives," European Commission , 05

July 2018. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02008L0098-20180705. [Accessed 16 October 2018].

[8] A. Śliwińska, D. Burchart-Korol and A. Smoliński, "Environmental life cycle assessment of methanol and electricity co-production system based on coal gasification technology," *Science of The Total Environment,* vol. 574, pp. 1571-1579, 2017.

[9] Suez in the UK, "Solid recovered fuel," Suez in the UK, [Online]. Available: https://www.suez.co.uk/en-gb/our-offering/businesses/what-are-you-looking-for/recycling-and-waste-management/products/solid-recovered-fuel. [Accessed 01 02 2021].

[10] N+P, "SUBCOAL," N+P, [Online]. Available: https://www.subcoal-international.com/. [Accessed 01 02 2021].

[11] E. Iacovidou, J. Hahladakis, I. Deans, C. Velis and P. Purnell, "Technical properties of biomass and solid recovered fuel (SRF) co-fired with coal: Impact on multi-dimensional resource recovery value," *Waste Management,* vol. 73, pp. 535-545, 2018.

[12] Ulster University, "ECLIPSE process simulator," Energy Research Centre, University of Ulster, Coleraine, Copyright 1992.

[13] Z. Navas-Anguita, P. Cruz, M. Martín-Gamboa, D. Iribarren and J. Dufour, "Simulation and life cycle assessment of synthetic fuels produced via biogas dry reforming and Fischer-Tropsch synthesis," *Fuel,* vol. 235, pp. 1492-1500, 2019.

[14] I. Okeke, K. Sahoo, N. Kaliyan and S. Mani, "Life cycle assessment of renewable diesel production via anaerobic digestion and Fischer-Tropsch synthesis from miscanthus grown in strip-mined soils," *Journal of Cleaner Production,* vol. 249, 2020.

[15] ISO, *BS EN ISO 14044:2006 Environmental management. Life cycle assessment. Requirements and guidelines,* BSI, 2006.

[16] B. Weidema, "ISO system expansion = substitution," LCA Consultants, 22 09 2014. [Online]. Available: https://lca-net.com/blog/iso-system-expansion-substitution/. [Accessed 05 03 2017].

[17] M. Goedkoop, M. Oele, J. Leijting, T. Ponsioen and E. Meijer, "Introduction to LCA with SimaPro,," PRé,, January 2016. [Online]. Available: www.pre-sustainability.com/download/SimaPro8IntroductionToLCA.pdf. [Accessed 2017 March 2017].

[18] J. Dong, Y. Tang, A. Nzihou, Y. Chi, E. Weiss-Hortala and M. Ni, "Life cycle assessment of pyrolysis, gasification and incineration waste-to-energy technologies: Theoretical analysis and case study of commercial plants," *Science of The Total Environment,* vol. 626, pp. 744-753, 2018.

[19] C. Chen, G. Habert, Y. Bouzidi, A. Jullien and A. Ventura, "LCA allocation procedure used as an incitative method for waste recycling: An application to mineral additions in concrete,," *Resources, Conservation and Recycling,* vol. 54, no. 12, pp. 1231-1240, 2010.

[20] A. Rolfe, Y. Huang, M. Haaf, A. Pita, S. Rezvani, A. Dave and N. Hewitt, "Technical and Environmental Study of Calcium Carbonate Looping versus Oxy-fuel Options for Low CO2 Emission Cement Plants," *International Journal of Greenhouse Gas Control,* vol. 75, pp. 85-97, 2018.

[21] G. Sauve and K. Van Acker, "The environmental impacts of municipal solid waste landfills in Europe: A life cycle assessment of proper reference cases to support decision making," *Journal of Environmental Management,* vol. 261, p. 110216, 2020.

[22] M. Otten and H. Croezen, "Climate analysis of Subcoal® in coal-fired power plants," Delft, April 2015. [Online]. [Accessed 22 April 2020].

[23] RIVM, "LCIA: the ReCiPe model," National Institute for Public Health and the Environment, 11 02 2018. [Online]. Available: https://www.rivm.nl/en/life-cycle-assessment-lca/recipe. [Accessed 16 June 2020].

[24] D. Turner, I. Williams and S. Kemp, "Combined material flow analysis and life cycle assessment as a support tool for solid waste management decision making," *Journal of Cleaner Production,* vol. 129, pp. 234-248, 2016.