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ORIGINAL PAPER

Methanol Production from Solid Recovered Fuel and Lignite: Techno-Economic and Environmental Assessment

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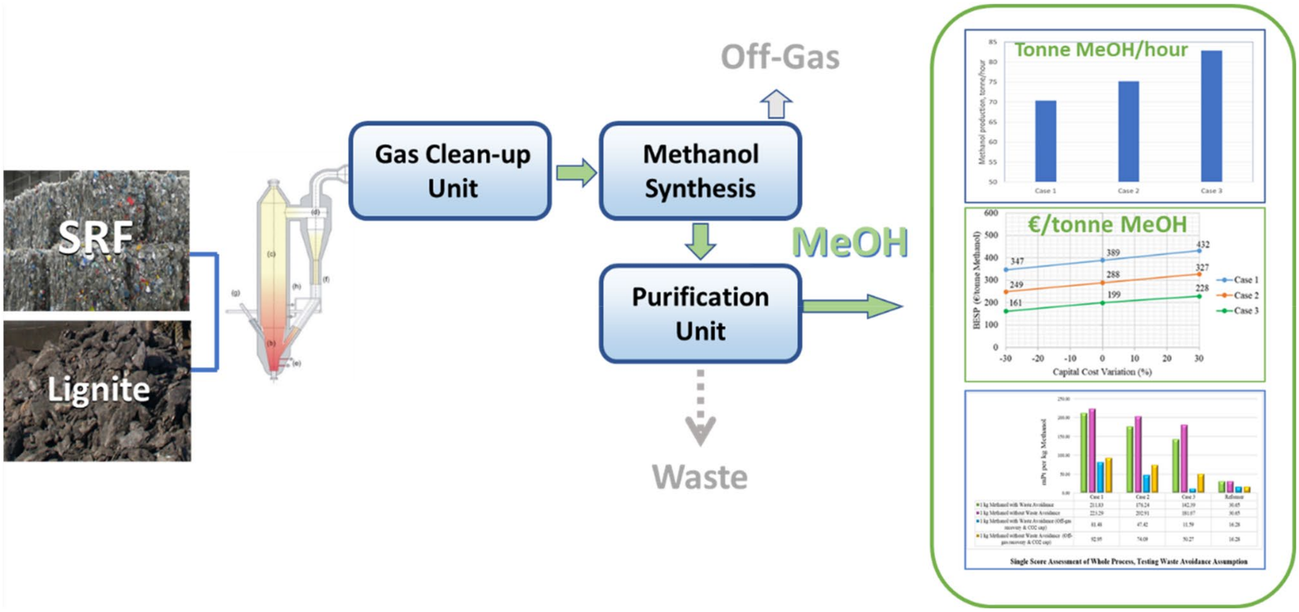
Abstract

The main purpose of this work is to examine the techno-economics and environmental assessment of the Solid Recovered Fuel and Lignite to methanol pathway. Methanol is produced by gasifying the solid fuels to carbon monoxide and hydrogen and then reacting to produce methanol under pressure during the methanol synthesis process. The data obtained from the partners is used to adapt this study for the liquid fuel synthesis application. The in-house personal computer-based process simulation package, ECLIPSE, is used to perform process modelling and the techno-economic assessment of methanol production. The @Risk 8.2© software is used to estimate the cost contingency of the project. The SimaPro© software package was used to carry out the Life Cycle Assessment (LCA). The gasifier plant contributes significantly to the capital costs. The results show that increased Solid Recovered Fuel (SRF) in the feedstock mix has favourable economics due to the negative SRF charges resulting in a lower break-even selling price (BESP) than feedstock mixes with higher ratios of Lignite. Plant availability, capital investment and the time value of money are the factors that have the greatest impact on BESP. Increasing the SRF in the feedstock mix decreases the Global Warming impact of the methanol production compared to higher proportions of Lignite. However, the resultant impact is much greater than that of a natural gas reformer. Furthermore, the employment of off-gas recovery and carbon capture can further reduce both the Global Warming impact and the overall Single Score of the process, making it favourably comparable to the natural gas water gas shift configurations.

Graphical abstract



Extended author information available on the last page of the article

Keywords Solid recovered fuel · Lignite · Techno-economic analysis · Life cycle assessment · Methanol production

Statement of Novelty

This paper analyses the use of novel mixed feedstocks in the gasification system to produce methanol. Techno-economic analysis and life cycle assessment are used to examine the economics and environmental impact of producing methanol from solid recovered fuel (SRF) and lignite blended feedstock, allowing the quantification of economic and environmental benefits from the utilisation of SRF and lignite. Both fuels are widely available within the EU and so their exploitation would increase security of supply within the block. However, new processes and feedstocks must not add to environmental burdens of fuel production and must be economically competitive compared to traditional methanol production routes. It is our understanding that no other study has performed the stated analysis on the SRF/Lignite to methanol pathway.

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). Economic competitiveness and growth are also an important factor to the EU [1]. These goals also tie into the UN Sustainable Development Goals, which aim to spur economic growth while improving health and education, at the same time reducing inequality and ending poverty, all while addressing the issue of climate change [2]. One promising option to address the EU goals are 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 [3]. 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 [4]. The methanol based fuel economy could allow for greater development of the fuel market in terms of balanced sustainability (environmental, economic and social) as it is compatible with existing infrastructure, thus, giving the automotive technology more time to evolve, continue long haul transportation security and allow lower income societies to participate in the transition to greener transportation fuel [5]. Methanol has around half the energy density of gasoline but a higher-octane number, which enables a higher compression ratio than traditional gasoline and as such, combustion is more efficient, and CO and CO_2 emissions are reduced [6]. The end goal is to produce methanol from renewable sources, eliminating fossil fuels from methanol production.

One of the cleanest methods to produce methanol is by a natural gas reformer [3, 7], however, there are issues with using natural gas 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 [8]. At the time of writing, there is a global ‘gas crises’, and while no academic analysis as to the cause is available yet, media outlets have been speculating the cause. They include a cold 2019/20 winter, a low wind summer, a post-lockdown rebound in energy demand, and a fire at a major power cable [9–12]. Regardless of what the actual cause or causes may be, the impact is being felt with warnings of shortages from fertilizer, food, and soft drinks producers. Small energy firms are expected to go bust and domestic gas prices have risen sharply [13]. It could be argued that there is a real time example of the importance of supply security.

In China, which is a leader in the methanol economy, there are restrictions on the use of natural gas for some applications, one such example, 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 [3]. 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 [14], 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 another aim of the EU. The EU Waste Framework [15], subsequently amended [16], 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. Solid recovered fuel (SRF) is a high-quality product made from household and industrial waste that has a higher heating value compared to municipal solid waste and is usually dried and processed into pallets or balled [17, 18].

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.

The three main fossil fuels used for methanol production are coal, coke oven gas and natural gas. In [3], 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 [7], 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 by using 100% renewable or nuclear electricity, the impact of the coal to methanol pathway 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.

In [19], a techno-economic and environmental assessment was carried out on several current and future methanol production pathways, including steam methane reforming (SMR), methane pyrolysis and electrolysis. SMR had the lowest annualised costs, however, due to natural gas use and high global warming impact, it is not sustainable. This demonstrated the requirement for methanol production to shift towards low carbon options that are economically feasible. Pyrolysis had greater profitability over solar driven electrolysis, although both are considered sustainable methods for methanol production.

Other routes to methanol production, such as electricity and methanol co-production from coal were studied in [20]. 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 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 economic and environmental impact of varying feedstock ratios on the technical performance, economics, and environmental sustainability of the processes, varying SRF and lignite feedstock ratios are examined and compared.

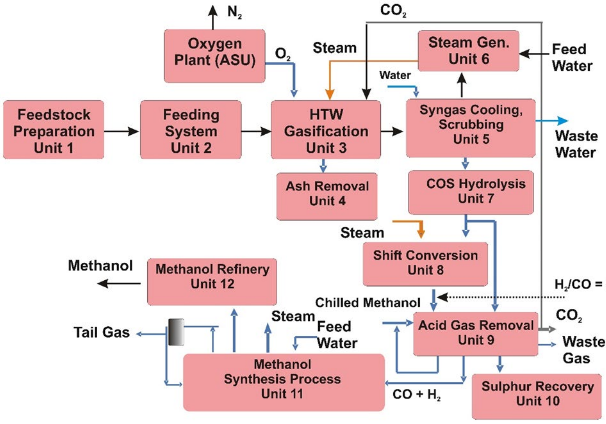


Fig. 1 Simplified block diagram of process configuration

The novelty of the wider project is the development of the co-feeding configuration 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 feedstocks, in this case the SRF and lignite mixtures. Within this paper, the resulting clean syngas is synthesised into methanol, it should be noted that Fischer–Tropsch synthesis is equally viable.

A demonstration HTW gasification plant was successfully commissioned with pre-dried lignite feedstock in [21]. The influence of temperature on the gas composition was also investigated. Cold gas efficiency of 70% was achieved. It was also found that low bed temperatures increased methane production, which result in a loss of cold gas efficiency due to the methane having to be reconverted to CO and H_2. In [22], the same pilot plant was used to study the gasification of high volatile bituminous coal. The aim was to increase the feedstock diversity applicable for the HTW technology. It was demonstrated that the content of combustible gasses was approximately 50vol% (dry) but that increasing temperatures in the fluidised and post gasification zone improved syngas quality. Carbon conversion rate of 88% was reached. In [23], experiments were carried out on lignite gasification in a bench-scale fluidised bed reactor using olivine as bed material. The aim was to study the impact of different operating conditions on gas quality. Results showed that increased operating temperature improved the gas quality with higher conversion rates and gas yields, and a lower production of tar. In [24], similar experiments were carried out, but in this case SRF was included in the tested feedstock and the bed material was HTW bottom product. Again, higher operating temperatures produced a higher quality gas, higher conversion rates and lower tar content. The gasification of the SRF and lignite mix produced a similar gas composition and tar content as the gasification of lignite alone. However, tar content, CH_4 and CO_2 were slightly higher in the presence of the SRF, most likely due to the plastic fraction. It was concluded that gasification of 20 wt% SRF blended with lignite, and HTW bottom product, could produce syngas with without any operating issues or substantial losses in gas quality. Similar conclusions were made in [25], which tested various ratios for O_2/fuel and Steam/fuel as well as the impact of temperature and other parameters and included 50 wt% SRF with lignite feedstock mix.

The novelty of the current paper, is that it is a whole system analysis of the proposed system, using feedstocks native to the EU. The work presented here is concerned with the techno-economic and environmental analysis of the entire process system. LCA is used to ensure 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. For any new process development, unfavourable economics would halt development and deployment, and therefore, a full techno-economic analysis is performed along with a sensitivity study.

Methods and Materials

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 [20]. 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.

SRFs 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 [26]. 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. There are three feedstock mix options considered in the process for methanol production, they are;

(i) Case 1: Ratio of Lignite to SRF is 80/20.
(ii) Case 2: Ratio of Lignite to SRF is 50/50.
(iii) Case 3: Ratio of Lignite to SRF is 20/80.

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 [27]. The data obtained from the partners was then used to adapt this study for the liquid fuel synthesis application. The @Risk 8.2© software is used to estimate the cost contingency of the project. The SimaPro© software package was used to carry out the Life Cycle Assessment (LCA).

Economic Methods

The economic analysis is based on the net present value concept. After establishing techno-economic models for the full process chain, the capital investment of individual components and equipment is then allocated according to their specification and operating conditions. Each individual equipment cost is further expanded by additional costs for installation and integration such as piping, valves, instrumentation, and civil work. Subsequently, the fixed and variable operating costs are determined. The overall process cost together with the individual input streams and operational and maintenance (O&M) costs, is used to calculate the annual cash flow and the breakeven selling price of methanol yielded at different financial options. Finally, a sensitivity analysis is carried out to disclose the effect of dominant parameters such as feedstock price fluctuations, uncertainties with plant capital investments and plant capacity factor and discounted cash flow rate.

Investment and operational costs

The most significant component of the direct costs of methanol production is the HTW based gas production capital cost. A bottom-up approach is adopted to estimate the overall unit cost for the HTW process. The method used to calculate the capital investment for other equipment, as shown in Fig. 2, is described as follows:

The process flow diagram, as illustrated in Fig. 1, includes all the component contained within the boundary fence that is required to be considered in the cost estimation. A mass and energy balance is then performed for the process flow diagram. The information produced by the

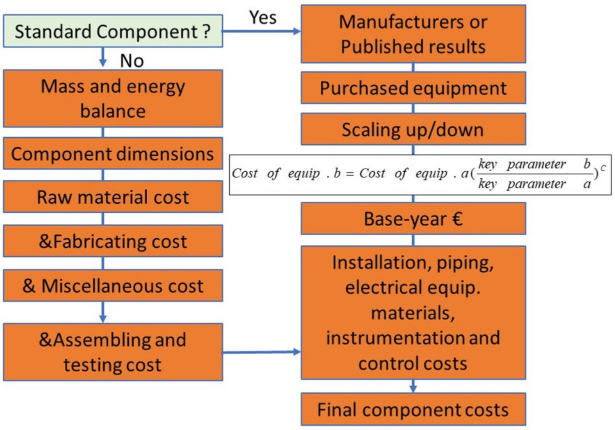


Fig. 2 Component capital cost estimation

mass and energy balance provides the basic design data for each item of equipment, i.e., flows, temperatures, pressures, heat transfer duties, etc. The calculation of capital costs is done using two approaches. If the equipment is standard then manufacturers' quotes, literature published prices or historical project data that is related, the basic capital cost of an item of equipment, to a specific size parameter, is used. If the capital cost of a similar component but with a different size or capacity, is known, the capital cost is scaled up or down by using the correlation:

$$Cost_2 = Cost_1 \left(\frac{Size_2}{Size_1} \right)^{Factor}$$

where:

$Cost_1$ = the reference cost (€) of equipment having corresponding capacity $Size_1$ (same units as $Size_2$).

$Cost_2$ = the approximate cost (€) of equipment having corresponding capacity $Size_{2.}$

Factor = the value of scaling factor ranging from 0.55 to 0.75 for most of the components.

If the equipment is a non-standard equipment, a seamless cost estimation within ECLIPSE simulation will be adopted. This method is based on the design data generated by the mass and energy balance calculation. Other correction factors are also considered, such as materials of construction and operating conditions. On top of the corrected basic capital cost, an allowance was then made for installation costs, such as civil works, pipework and valves, electrics and instrumentation, and other services.

Whilst every effort is made to validate the capital cost estimation data, using published information, actual quotations from equipment vendors or bottom-up calculations, the absolute accuracy of this type of capital cost estimation procedure has been estimated at about ± 25–30%. However, although the absolute accuracy of a single cost estimate may be only ± 25–30%, these studies compare families of similar technologies, composed of similar types of equipment. Therefore, the comparative capital cost estimates, which are based on the accurate calculation of a difference in basic design data by the mass and energy balance program, should be valid. Subsequently, the chemical engineering plant cost index is used to normalise the data to selected base period values.

Economic boundary conditions

A set of assumptions and expected range of values relevant for the assessment of methanol production is given in Table 1. The variation to the default value serves as indicators for an economic sensitivity analysis.

Environmental Analysis

The environmental analysis is performed via LCA. LCA has four stages: Goal and Scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and interpretation.

Goal and Scope

The goal of this study is to evaluate the environmental impact and sustainability of the methanol production produced from the three SRF and Lignite cases with increasing proportions of SRF in the feedstock mix.

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 1 kg of methanol produced at plant. This is similar to [29], where the FU was 1 kg of synthetic biodiesel produced at plant, [7] where the FU was defined as 1t methanol produced by the selected technical route, and [30] that used: one gasoline gallon equivalent of drop-in diesel, which is compared against the conventional petroleum-derived diesel.

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 [31, 32]. In SimaPro "avoided products" is the method used to expand the system. The impacts of the avoided products are subtracted from the total impacts [33]. 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 [34], 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.

Table 1 Economic assumptions

	Min	Default	Max	
Construction time		3		Years
Project life (years)		25		Years
Discounted cash flow (DCF) rate	4	8	12	%
Owner's cost		10		% Engineering, Procurement and Construction (EPC)
Project contingencies		10		% EPC
Plant occupancy		90		% (i.e., a 330-day production schedule)
Lignite price (pre-dried)	36.0	51.4 [*]		€/tonne
Solid recovered fuel price	− 31.5	− 45	− 58.5	€/tonne
Plant insurance cost		1.5		% Total Capital Investment
Water price		1.5		€/tonne
Electricity cost		130		€/MWh
Ash disposal cost		25		€/tonne
Solid Sulphur selling price		55		€/tonne

[*] the pre-dried lignite price is based on the EUCO scenario [28], i.e., 2.3 €/GJ as received. In addition, a transportation cost and the cost associated with lignite handling and drying are included

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 [35], 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 [36], electricity generated as a by-product of the process displaces electricity generated elsewhere. This approach is used in the sustainability optimisation 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 [37]. Therefore, to capture the benefits of avoiding landfill, a high level LCA for the SRF process was constructed using waste as an avoided product. A sensitivity study has been performed to test this assumption. 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 [38]. 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 to landfill.

This evaluation uses the midpoint environmental indicators and endpoint single score, the latter for a quick, general comparison for the overall process. The ReCiPe method [39] is used for the Life Cycle Impact Assessment (LCIA). The LCIA translates emissions and resource extractions into several 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 LCA 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 [40], 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 [16], 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 39.5 MJ/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 1.36 MJ 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.

The LCA in this work is a cradle to gate study that considers material and fuel extraction, transportation, fuel manufacture and drying, HTW gasification and methanol synthesis. Capital goods are not included.

Results and Discussion

Technical results

To date an industrial scale system of around 900 MWth has been simulated using different Lignite and SRF blending ratios (i.e., 80/20, 50/50, 20/80) based on a mass basis. Table 2 shows the main input and output streams of the Lig2Liq systems. Increasing the SRF ratio from 20 to 80% will increase Methanol production by 17.7%. Waste heat recovery similar increases with increasing SRF.

Table 2 The main technical results for the three cases

	Lignite to SRF		
Feedstock blending ratio	80%/20%	50%/50%	20%/80%
Lignite (tonne/hr)	120	75	30
SRF (tonne/hr)	30	75	120
Total thermal input (MWh/hr)	800	867	935
Electricity consumption (MWh/hr)	53.0	56.4	60.2
Raw methanol production (tonne/hr)	70.4	75.2	82.9
Overall conversion efficiency, %	73.7	73.9	74.7

Economic Results

Capital Costs

The capital expenditure (CAPEX) requirement for the whole methanol production plant is estimated by using ECLIPSE software package. It is assumed that the storage stores the feedstock for at least 48 h in a carbon steel storage tank. The feedstock is then conveyed from the storage tank to a supply vessel. The capacity of the supply vessel is set to 150 tonnes, this supports the gasifier for a one-hour run. As mentioned, the HTW gasifier cost is calculated by using structure dimensions of the gasifier and operating conditions. Based on a preliminary process configuration, it is estimated that the installed capital cost, with an installation factor of 2.65, for the HTW gasifier, is about €135.56 million. This cost includes labour for handling and installing bare equipment, and materials for piping, valves, civil works, instruments, structure, painting, and insulation, electrical, erection and indirect costs. The estimated total capital requirement amounts to €317.35 million, if feedstock storage, the fuel feeding system, the oxygen plant, and balance of plant (BOP) are included. The costs of the gasification section are substantially high. However, it must be mentioned that the required capital cost for the lignite drying process (based on a rough estimate) is included.

After the initial particulate removal is accomplished by the cyclones, raw syngas is cooled through heat exchanges with steam generation. A wet scrubber is also used to remove impurities such as particulates and ammonia along with any residual tars. The next section of the process conditions and cleans the syngas so that the syngas can be synthesised into methanol. The installed costs for gas cleaning, the CO shift conversion, acid gas removal (the Rectisol process) and sulphur recovery systems are estimated as €190.67 million.

The methanol synthesis process plant uses low-pressure synthesis loops with copper-based catalysts. A multibed catalytic reactor with intercooling is designed to minimize reactor size. The cost for the methanol synthesis section is estimated as €65.69 million.

For the methanol production plant, with a capacity range of 1690 to 1989 tonne per day of raw methanol, the total plant capital cost is €688.77 million, including building, ancillary facility, and owner costs. Adding plant construction, commissioning time and contingency to the plant increases the total capital investment to €751.38 million. Owner costs and contingency depend on the technology and amount of owners work before the project is commissioned. As a typical chemical plant, both the owner's cost and the contingency are taken as 10% of the EPC price.

Estimation of operation and maintenance costs for methanol production plants

The whole yearly cost of plant operation and maintenance for the methanol plant is shown in Table 3. In this study, the expected equivalent availability of the plant is assumed to be 7,884 h during the operational years. Within the O&M cost, consumables such as electricity, solvent and water consumption, waste disposal, labour, administration and general overheads, annual maintenance (materials and labour) and insurances are included. Catalyst costs are not estimated on an annual basis since the catalysts for all reactors are assumed to be replaced every 3 years.

Estimation of project cost contingency for methanol production plants

To pursue the completion of the project within the construction budget the project cost contingency will be estimated carefully and added to the project execution by using Monte Carlo simulation (@Risk 8.2 software) which is the most widely used method for estimating the required cost contingency [41]. This is the cost contingency that must be added to the sum of the base cost estimate. Figure 3 illustrates the result of the overall cost distribution generated by the Monte Carlo simulation. For the methanol plant, it was found that the cost has a 26.5% likelihood of being equal to, or less than the estimated capital cost and 73.5% chance of being cost overrun. If the baseline budget is set to 688.78 M€, and the

Table 3 O&M costs for the methanol production plant

	Lignite to SRF		
Fuel blending ratio	80%/20%	50%/50%	20%/ 80%
Annual lignite cost (M€/a)	48.63	30.39	12.16
Annual SRF (M€/a)	− 10.65	− 26.61	− 42.57
Annual utility usages (i.e., Electricity, water, and solvent, etc.) (M€/a)	66.97	69.39	73.78
Operating, maintenance and service labour, overheads, and spare parts (M€/a)	21.89	22.25	22.50
Insurance cost (M€/a)	6.81	6.81	6.81
Total O&M (M€/a) (net)	132.65	102.23	72.73
Income from sale of LP/MP steam (M€/a)	–	7.89	19.30

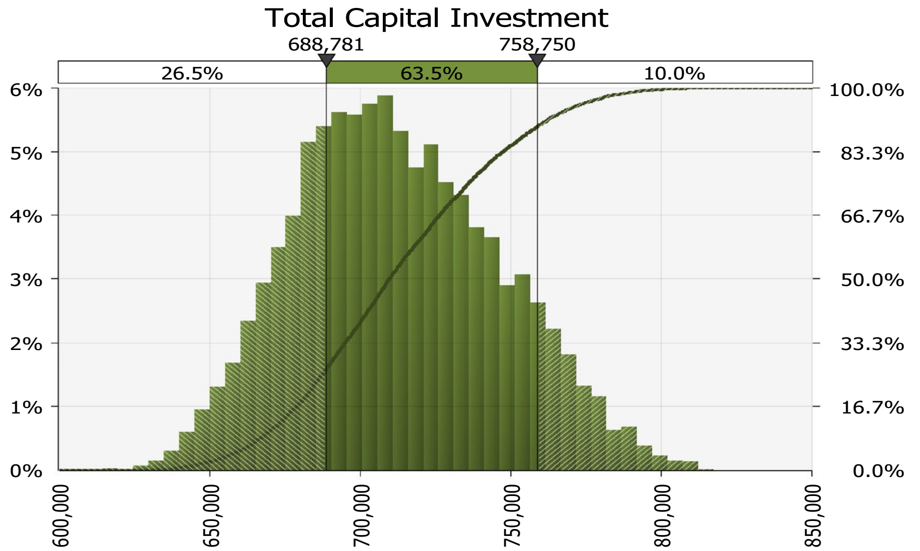


Fig. 3 Probability Distribution for the Total Project Capital Cost

Table 4 Cost structure for the methanol production plant

	Lignite to SRF		
Fuel blending ratio	80%/20% (Case 1)	50%/50% (Case 2)	20%/80% (Case 3)
Total installed cost (M€)	626.15	638.69	641.51
Owner cost (M€)	62.62	63.87	64.15
TCI (Inc. Contingency) (M€)	751.38	766.43	769.82
Annual feedstock cost (M€)	37.98	3.78	− 30.42
Annual O&M costs (M€)	94.67	98.40	103.24
Annual CAPEX return (M€)	75.27	76.77	77.11
Gross annual income (M€)	208.14	178.95	149.93
BESP (€/t Methanol)	389	287	199
Payback period (DCF = 8%)	20.9 (years)		

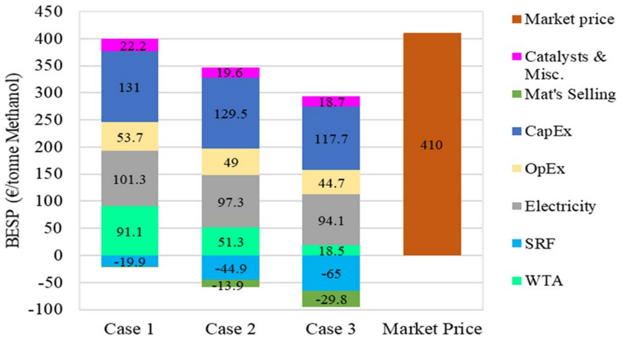


Fig. 4 Breakdown of Individual Cost Components for Methanol Production

estimated contingency is expected to have a 90% chance of not being exceeded, then the probabilistic project cost would be 758.75 M€. Equivalently, the expected contingency is around 10% of the original budget estimated.

Economic assessment results

Net Present value calculations were performed to determine the breakeven selling price (BESP) (Minimum selling price in markets) of produced methanol using the discounted cash flow rate (DCF) of return analysis. The significant economic parameters (e.g., annual CAPEX return, BESP and Payback Period) are shown in Table 4. The BESP represents the selling price of methanol in a 25-year period (project design lifetime) with a capacity factor of 90%. The BESPs also assume that the SRF is available at negative charges.

Using assumed boundary conditions, the calculated capital investment, and O&M costs, the BESPs of methanol produced are estimated to be €389, €287 and €199/tonne for Cases 1, 2 and 3 respectively. Figure 4 illustrates the cost contribution to BESP for feedstocks, electricity, capital investment, and O&M costs by process areas for methanol (the contribution in terms of €/tonne of methanol). Both capital charges and electricity costs dominate the BESP in comparison with the operating costs.

The lowest methanol production prices are found for cases using the blend of lignite/SRF at the ratio of 20%:80%. This is because the SRF would help to offset up to 33% of product costs. Case 1 is unfavourable since there is little margin for profits compared to current methanol market prices. The income from by-products, such as low-grade heat and sulphur recovered decreases the product selling price. But the impact is minor. Regarding the average market price of methanol reported by Methanex (€410/tonne in Methanex reference [42]) in Europe is much higher than the BESP of the cases in this study because their prices may include other significant costs of methanol refinery, and distribution.

Economic Sensitivity Study

Regarding first-of-a-kind engineering costs for new plant designs characterised by higher lead times, construction delays and increased techno-economic uncertainties, the total capital investment can be considered as volatile, imposing a negative impact on the plant profits and competitiveness. This unpredictability is expressed in the sensitivity analysis performed within this report at ± 30% of capital investment.

Figures 5, 6, 7, 8, 9, 10, 11 illustrates the results of the sensitivity analysis. The results indicate that when the capital investment is varied from -30% to + 30%, the BESP will be increased by 21.9%, 27.1% and 33.5% for Cases 1, 2 and 3 respectively, Fig. 5.

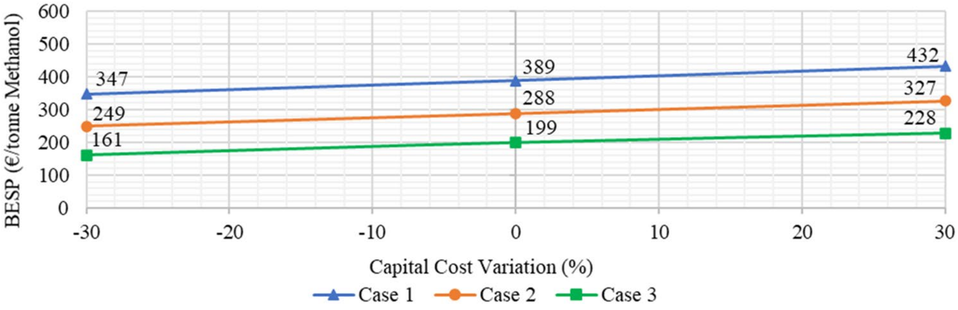


Fig. 5 BESP versus Capital Costs for the Methanol Plant

Fig. 6 BESP versus Plant Availability for the Methanol Plant

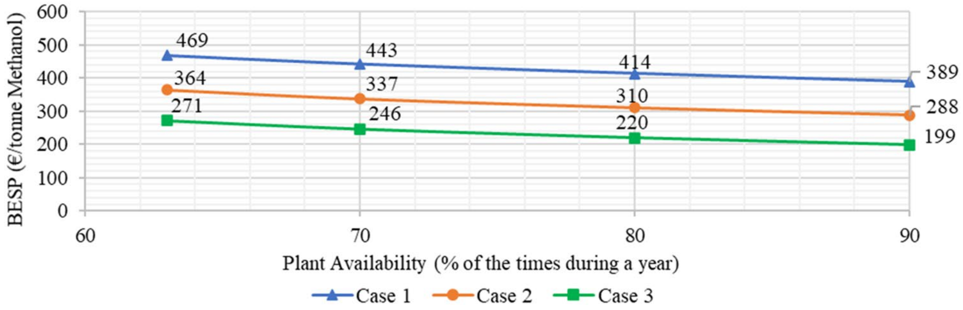


Fig. 7 BESP versus the DCF Rate for the Methanol Plant

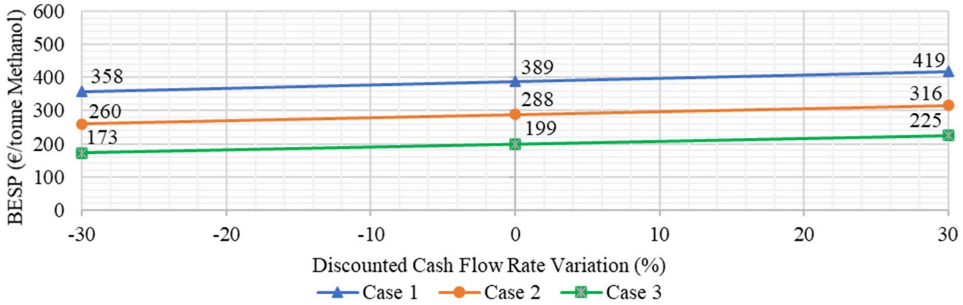


Fig. 8 BESP versus the Price of Lignite for the Methanol Plant

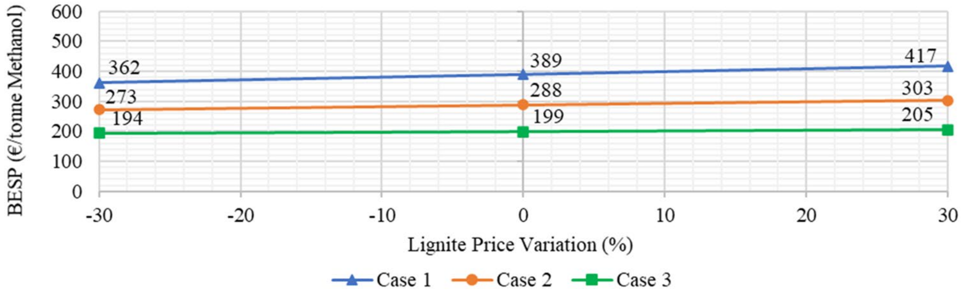


Fig. 9 BESP versus the Price of SRF for the Methanol Plant

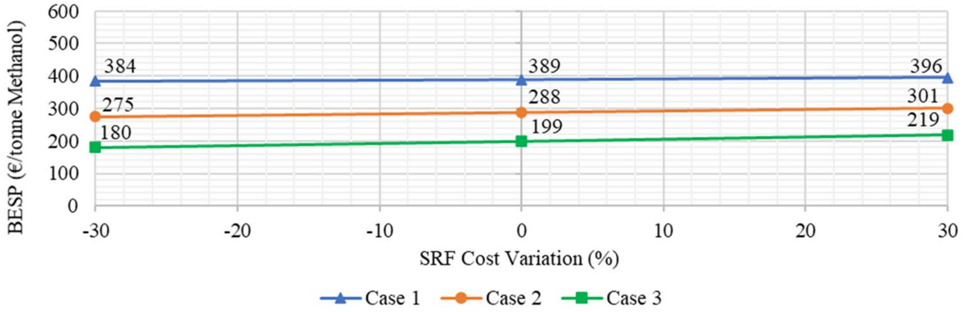


Fig. 10 BESP versus O&M Costs for the Methanol Plant

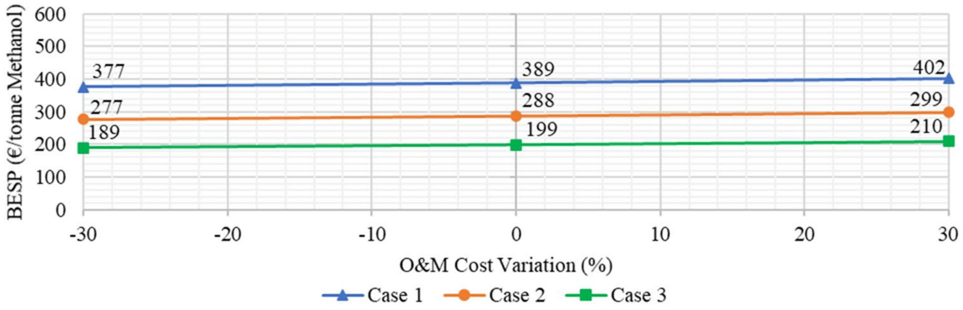
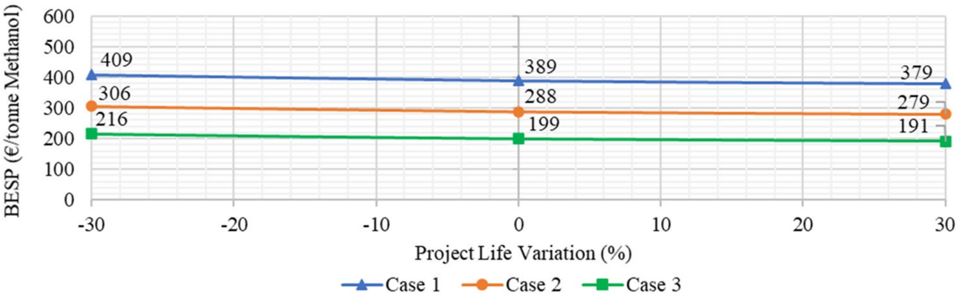


Fig. 11 BESP versus Project Life for the Methanol Plant Table 5: Impact Characterisation ReCiPe 2016 Midpoint 1 kg of Methanol



The next important factor analysed was the plant availability. The results indicate that when the plant availability is reduced by 30%, the BESP will be increased by 20.6%, 26.3% and 36.2% for Cases 1, 2 and 3 respectively. However, it is worth mentioning that the availability of an actual fuel synthesis plant would be unlikely to be lower than 85% after carrying out a series of trials.

It can be seen from Fig. 7 that when the DCF rate is changed from -30% to + 30% (the base DCF rate is 8%) the BESP will be increased by 15.9%, 19.4% and 26.1% for Cases 1, 2 and 3 respectively.

If the lignite price is varied from -30% to 30% the BESP will be increased by 14.1%, 10.4% and 5.5% for Cases 1, 2 and 3 respectively. The BESP becomes less sensitive to lignite prices when the blend ratio of lignite to SRF is low, Fig. 8.

Figure 9 indicates that when the SRF price is varied from -30% to + 30%, the BESP will be increased by 3.1%, 9.0% and 19.6% for Cases 1, 2 and 3 respectively. The BESP becomes more sensitive to SRF prices when the blend ratio of Lignite to SRF is low.

Figure 10 indicates that when the O&M cost is varied from -30% to + 30%, the BESP will be increased by 6.4%, 7.6% and 10.6% for Cases 1, 2 and 3 respectively. Compared with capital investment and availability of plants, the influence of O&M cost on BESP is modest.

Figure 11 indicates that when the project life is varied from -30% to + 30%, the BESP will be reduced by 7.7%, 9.4% and 12.6% for Cases 1, 2 and 3. Again, compared with capital investment and availability of plants, the influence of project life on BESP is modest.

Environmental Results

The LCI for the feedstocks, each case scenario and each process stage has been conducted. The data can be found in Appendix.

Methanol Midpoint Results.

The ReCiPe method has 18 midpoint indicators. The characterisation results of each case and the natural gas reformer to produce 1 kg Methanol are shown in Table 5. The units for each indicator are also shown. The units change for each indicator and are uncommon, thus the indicators are not directly comparable. In many of the indicators, such as, human carcinogenic and terrestrial ecotoxicity etc., the impact reduces as the SRF is increased in the feedstock mix. However, the impacts do not reduce sufficiently to be on par with the natural gas reformer. Some indicators, such as, fine particulate matter formation is increased with increasing fractions of SRF in the feedstock mix.

Sustainability Optimisation Study.

CO_2 reduction in the methanol process and other fuel processes is a key goal within the EU. In Table 5 as the SRF is increased in the feedstock mix, the Global Warming indicator decreases. However, for Case 3, which has the lowest Global Warming impact of the three cases that includes the Lignite/SRF to methanol pathway, its impact is still much greater than the natural gas reformer. To lower the Global Warming Impact, a sustainability optimisation study, which considers flue gas conditioning techniques, was performed with the aim of reducing the Global Warming Impact. Therefore, the LCI was reviewed, and it was seen that the emissions in the acid gas removal stage and the methanol synthesis stage, had high CO_2 and methane components respectively.

Considering the Methanol Synthesis stage first, Table 6 shows the elements available for off-gas recovery and the potential for heat generation. For this analysis, it is assumed that the heat generated offsets the requirement for heat to be generated by a natural gas elsewhere, and that the heat is utilised.

The emissions in the acid gas removal stage contained 31.56 kg, 31.56 kg and 31.93 kg of CO_2 for Case 1, Case 2, and Case 3 respectively. In each case, this accounted for approximately 92% of the emission stream, and is suitable for capture, compression, and storage, without the requirement of a carbon separation technology. An indicative assessment of the impact of carbon capture was studied. Figure 12 shows the impact of carbon capture and off-gas recovery on the Global Warming impact.

In terms of Global Warming Impact, Cases 1–3 are negative once heat recovery and CO_2 capture is considered. To achieve the negative values, the SRF avoids sending waste to landfill and therefore, avoids the associated emissions, the heat that is generated from the off-gas recovery offsets heat generation from natural gas and the high purity CO_2 stream from the acid gas removal stage is captured for storage.

Table 5 Impact Characterisation ReCiPe 2016 Midpoint 1 kg of Methanol

Impact category	Unit	Case 1	Case 2	Case 3	Reformer
Global warming	kg CO2 eq	7.19E+00	6.21E+00	5.27E+00	1.32E+00
Stratospheric ozone depletion	kg CFC11 eq	2.61E-07	2.43E-07	2.20E-07	9.22E-08
Ionizing radiation	kBq Co-60 eq	1.84E-01	1.93E-01	1.95E-01	3.38E-02
Ozone formation, Human health	kg NOx eq	2.12E-02	2.19E-02	2.19E-02	7.23E-04
Fine particulate matter formation	kg PM2.5 eq	2.32E-03	2.47E-03	2.53E-03	4.29E-04
Ozone formation, Terrestrial ecosystems	kg NOx eq	2.50E-02	2.54E-02	2.51E-02	7.77E-04
Terrestrial acidification	kg SO2 eq	7.10E-03	7.56E-03	7.72E-03	1.33E-03
Freshwater eutrophication	kg P eq	7.96E-03	4.85E-03	2.00E-03	6.23E-05
Marine eutrophication	kg N eq	6.07E-03	6.32E-03	6.37E-03	5.68E-06
Terrestrial ecotoxicity	kg 1,4-DCB	1.79E+00	1.67E+00	1.50E+00	1.19E-01
Freshwater ecotoxicity	kg 1,4-DCB	2.24E-01	1.50E-01	8.21E-02	2.91E-03
Marine ecotoxicity	kg 1,4-DCB	3.08E-01	2.05E-01	1.13E-01	4.03E-03
Human carcinogenic toxicity	kg 1,4-DCB	3.60E-01	2.25E-01	1.02E-01	3.88E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	9.42E+00	6.39E+00	3.70E+00	8.83E-02
Land use	m2a crop eq	9.58E-02	9.71E-02	9.52E-02	1.50E-02
Mineral resource scarcity	kg Cu eq	8.65E-04	5.59E-04	2.79E-04	1.95E-04
Fossil resource scarcity	kg oil eq	9.45E-01	6.71E-01	4.10E-01	9.43E-01
Water consumption	m3	8.64E-03	8.66E-03	8.59E-03	5.10E-03

Table 6 Available elements for off-gas recovery and heat generated

Available elements for off-gas recovery and heat generated					
	Case 1	Case 2	Case 3	Reformer	Unit
Methane	3.234	3.4065	3.6496	–	kg
Hydrogen	0.3327	0.3689	0.4092	1.6847	kg
Hydrogen Sulphide	0.0016	0.0013	0.0009	–	kg
Heat Generated	202	235	255	226	MJ

A single score in LCA is an aggregation of all the midpoint indicators into endpoint results, that are then normalised, weighted, and summed together to give a single numerical score for the process. Figure 13 shows the single score for the three cases and the natural gas reformer with and without off-gas recovery and carbon capture. Once all the environmental indicators are considered, Case 3 with 20% Lignite and 80% SRF, has a lower score than the natural gas reformer.

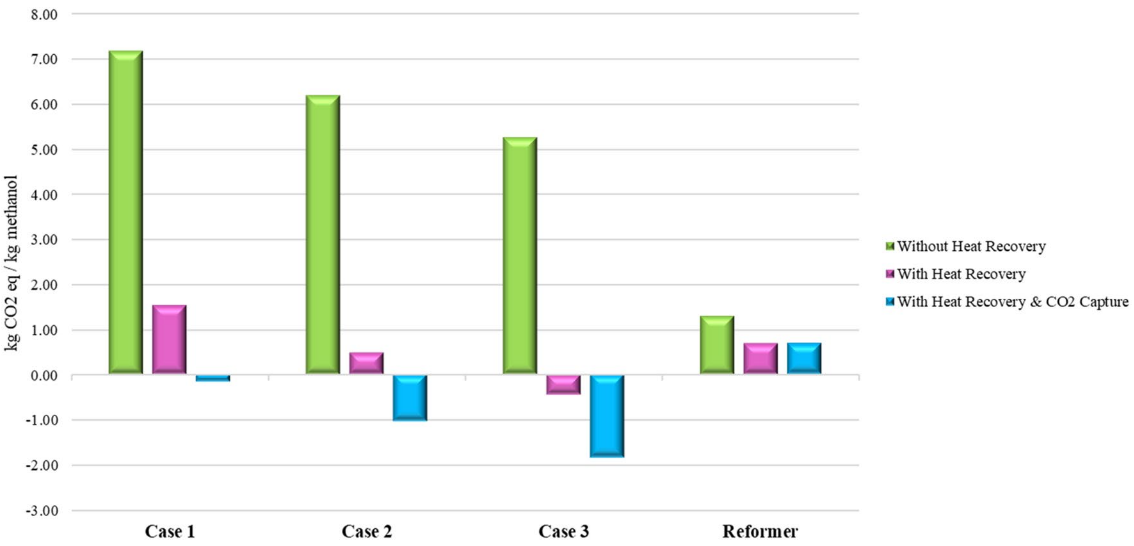
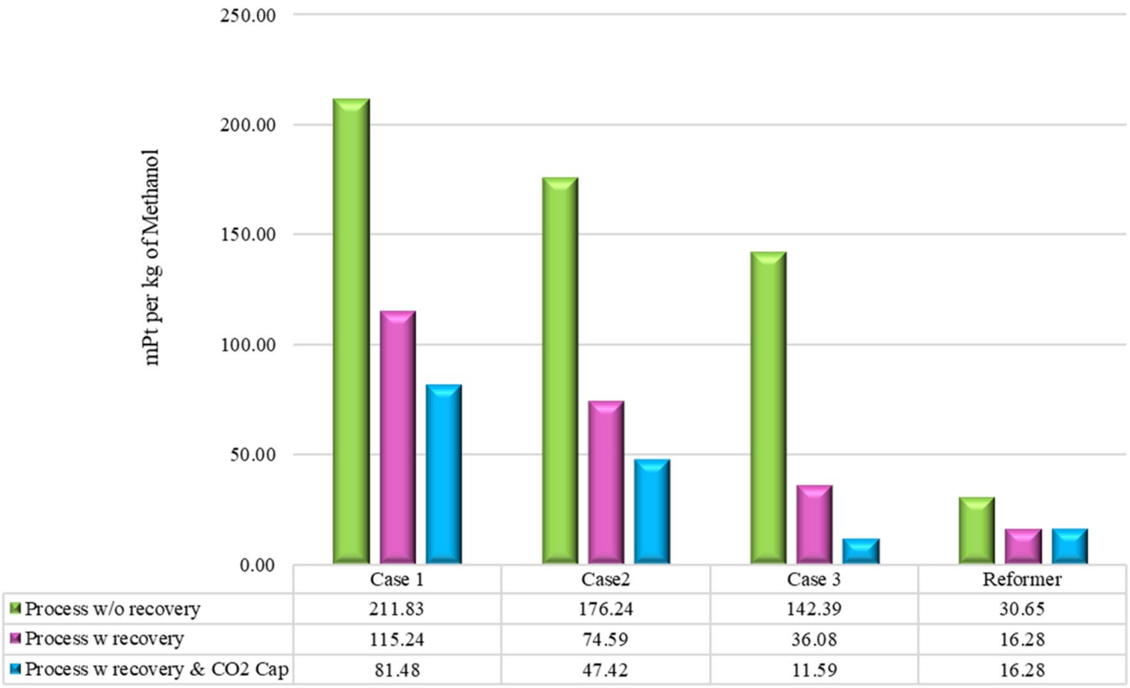


Fig. 12 Global Warming Impact with and without Heat Recovery and CO_2 Capture



	Case 1	Case2	Case 3	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

Fig. 13 Single Score Assessment of Whole Process

Sensitivity Study: Testing the Waste Avoidance Assumption

In the initial study, the landfill waste was modelled as an avoided product, i.e., by producing SRF, a quantity of waste is no longer is sent to landfill, and the SRF process receives an environmental credit for avoiding landfill and the associated emissions and pollutants. In this section, the impact of this assumption is examined. The scenarios previously discussed, the nominal process and the process with recovery and capture included in the study. This time, the SRF process does not get an environmental credit for not sending waste to landfill. Waste collection, sorting and transportation is still modelled but the waste itself, as an input, is neutral.

Figure 14 and Fig. 15 show the results of this study on the Global Warming impact and the Single score respectively. As the SRF increases in the feedstock mix from Case 1 to Case 3, the waste avoided product assumption becomes more critical with an increase in the Global Warming indicator of 9%, 25% and 42% respectively, for the scenario without recovery and capture. In the scenario with recovery and capture, the Global Warming indicators for all three cases, have moved from negative (environmentally beneficial) to positive (environmentally damaging) impact. In terms of the Global Warming impact, the scenarios with recovery and capture, are environmentally better than the natural gas reformer, which only has heat recovery, even when landfill avoidance is not considered.

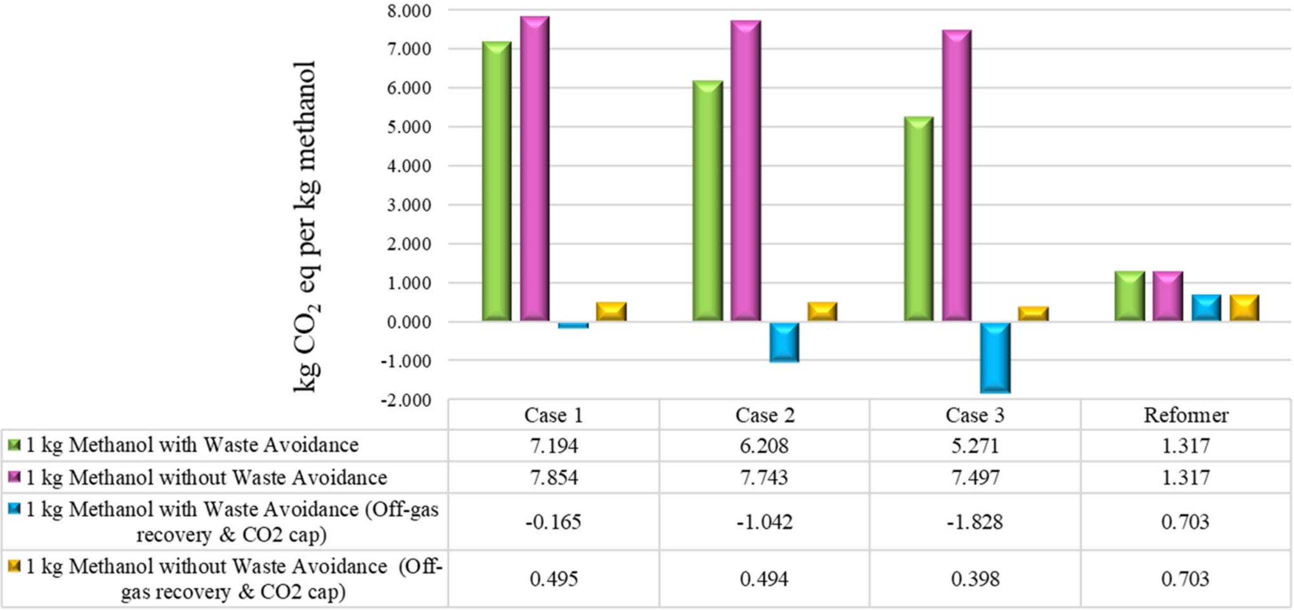
Once all the environmental indicators are considered, the Single Score for Case 3 with recovery and capture and no waste avoidance, is over four times greater than the same scenario when waste avoidance is considered. This makes it a more damaging process than the natural gas reformer, though, still the least damaging of the processes that use feedstocks native to the EU.

This shows that the landfill avoidance is a critical assumption in processes that utilise SRF. An overestimation of the benefits of avoiding landfill would overestimate the environmental benefits of processes that utilise SRF as a feedstock. Underestimation would do the opposite. To improve the certainty and capture the full benefit of utilising landfill waste for fuel production, a detailed study of the impact on avoiding sending waste to landfill is recommended.

Interpretation.

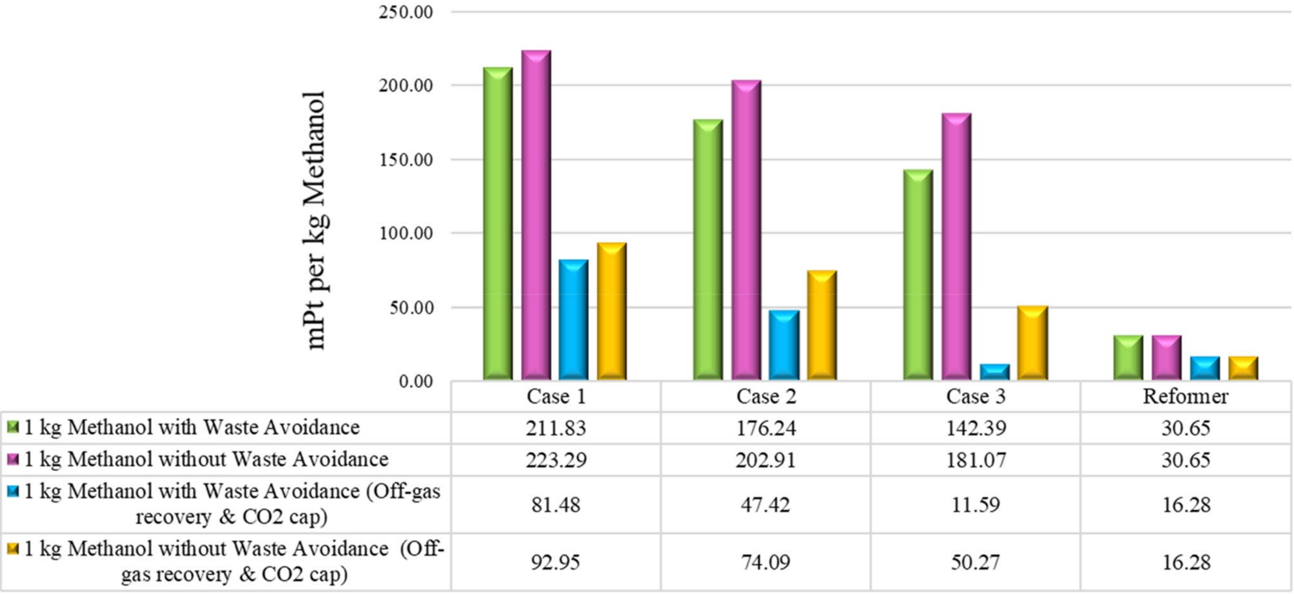
The goal of this study was to evaluate the environmental impact and sustainability of the methanol production produced from three SRF and Lignite cases with increasing proportions of SRF in the feedstock mix. The first step was to construct mass and energy balance models within the ECLIPSE software and validate the results with data from the wider project. The results from the mass and energy balance model were then used to inform the economic assessment and the LCA. 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. All processes are compared on a per kg of methanol produced basis.

The midpoint analysis shown in Table 5 shows that for the most part, reducing lignite in the Lig2Liq process has



	Case 1	Case 2	Case 3	Reformer
🟩 1 kg Methanol with Waste Avoidance	7.194	6.208	5.271	1.317
🟪 1 kg Methanol without Waste Avoidance	7.854	7.743	7.497	1.317
🟦 1 kg Methanol with Waste Avoidance (Off-gas recovery & CO2 cap)	-0.165	-1.042	-1.828	0.703
🟨 1 kg Methanol without Waste Avoidance (Off-gas recovery & CO2 cap)	0.495	0.494	0.398	0.703

Fig. 14 Global Warming Impact with and without Heat Recovery and CO_2 Capture, Testing Waste Avoidance Assumption



	Case 1	Case 2	Case 3	Reformer
🟩 1 kg Methanol with Waste Avoidance	211.83	176.24	142.39	30.65
🟪 1 kg Methanol without Waste Avoidance	223.29	202.91	181.07	30.65
🟦 1 kg Methanol with Waste Avoidance (Off-gas recovery & CO2 cap)	81.48	47.42	11.59	16.28
🟨 1 kg Methanol without Waste Avoidance (Off-gas recovery & CO2 cap)	92.95	74.09	50.27	16.28

Fig. 15 Single Score Assessment of Whole Process, Testing Waste Avoidance Assumption

environmental benefits in most of the indicators. However, natural gas reforming is again shown to have the least impact on all the indicators except for fossil resource scarcity. This is similar to other studies previously mentioned that considered solid fuel feedstocks to natural gas for methanol production. In the sustainability optimisation study, the Global Warming Impact indicator was analysed in more detail (Fig. 12) for the original study and for flue gas process recycling and treatments, namely, off-gas recovery and carbon capture. For the original study, The Global Warming Impact reduced as the quantity of SRF increased in the feedstock mix, however the reduction was modest and even for Case 3, the Global Warming Impact was four times greater than for the natural gas reformer. On review of the emissions in the acid gas removal stage and the methanol synthesis stage, it was found that there were large amounts of methane and CO_2 respectively, emitted. This led to testing the impact of off-gas recovery from the methanol synthesis stage and CO_2 capture from the acid gas removal stage. The results can be found in Fig. 12. For all three cases, the off-gas recovery, which received an environmental credit for off-setting natural gas heat generation, lowered the Global Warming impact, and for Case 3, resulted in a negative impact. Once carbon capture was also considered, all three cases had a negative score for the Global Warming impact. In comparison to the Natural Gas Reformer, all three cases with flue gas conditioning, apart from Case 1 with off-gas recovery but not CO_2 capture, had a lower Global Warming impact than the Natural Gas Reformer. This is on trend with what was stated in [7], flue gas process recycling and treatments, could reduce the burden from coal to methanol production. In this case, flue gas recycling and treatment can reduce the carbon burden from SRF and Lignite to methanol production. Figure 13 considered the Single Score of the flue gas conditioning process, taking into consideration all the environmental indicators. Again, as SRF is increased in the feedstock mix, the single score reduces, however, only Case 3 with off-gas recovery and carbon capture is environmentally better than the Natural Gas Reformer.

The assumption that the SRF process receives an environmental credit for diverting waste from landfill, as a significant impact on both the Global Warming impact and Single Score results, more so, as the quantity of SRF is increased in the feedstock mix. This assumption was removed and the waste input to the SRF process set to neutral. The Global Warming impact and Single Score results are shown in Fig. 14 and Fig. 15 respectively. The three cases with flue gas conditioning and no environmental credit for landfill avoidance still have a lower impact score for Global Warming than the Natural Gas Reformer. However, once all indicators are considered in the Single Score the natural gas reformer is environmentally better than the three cases. This indicates that a comprehensive study should be carried out to fully understand the benefit of avoiding sending waste to landfill.

There are other operations that could be considered to lower the environmental burdens of SRF to methanol production that have not been tested here. These include onsite renewable electricity generation for the SRF to methanol process, considering the process location to reduce freight distances and examining procurement procedures to ensure materials brought into the process are manufactured in line with environmental best practice. This agrees with [3, 7], whereby they recommend the improvement of current methanol pathways by improving efficiency, including renewable energy, and reducing water consumption.

Conclusions

Lignite and SRF are fuels that are native to the EU. Their utilisation to produce high value fuels such as methanol would increase security of supply within the block. However, the EU also has the aim to decarbonise fuel production to achieve climate commitments, and to ensure that energy and fuel supplies remain economically competitive.

The ECLIPSE process simulator has been used successfully to model and simulate the Lignite/SRF to methanol process. Based on the results of mass and energy balance generated, the installed capital investment and operational costs are estimated, and the LCA performed. Both the economic and environmental analysis favour the feedstock ratios with higher quantities of SRF. From the economic perspective, this is due to the valorisation of landfill waste materials, and from the environmental perspective, it is due mainly to the avoidance of associated landfill pollutants.

Increasing SRF in the feedstock mix increases the total capital investment, ranging from €751 million to €770 million, and the Annual O&M costs, €95 to €103 million. However, the Annual feedstock costs are reduced from €38 to €-30 million, thus, the BESP is reduced by 49%, from €389/tonne for Case 1, to €199/tonne for Case 3. The BESP is affected by many different factors that can be technical, environmental, or economic. The three main parameters that have a strong influence on the plant economic performance are as follows, the first factor is the availability of the plant, this plays a critical influence on the BESP. High availability has always been recognised as one of the key parameters to achieve competitiveness in the fuel market, as it allows capital costs to be recovered more quickly. The sensitivity to the plant availability of methanol plants varies from €2.40 to €2.66/tonne per percent change in plant availability. The next economic parameter that influences the BESP is the capital investment, which represents one of the most important factors in achieving competitiveness. The sensitivity to the capital investment of methanol plants varies from €1.11 to €1.42/tonne per percent change in capital investment. The costs related to the time value of the money, such as borrowing costs, inflation, and depreciation, are also an important aspect of the economic viability of the project. The sensitivity of the methanol plants to DCF ranges from €0.87 to €1.02/tonne per percent change in DCF.

Increasing SRF in the feedstock mix decreases the Global Warming impact even when landfill avoidance is not considered in the model. Furthermore, by employing tail end flue conditioning technologies, such as, methane heat recovery and carbon capture, the SRF/Lignite to methanol production pathway can become more sustainable. Utilising more general actions, including the installation of renewable electricity can further increase sustainability.

Appendix: LCI data tables used in the LCA study

See Tables 7, 8, 9 and 10

Table 7 LCI Case 1 (20% SRF/80% Lignite)

		Input			Wastes & Emissions			Product		
	Process	Name	Value	Unit	Name	Value	Unit	Name	Value	Unit
Case 1	Gasifier	Electricity	1.0382	MJ	Ash	0.3070	kg	Raw syngas	3.6288	kg
	Cold Scrub	Water	1.8358	kg	ASH	0.0586	kg	Clean syngas		kg
		Electricity	0.0398	MJ	Water H2O (L)	0.0010	m^3			
					HCL	0.0002	kg			
					Ammonia	0.0229	kg			
	Shift Reaction	Electricity	0.0209	MJ	Water (L)	0.0003	m^3	Syngas	3.3009	kg
	Acid gas removal	Methanol	0.1147	kg	Methane	0.0005	kg	H2, CO Gas	1.2749	kg
		Electricity	0.9720	MJ	Carbon monoxide	0.0005	kg			
					Carbon dioxide	1.6094	kg			
					Hydrogen	0.0002	kg			
					Hydrogen sulphide	0.0015	kg			
					Methanol	0.1280	kg			
					Ammonia	0.0001	kg			
					Nitrogen dioxide	0.0138	kg			
	Methanol synthesis	Electricity	0.3151	MJ	Methane	0.1647	kg	Methanol product	1.0000	kg
					Carbon monoxide	0.1260	kg			
					Carbon dioxide	0.0031	kg			
					Hydrogen	0.0168	kg			
					Hydrogen sulphide	0.0001	kg			
					Methanol	0.0005	kg			
					Nitrogen dioxide	0.00001	kg			

Table 8 LCI Case 2 (50% SRF/50% Lignite)

		Input			Wastes & Emissions			Product		
	Process	Name	Value	Unit	Name	Value	Unit	Name	Value	Unit
Case 2	Gasifier	Electricity	1.1379	MJ	Ash	0.2590	kg	Raw syngas	3.6132	kg
	Cold Scrub	Water	1.8191	kg	Ash	0.0522	kg	Clean syngas	2.9177	kg
		Electricity	0.0373	MJ	Water H2O (L)	0.0010	m^3			
					HCL	0.0001	kg			
					Ammonia	0.0244	kg			
	Shift reaction	Electricity	0.0196	MJ	Water (L)	0.0005	m^3	Syngas	3.2317	kg
	Acid gas removal	Methanol	0.1077	kg	Methane	0.0005	kg	H2, CO Gas	1.3293	kg
		Electricity	0.9124	MJ	Carbon monoxide	0.0010	kg			
					Carbon dioxide	1.5108	kg			
					Hydrogen	0.0002	kg			
					Hydrogen sulphide	0.0010	kg			
					Methanol	0.1202	kg			
					Ammonia	0.0001	kg			
					Nitrogen dioxide	0.0148	kg			
	Methanol synthesis	Electricity	0.2958	MJ	Methane	0.1632	kg	Methanol product	1.0000	kg
					Carbon monoxide	0.1340	kg			
					Carbon dioxide	0.0029	kg			
					Hydrogen	0.0177	kg			
					Hydrogen sulphide	0.00005	kg			
					Methanol	0.0005	kg			
					Nitrogen dioxide	0.000005	kg			

Table 9 LCI Case 3 (80% SRF/20% Lignite)

		Input			Wastes & Emissions			Product		
	Process	Name	Value	Unit	Name	Value	Unit	Name	Value	Unit
Case 3	Gasifier	Electricity	1.1963	MJ	Ash	0.2301	kg	Raw syngas	3.4572	kg
	Cold Scrub	Water	1.7803	kg	ASH	0.0460	kg	Clean syngas	2.7785	kg
		Electricity	0.0339	MJ	Water H2O (L)	0.0009	m^3			
					HCL	0.0000	kg			
					Ammonia	0.0256	kg			
	Shift Reaction	Electricity	0.0178	MJ	Water (L)	0.0004	m^3	Syngas	3.0608	kg
	Acid Gas Removal	Methanol	0.0977	kg	Methane	0.0004	kg	H2, CO Gas	1.3196	kg
		Electricity	0.8276	MJ	Carbon monoxide	0.0004	kg			
					Carbon dioxide	1.3865	kg			
					Hydrogen	0.0002	kg			
					Hydrogen sulphide	0.0004	kg			
					Methanol	0.1090	kg			
					Ammonia	0.0001	kg			
					Nitrogen dioxide	0.0152	kg			
	Methanol Synthesis	Electricity	0.2683	MJ	Methane	0.1585	kg	Methanol product	1.0000	kg
					Carbon monoxide	0.1350	kg			
					Carbon dioxide	0.0026	kg			
					Hydrogen	0.0178	kg			
					Hydrogen sulphide	0.00004	kg			
					Methanol	0.0004	kg			
					Nitrogen dioxide	0.000004	kg			

Table 10 LCI Natural Gas Reformer

	Reformer								
	Inputs			Emissions & Wastes			Products		
Reformer	Water	5.323	kg	Argon	0.0681	kg	Clean gas	1.2116	kg
	Electricity	0.746	MJ	Carbone dioxide	0.7651	kg			
	NG	0.080	kg	Water	0.6164	kg			
				Nitrogen	3.9965	kg			
				Oxygen	0.1503	kg			
				Water (L)	0.0001	m^3			
Methanol synthesis	Electricity	0.447	MJ	Carbon monoxide	0.1224	kg	Methanol	1.0000	kg
				Carbon dioxide	0.0052	kg			
				Hydrogen	0.0791	kg			
				Methanol	0.0004	kg			
				Nitrogen	0.0042	kg			

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Data Availability Some of the data analysed during the current study are not publicly available due ongoing project and industrial partner involvement, therefore, there is some commercial sensitivity, but are available from the corresponding author on reasonable request. Generated data for the LCA study (the LCI) are published in the appendix. Data taken from other literature or non-open-sourced datasets (Ecoinvent 3) included with the relevant software, are indicated within the text.

Declarations

Conflict of interests The authors declare they have no financial or non-financial interests.

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