INTEGRATED UTILISATION PATHWAYS FOR BIOGENIC CARBON DIOXIDE IN BIOMASS DRIVEN INDUSTRY SECTORS

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ABSTRACT: The climate change forces us to shift from fossil to renewable resources. Integrated utilisation of biogenic CO_2 is a promising way to produce sustainable raw materials and fuels. CO_2 capture and utilisation (CCU) enables sustainable routes for carbon-based products and guiding the development to utilising especially biogenic instead of fossil CO_2 directs the investments towards sustainable targets in the long term. Integrated CCU options benefit from a local CO_2 source – substantially reducing the CO_2 transportation costs, energy integration, customisable CO_2 purity and the possibility to utilise the produced fuels and chemicals on-site. The key objective of this paper is to find out feasible utilisation pathways for biogenic CO_2 in Finnish biomass driven industry sectors. As main results operational costs and incomes as well as profitability indicators are presented for each biogenic CO_2 utilisation pathway.
Keywords: carbon dioxide (CO_2), carbon capture and utilisation (CCU), biogenic, biobased economy, power-to-X

1 INTRODUCTION

The climate change forces the society and the industries to shift from fossil to renewable resources. Mitigation of the climate change will require major changes in energy use, the energy system and industrial production. Integrated utilisation of biogenic CO_2 is a promising way to produce sustainable raw materials in the future energy system, because it may provide fossil-free production methods also for sectors, which are difficult to decarbonise as well as balance intermittent renewable energy production [1]. A world-wide change of the energy system is already going on, which can be seen as major investments on renewable energy, especially solar and wind energy [2]. Raw materials made utilising biogenic CO_2 could have a remarkable role in the future providing also the potential for even negative CO_2 balance, given permanent fixation through mineralisation.

The key objective of this paper is to find feasible near-term utilisation pathways for biobased CO_2 in Finnish biomass driven industry sectors. Finland has traditionally wide and comprehensive experience to utilise wood for example in pulp and paper industry and in energy production. Creation of valuable products from biogenic CO_2, such as synthetic fuels, upgraded biogas and chemicals, could perhaps give additional boost for the Finnish industry.

High share of solar and wind energy challenges energy systems currently and even more so in the future, as the production is intermittent and seasonal. Power-to-gas, or more widely, power-to-product (power-to-X) technologies producing synthetic gaseous fuels or other products have the potential to address the issue of intermittency and simultaneously contribute to the reduction of CO_2 concentration in the atmosphere. In this paper technologies for integrated production of synthetic natural gas (power-to-SNG), methanol (power-to-MeOH) and formic acid (power-to-FA) in conjunction with selected biobased industrial processes have been analysed. In this paper the process environments include a sawmill, a bio-waste digesting biogas plant and a biogas plant at a wastewater treatment plant. Other significant process environments in biobased industries include facilities in the pulp & paper and combined heat & power (CHP) sectors. Power-to-X concepts in these environments have been studied earlier: CHP environment for example in [3] and pulp & paper in [4]. The goal in this study is to identify business candidates for near term deployment in Finland.

The work includes techno-economic feasibility analyses of specific system operations from operator's and investor's point of view in different market scenarios. As main results operational costs and incomes as well as profitability indicators including profit, EBIT, EBIT DA, payback time and LCOF are presented for each biogenic CO_2 utilisation pathway.

2 BACKGROUND

Carbon capture and utilisation (CCU) includes processes in which CO_2 is captured from point sources or air and is then used as a raw material for value-added products [5]. In other words, CO_2 is considered a resource, rather than a harmful greenhouse gas. CO_2 can be used for example in the production of synthetic fuels, bulk and specialty chemicals as well as polymers, and construction materials through mineralisation.

There are three major drivers for CCU:

- reducing the dependency on fossil resources by broadening the resource base,
- climate change mitigation and
- enabling higher penetration of intermittent renewable electricity.

CCU enables sustainable production alternatives utilising only renewable or recycled raw materials and energy. This will help reducing import dependency on fossil feedstocks and increasing energy self-sufficiency and security. Furthermore it promotes transition to a circular economy and offers new business opportunities.

CCU can also enable 'indirect electrification' of processes and products that are difficult to decarbonise with direct electrification. For example electric drive is a feasible solution for passenger cars, whereas aviation and heavy trucks will depend on liquid fuels for years, which may create a business opportunity for CCU.

Carbon capture and utilisation is closely related to carbon capture and storage (CCS), but their impact on CO_2 emissions is different. In CCS the CO_2 is captured and permanently stored in geological formations while in most CO_2 utilisation applications – such as production of fuels or chemicals – the CO_2 is eventually released back into the atmosphere. The climate benefit of such CCU applications comes primarily from the fact that they can reduce the use of their fossil counterparts. Ultimately, the goal should be to use biogenic CO_2 or capture it directly from air to provide a fossil-free source of carbon.

Production of fuels from CO_2 requires an energy source which is typically electricity. The emission factor of electricity will have a crucial impact on the overall climate impact of such fuels; therefore, applications with high shares of renewable energy should be favoured.

The CCU technology portfolio is wide and diverse and so are the related climate impacts. Important factors to consider include the product lifetime, energy consumption, consequences to the energy system and the CO_2 intensity in the replaced fossil product. To guarantee a significant positive climate impact of a CCU process, a life cycle analysis (LCA) is necessary.

One of the main challenges for 100 % renewable energy system having high shares of wind and solar power is to manage the balance between energy supply and demand. For this better interconnectivity of grids, demand side response and energy storages are needed. Producing synthetic fuels from CO_2 and electricity at times of cheap electricity generation offers one attractive solution, especially for long-term or seasonal energy storage.

Compared to current global anthropogenic CO_2 emissions the potential of CO_2 utilisation is quite limited (Figure 1). The estimated long-term potential is one magnitude and the current utilisation two magnitudes lower than the anthropogenic CO_2 emissions. [6; 7] Currently vast majority of the utilised CO_2 is used for synthesis of urea and inorganic carbonates and for boosting methanol production. [7] These applications, however, bind only the CO_2 that was released by earlier production steps. The 'true CO_2 utilisation applications' are just beginning to emerge and thus offer vast growth potential. Still, CCU alone will not solve the climate change problem but can still play a significant role - battling climate change calls for a combination of various technologies.

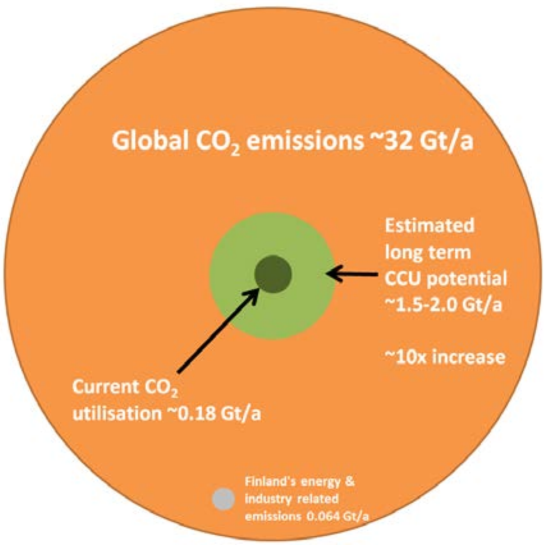


Figure 1: CCU potential versus global CO_2 emissions. [6; 7]

The progress of CCU technologies has been reviewed a number of times lately [7; 8; 9] and the field is rapidly getting more attention. For instance, a single project database [10] comprise more than two hundred CCU related projects from recent years. Most of the research has focused on the following CCU pathways:

- conversion of CO_2 to fuels (e.g. methane and diesel),
- production of chemical intermediates (e.g. methanol, formic acid and syngas),
- new production routes for polymers and
- mineralisation of CO_2 (concrete, waste treatment and building materials).

In Figure 2 these pathways are compared with respect to their technological readiness, market size, number of developers and climate impact mitigation potential.

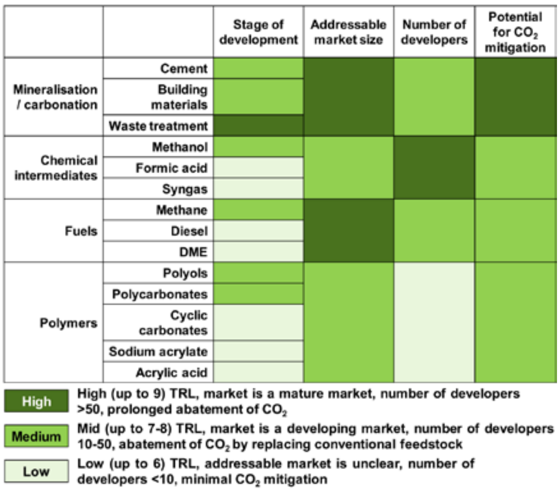


Figure 2: Technological maturity and market analysis of the main CCU pathways. Adapted from [8; 9].

It was seen that for efficient near-term implementation of CCU in the Finnish biobased industries at least the possibilities of the most researched pathways should be investigated.

Another crucial point for the future of CCU and CCS in Finland is that there are no suitable geological formations in Finland for CO_2 storage [11]. Providing means to permanently bind CO_2 into products, such as construction materials, through mineralisation may therefore be of special interest for Finland. One vision for CO_2 utilisation in Finland would be to first utilise CO_2 in concrete curing and continue with developing materials and applications with growing CO_2 storage potential. In the long-term future this would serve as to develop the mineralisation processes efficient enough to make the process economically feasible. Early co-operation between the biomass based industries and the construction material industry could benefit both parties; such co-operation could be eased for example by planning future facilities in close proximity with each other. On the legislative front it is essential to include mineralisation as a valid option for CO_2 storage in the EU ETS.

3 METHODS

3.1 Evaluating economic feasibility in power-to-X processes

The economic feasibility of power-to-X processes is dictated by the costs of process inputs and the values of the products and by-products together with CAPEX and O&M costs. A generic power-to-X process is illustrated in Figure 3.

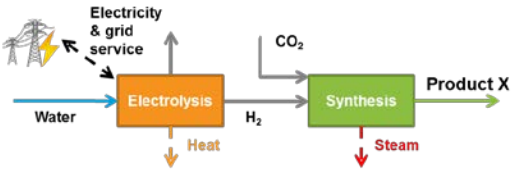


Figure 3: Main inputs and outputs of a generic power-to-X process.

For a power-to-X process, the main inputs are electricity, CO_2, water, (steam) while the outputs are product X, heat, (steam) and oxygen. The value of these inputs and outputs can be markedly different at different sites and each power-to-X process will have specific mass and energy balances. Additional revenue might be generated by taking advantage of the fast load following capability of electrolysers which makes it possible to participate in frequency containment markets. This forms the basis of the economic analysis for this paper.

The first step of the analysis is determining the mass and energy balances for each process and finding out the CAPEX and O&M costs. The economic feasibility analysis is then carried out using a simple hourly operational model which selects the most profitable operation mode for each hour based on the given hourly electricity spot prices and all the other market parameters. The possible operation modes are:

- Full capacity operation
- Frequency containment reserve (FCR) operation
- Stand-by

When capacity is offered for the FCR market named FCR-N [12], the operation set point of the electrolyser is 55% of the max capacity leaving ±45 % of the capacity for FCR. FCR might be significant source of income at least for the first power-to-X plants. The model and the calculation routines are described in closer detail in [3].

The main results of the model include annual operational costs and incomes as well as profitability indicators including profit, earnings before interest and taxes (EBIT); earnings before interest, taxes, depreciation and amortisation (EBIT DA); payback time; pre-tax internal rate of return (pre-tax IRR) and levelised cost of product (LCOP).

3.2 Market scenarios

Two sets of the market related assumptions – representing optimistic and conservative views – are used in the analysis. The conservative scenario depicts the competitiveness of Power-to-X today while in optimistic case favourable assumptions have been made e.g. for the value of products, electricity price and utilisation possibilities of the side-product oxygen.

In the conservative scenario, the realised spot electricity prices in Finland in 2016 are used and the product values have been estimated based on their current value. Furthermore, if there is no demand of oxygen at the site, oxygen is assumed to be vented into atmosphere.

In the optimistic scenario, the average electricity price has been assumed to have been decreased by 20% and price volatility increased by 30% (highest prices are 30% higher and lowest prices 30% lower). The higher price volatility is caused by the assumed increased share of intermittent renewable energy connected to the grid. The products are more valuable due to higher premiums of renewable products or due to price increase of fossil options as the price of crude oil is relatively low at the moment. The costs of CO_2 are lower, which represents either an advantageous site selection or the development of CO_2 capture and purification technologies. Finally, an investment subsidy is assumed to be granted. The subsidy can also represent reduction of CAPEX in future.

3.3 Case descriptions and parameters

In this paper, the feasibility of power-to-X concepts in mechanical wood industry (sawmill) and biogas production are studied. For the sawmill environment, production of three different products are considered while for the biogas case, two different biogas plant types have been studied. The included cases in this paper are:

Case 1: production of SNG at sawmill
Case 2: production of methanol at sawmill
Case 3: production of formic acid at sawmill
Case 4: boosting methane production in an existing biogas plant using bio-waste
Case 5: boosting methane production in an existing biogas plant at a waste-water treatment plant

In Cases 1-3 the integrated production of synthetic natural gas (SNG), methanol (MeOH) and formic acid (FA) at a sawmill site are evaluated. In these cases a 9 MW_e alkaline electrolysis cell (AEC) electrolyser is integrated to the sawmill site with CO_2, power, heat and steam connections. It is assumed that the by-product heat and steam can be fully utilised or sold. In these cases it is assumed that there is no possibility for on-site utilisation of the by-product oxygen.

The integrated SNG production at the sawmill is presented in a block diagram in Figure 4.

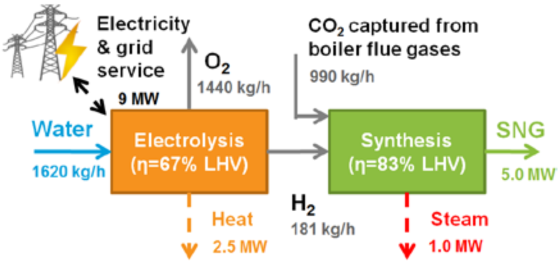


Figure 4: SNG production at the sawmill (Case 1).

The electrolyser uses water and electricity to produce hydrogen for the synthesis and oxygen as a side product. In addition, 2.5 MW of excess heat is generated. The synthesis unit utilises the H_2 from the electrolyser as well as the CO_2 captured from the flue gases of the existing boiler at the sawmill. As a result, 5.0 MW of SNG is produced as well as excess steam.

The integrated MeOH production at the sawmill is presented in a similar block diagram in Figure 5.

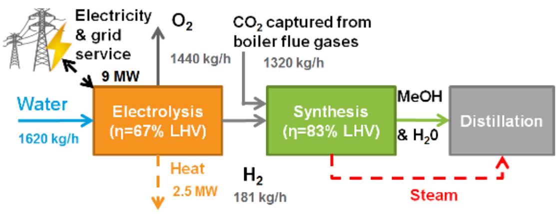


Figure 5: MeOH production at a sawmill (Case 2).

Notable differences to the SNG process are the additional step of distillation and the larger volume of CO_2 used per ton of hydrogen. Moreover, the distillation unit consumes all of the excess steam generated in the synthesis.

Next up, the integrated FA production is presented in a block diagram in Figure 6.

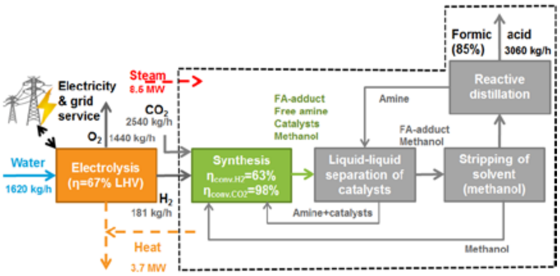


Figure 6: FA production at a sawmill (Case 3).

The FA production involves three additional main steps: liquid-liquid separation of catalysts, stripping of solvent and reactive distillation. In addition, the amine and catalysts are circulated back in the process. The thermal balance is also different; the entire process consumes 8.5 MW steam and generates 3.7 MW of low-temperature heat. The process is presented in closer detail in [13]. Mass and energy balances and cost data for the synthesis section were adopted from [13] and made coherent with the methodology used in this paper.

The key financial parameters used in the first three cases are summarised in Table I.

Table I: Summary of financial parameters in Cases 1-3.

	Optimistic	Conservative
Product:		
Case 1: SNG [€/MWh]	80	60
Case 2: MeOH [€/MWh]	100	70
Case 3: HCOOH [€/MWh]	700	600
Electricity Spot		
Spot price scenario	FIN-2016 * 80 %	FIN-2016
Increased volatility	± 30 %	0 %
Avg. price [€/MWh]	25.6	32.0
Electricity transmission + net taxes [€/MWh]	11	11
FCR scenario:	FIN-2016	FIN-2016
fixed [€/MW, h]	17.4	17.4
CO_2 capture + purif. [€/t_{CO2}]	30	50
O_2 sold [€/t_{O2}]	50	0
Heat sold [€/t_{O2}]	30	20
Steam sold [€/t_{O2}]	30	20
Investment subsidy	30 %	None

It is challenging to estimate the true value of the sustainable products of the studied cases. Therefore the price assumptions in the conservative scenario are estimated with respect to the closest corresponding product in the market today and the optimistic prices estimate the future price with possible benefits from a better brand or 'green premium'. The price of biogas at filling stations has been around 100 €/MWh (approximately 0.93 €/l gasoline equivalent) with 24 % value added tax (VAT), which in turn corresponds to around 80 €/MWh with 0 % VAT [14; 15]. The price includes distribution costs and profit margin and thus the conservative price assumption is lower. The methanol price has varied between 40 and 80 €/MWh depending much on the price of oil [16; 17], It has been estimated that the price of sustainably produced methanol could be around 100 €/MWh [18]. The price of formic acid was 510-600 €/t in 2014 [19] and since then the price has increased several times: by 40 €/t in 2015 [20], by 30 €/t in 2016 [21] and by another 40 €/t in 2017 [22] leading to a more optimistic price estimate of 700 €/t and a conservative price estimate of 600 €/t. The electricity spot prices in 2016 were retrieved from the Nordpool historical data archives [23].

Next, the Cases 4 and 5 in the biogas plant process environment are described. In these cases CO_2 is separated from a biogas plant and utilised in methane synthesis aimed at selling the produced SNG as transportation fuel. In these cases the electrolyser scale of 2 MW_e is chosen, which enables the conversion of all the available CO_2 (220 kg/h) at full load. There are two alternative ways to produce methane: biological methanation and chemical catalysis. Biological methanation is preferred over chemical catalysis in these cases for a number of reasons. Firstly, there is no need for the excess steam at the sites. The process is also more tolerable towards impurities, such as H_2S, the scale is more favourable and the process is likely more familiar to biogas plant operators.

The modelled process in Cases 4 and 5 is the same, with differences only in the economic parameters, such as by-product utilisation, resulting from the different process environment. The process is illustrated in Figure 7.

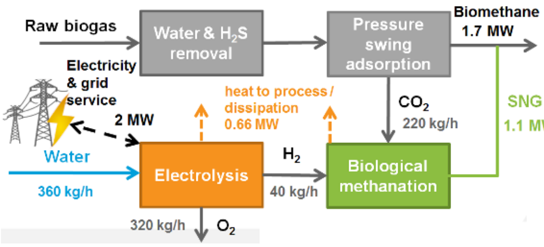


Figure 7: Biogas upgrading through biological methanation (Cases 4 & 5).

H_2S and water are first removed from the raw biogas, after which CO_2 is separated with pressure swing adsorption for the methane synthesis. The hydrogen from the electrolysis is fed to biological methanation and the resulting SNG is added to the produced biomethane.

In Case 4 the amount of heat that can be utilised is assumed to depend on the season as follows: winter 100 % utilisation; 50 % in the spring and in the autumn and 10 % during the summer. The utilised heat replaces raw biogas that otherwise would be used for heating.

In Case 5 there are two possible improvements for the economics: in the wastewater treatment plant there is more demand for heat and the by-product oxygen can be utilised in aeration in the activated sludge process. It is also assumed that the plant consumes district heat. The value of using oxygen instead of air in a plant with traditional air-based aeration is, however, based only on reduction of compressor power. There is also a possibility that the oxygen use in aeration could help to cope with peak loads if the current aeration capacity is insufficient. In plants with high purity oxygen based aeration, the value of O_2 would be higher but no such municipal wastewater treatment plants exist in Finland.

The key financial parameters in Cases 4 and 5 are summarised in Table II.

Table II: Summary of financial parameters in Cases 4 and 5.

	Optimistic	Conservative
Products		
SNG [€/MWh]	85	65
Electricity Spot		
Spot price scenario	FIN-2016 * 80 %	FIN-2016
Increased volatility	± 30 %	0 %
Avg. price [€/MWh]	25.6	32.0
Electricity transmission + net taxes [€/MWh]		
Case 4:	15	15
Case 5:	11	11
FCR scenario:	FIN-2016	FIN-2016
fixed [€/MW, h]	17.4	17.4
CO_2 capture [€/t_{CO2}]	5	10
O_2 sold [€/t_{O2}]		
Case 4:	50	0
Case 5:	50	15
Heat sold [€/t_{O2}]		
Case 4:	80	60
Case 5:	60	50
Investment subsidy	30 %	None

In the biogas plants the value of SNG is assumed to be 5 €/MWh more valuable than at the sawmill because of existing gas distribution equipment. In Case 4 the electricity and net taxes are slightly higher due to the tax return system, in which the first 50 k€ spent on energy taxes are not eligible for tax refund. In Case 4 the value of heat is assumed to be same as the value of biomethane subtracted by the variable upgrading costs of raw biogas and considering the efficiency of the boiler. In Case 5 the value of heat is assumed to be the energy component of the district heat price.

The investment costs were scaled according to Equation (1)

Scaled investment cost
= Reference cost x
(Capacity / Reference capacity) ^ Scaling factor (1).

Annuities were calculated using weighted average cost of capital and timeframe as inputs for the PMT function in Microsoft Excel. The used investment parameters as well as the operating and management (O&M) costs for all cases are summarised in Table III.

Table III: Investment parameters and O&M costs for all cases.

	Reference specific cost	Reference capacity	Scaling factor
Alkaline electrolyser (eff. 67 % LHV)	1000 k€/MW_e	9 MW_e	0.93
Chemical methanation	1000 k€/MW_{SNG}	5 MW_{SNG}	0.67
Biological methanation [24] (raw biogas feed)	730 k€/MW_{SNG}	5 MW_{SNG}	0.40
Biological methanation [24] (pure CO_2 feed)*	510 k€/MW_{SNG}	5 MW_{SNG}	0.40
Methanol synthesis	1000 k€/MW_{MeOH}	5 MW_{MeOH}	0.67
Formic acid synthesis	5400 k€/(t_{FA}/h) [13]	1.5 t_{FA}/h [13]	0.67

* Same as in [24], but assuming 30% cost reduction for pure CO_2 feed compared to feeding the whole raw biogas stream.

<u>Common parameters for all cases:</u>

WACC	6 %
Timeframe	20 years
Installation and demo costs	15 % of investment
Fixed O&M costs	2.5 % of investment

Additional variable O&M: process dependent catalysts etc.

The electrolyser is the only common investment in all the cases, although the scale is different between Cases 1-3 and Cases 4 & 5; other unit investments are case specific.

4 RESULTS & DISCUSSION

4.1 Results from power-to-X concepts at the sawmill (Cases 1-3)

The annual income and cost breakdown for Cases 1-3 in both market scenarios is presented in Figure 8. With the optimistic financial assumptions, all three product alternatives have at least marginally positive profits. However, in the conservative scenario SNG and MeOH production are rather clearly unprofitable. Formic acid (FA) production on the other hand seems very profitable with both assumptions.

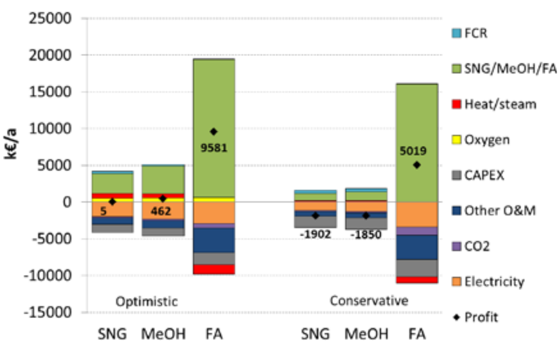
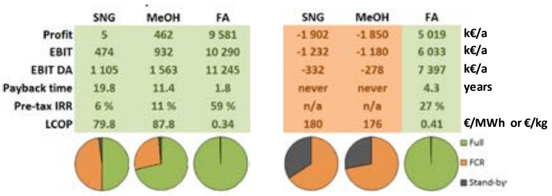


Figure 8: Annual incomes and costs in Cases 1-3.

The key financial indicators in Cases 1-3 are summarised in Figure 9. These include profit, earnings before interest and taxes (EBIT); earnings before interest, taxes, depreciation and amortisation (EBIT DA); payback time; pre-tax internal rate of return (pre-tax IRR) and levelised cost of product (LCOP). LCOP is given in units of €/MWh for SNG and MeOH and in €/kg for FA. The diagrams below visualise the proportion of each operational mode of the plant (full operation, FCR operation and stand-by) during the year.



	SNG	MeOH	FA	SNG	MeOH	FA	
Profit	5	462	9 581	-1 902	-1 850	5 019	k€/a
EBIT	474	932	10 290	-1 232	-1 180	6 033	k€/a
EBIT DA	1 105	1 563	11 245	-332	-278	7 397	k€/a
Payback time	19.8	11.4	1.8	never	never	4.3	years
Pre-tax IRR	6 %	11 %	59 %	n/a	n/a	27 %	
LCOP	79.8	87.8	0.34	180	176	0.41	€/MWh or €/kg

Figure 9: Summary of key financial indicators in Cases 1-3.

The economic performances of the studied cases are most sensitive to the price of the main product, electricity price and capital expenses (CAPEX). The slightly better financial performance of MeOH over SNG could also be attributed to the perhaps more optimistic product price assumptions for MeOH.

The FA case is very uncertain due to the low TRL level (see Fig. 2). One of the biggest uncertainties is the other operation and management (O&M) costs, specifically the amount and price of catalyst needed. The assumed catalyst consumption corresponds to renewal of the whole catalyst batch once a year similarly as presented in [13]. The average price of catalysts (€/kg) used in this study represent industrial bulk prices and was only about 4.5 % of the price assumed by [13], which corresponded to analysis lab quality prices. In further sensitivity analysis it was found that an eight-fold increase in the catalyst costs would be needed to turn the FA case unprofitable even under the pessimistic economic assumptions.

The cost of CO_2 has only a limited impact in the overall economic performance in all the studied cases. The impact of each single source of additional income from by-products or FCR is also limited. Contrary to the SNG and MeOH production, FA production is a net consumer of heat and steam. In some applications it might be more sensible to use a different price for purchased and sold heat and steam, but this aspect loses importance when considering the integration to the sawmill environment. Nevertheless the combined value of all the side products is considerable at least for the economically less viable cases.

In the highly profitable FA production the plant operated always with full capacity and the FCR was never in use. On the contrary, in the less profitable cases optimal profit is realised with FCR production. For instance, SNG production in the optimistic scenario operated nearly half the time in FCR mode still realising a marginally positive profit. These results suggest that for economically less favourable years it could be beneficial to prepare for offering FCR capacity.

In Figure 10 the payback time of the investment in Cases 1-3 is presented as a function of the electricity price level. The curves for SNG and MeOH production under the conservative assumptions are missing, because these cases would never pay back.

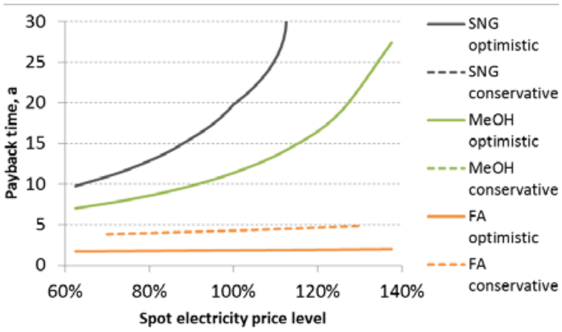


Figure 10: Payback time in Cases 1-3 as a function of the electricity price level.

FA production has clearly the most promising results with a payback time of less than five years with all the studied financial assumptions. These results are also most robust towards changes in the electricity price due to the lower need of electricity per ton of CO_2. Under the optimistic assumptions the limit of electricity price for profitable operation would be 100 % and 130 % of the assumed electricity price level for SNG and MeOH production, respectively. In the optimistic market scenarios it was assumed that the volatility of the electricity market is increased due to increased share of intermittent renewable energy. In one analysis it was found that the increased volatility had only a minor beneficial impact on the overall economic performance of these cases. In reality the changes in production, especially when FCR operation is considered, could also require additional investments in larger buffer storages, over-dimensioning of the electrolyser or impose other non-beneficial effects, such as shorter equipment lifetime.

4.2 Results from boosting biogas production in a biogas plant (Case 4)

The annual incomes and costs for boosting biogas production in a bio-waste digester are presented in Figure 11.

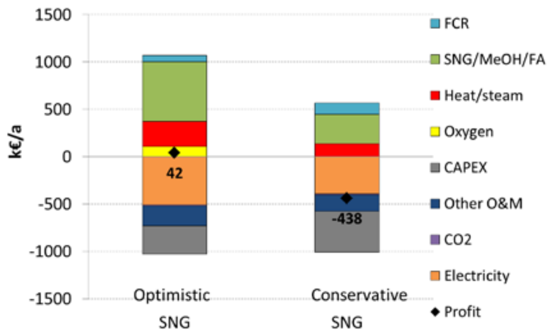


Figure 11: Annual incomes and costs in Case 4.

Optimistic financial assumptions lead to a marginally profitable investment, whereas in the conservative scenario the case is clearly unfeasible. By-products contribute significantly to the economic performance of the case, especially heat and steam sales. The key financial indicators of Case 4 are summarised in Figure 12.

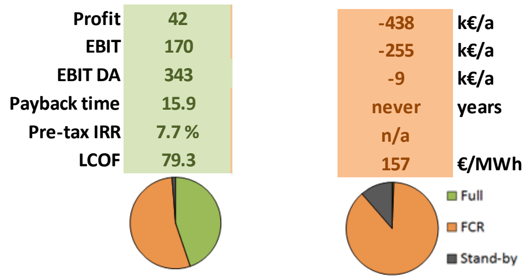


Figure 12: Summary of key financial indicators in Case 4.

In both scenarios the plant would operate in the FCR mode most of the time and in the conservative scenario there would be no full load operation at all. A payback time of around 16 years is achieved in the optimistic scenario, whereas in the conservative scenario the investment would never pay back.

The case is most sensitive to SNG and electricity prices; 10 % decrease in the sold SNG price or 15 % increase in the electricity price level would turn the case unfeasible. On the other hand, an increase of 30 % is required to turn the case profitable also in the conservative scenario.

CAPEX is a very significant for this case due to the relatively small scale of the plant and low capacity factor and the significance of CAPEX is even more pronounced under the conservative economic assumptions. An increase of 15 % in CAPEX would turn the case also in the optimistic scenario unprofitable. Moreover, if the value of oxygen decreases below 30 €/t, the profitability is lost.

4.3 Results from boosting biogas production in a wastewater treatment plant (Case 5)

The annual incomes and costs for boosting biogas production in a wastewater treatment plant are presented in Figure 13.

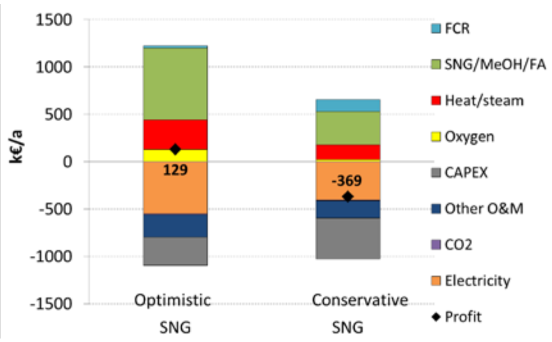


Figure 13: Annual incomes and costs in Case 5.

The results from Case 5 are similar to Case 4, but slightly more profitable due to lower net electricity taxes and higher heat utilisation. This is realised as a payback time of around 11 years (5 years shorter than Case 4) and a levelised cost of fuel (LCOF) 11 % lower than in Case 4. Still, the case remains clearly unprofitable in the conservative scenario. The key financial indicators are summarised in Figure 14.

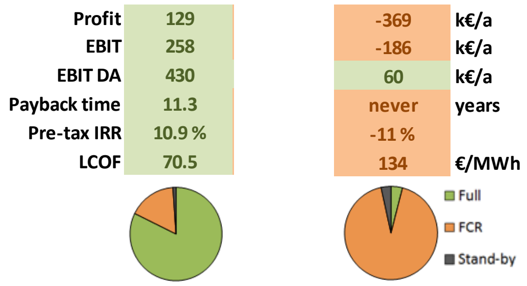


Figure 14: Summary of key financial indicators in Case 4.

Despite the similarities, there is a notable difference in the full and FCR operation times between the Cases 4 and 5 in the optimistic scenario: in Case 5 the FCR operation time is less than one fifth, whereas in Case 4 it is more than half. Nevertheless FCR remains a significant backup possibility for additional revenue for both cases, as the conservative scenarios reveal. The economic performance of Case 5 is also more robust to change; for instance, the profit would remain positive even if the revenue from O_2 were lost.

4.4 Discussion concerning all cases

The studied environments and cases are very different; even so, some generalisations can be made. Firstly, all results are highly sensitive to changes in the prices of products and electricity. Secondly, finding sites, where the side-products can be utilised at good value, is essential. Lastly, reductions in CAPEX are like to help in the future, since all of the examined technologies are relatively new. However, the investment subsidy can hardly be applied for every plant in the future. It should also be reminded that the parameters used and thus also the analyses are generic in nature – none of the cases represent a real specific site, which leads to further uncertainties regarding for instance the utilisation of by-products.

Although the results for producing FA seem very promising, none of the studied cases is both technologically ready and economically feasible. As the goal of the study was to find concepts for near term implementation, the search continues. In the meanwhile, the integrated production of FA deserves a more specific analysis as well as efforts to develop the technology.

Also the integration of FA production to different process environments could be studied. One interesting option could be FA production at a pulp mill for a number of reasons, such as available surplus steam, oxygen use in pulp bleaching, several possible CO_2 sources as well as other possible CO_2 uses, which could decrease the unit cost of CO_2. In the case of FA production, the income from the high-value product is the dominant factor for profitability. This in mind, the possibility to offer capacity for the FCR market seems less important, as supported by the optimal operating hours in Case 3. Moreover, even though the electrolyser can ramp up and down the production, the synthesis of FA is not as flexible necessitating further investments in larger buffer storages for H_2 and CO_2. These extra investment costs could be avoided by not preparing for FCR operation.

In some cases, direct air capture (DAC) might be a better option for providing the CO_2 for the process. Firstly, if biogenic CO_2 is difficult to access, DAC could provide another sustainable source of CO_2. Also if the purity of CO_2 becomes an issue, DAC may have an advantage, since DAC systems can provide CO_2 in the purity range of 95-99 %-vol. [25]

During the study some further integration possibilities emerged. For instance, MeOH produced at the sawmill could be used as a raw material for the glues and resins needed later in the production of plywood and other wood products – still at the same site. Another option could be to use the CO_2 to produce polymers for paints. These new possibilities could bring added value to the end product, thus making some power-to-X pathways already economically feasible. The value of a green brand could be very significant, allowing a higher profit with the 'green premium' market price. Finding new production routes utilising renewable raw materials are essential when creating a highly valuable sustainable brand.

A possible future research topic could be utilising biogenic CO_2 in mineralisation. Utilising the biogenic CO_2 in concrete curing, for example, could improve the value of the concrete product by improving its strength and other properties as well as contributing significantly to the CO_2 balance of the entire process, as CO_2 is stored permanently in the product. For such cases, the close proximity of the CO_2 source and the concrete factory is essential; an aspect worth considering when seeking future collaboration. Whether the CO_2 used in the production of the concrete becomes a cost or an income, remains open and may change in the future. Currently, there is no financial incentive to store biogenic CO_2 and the benefits of improved properties of the concrete product would be the main driver. In the future though, it might be more economical for the CO_2 emitter to purchase storage capacity in the concrete products rather than purchase emission allowances. Such considerations are however not relevant for the near term future, as the legislation of the EU Emissions Trading System (EU ETS) does not acknowledge 'negative emissions' from storing biogenic CO_2 emissions neither the storage through mineralisation.

5 CONCLUSIONS

The economic feasibility of selected power-to-X concepts utilising biogenic CO_2 was studied in this work. The goal of the study was to find feasible concepts for near term implementation. The power-to-X production was integrated to a sawmill or to a biogas plant and the product alternatives included synthetic natural gas (SNG), methanol (MeOH) and formic acid (FA).

From the studied cases, formic acid production at a sawmill (Case 3) showed clearly the best economic performance with payback times less than five years in both conservative and optimistic market scenarios. However, the technology is far less mature than the other alternatives leaving significant uncertainties, such as catalyst costs. Nevertheless the concept is worth more attention and the following research should aim at further development and piloting of the process. Pulp mill site was identified as a favourable environment for the process.

For SNG and MeOH production at the sawmill (Cases 1 and 2) the current market situation seems unprofitable. Higher value of products resulting for example from a 'green premium' or further refining into glues, resins or other products used at the same site in later process steps could turn the financials positive. Alternatively, a significant decrease in electricity prices or political decisions for financial incentives might be reasons to look closer into these cases.

Another option is to look for other environments to integrate these power-to-X processes. Crucial for these other integration options would be to find good value for the by-product heat, steam and oxygen; find concepts with reasonable large applications as well as to find sites where the plants are located close enough to each other to avoid long CO_2 transportation distances. Innovative and flexible CO_2 transport operators could also help by enabling economically feasible cooperation between companies separated by longer distances.

To support the electricity grid stabilisation, offering capacity for frequency containment reserve (FCR) markets appears to be a potential source of additional income, especially, when the profitability of the process is otherwise insecure. For such processes it might be reasonable to at least prepare for offering capacity for the FCR market. Other factors pronouncing the significance of the FCR market would be a highly electricity intensive product and high electricity prices. However, with highly valuable main products, such as formic acid, the importance of FCR operation is diminished.

The field of carbon capture and utilisation (CCU) provides a broad and diverse selection of alternative processes, which in combination with all the possible integration environments results in an immense arsenal of potential process combinations. This multitude of options can be approached by reviewing the general attributes of each process, such as addressable market size, followed by coarse techno-economic analyses to screen processes leading to a handful of most potential integration possibilities. In this work, a few of those processes were screened and the integrated formic acid production (Case 3) was identified as potential for implementation already in the market of today requiring closer analysis. Moreover, the possible situations, when the other alternatives could be economically feasible, were identified. It was found that the cost of CO_2 has only a limited impact in the overall economic performance in all the studied cases.

Integrating the utilisation of biogenic CO_2 to existing production is an excellent way to produce sustainable raw materials and widen the available resource base. Although of the current selection of integrated processes none showed both the technological readiness and the economic viability with market prices of today, the research revealed significant potential for producing formic acid from CO_2. In the following research efforts within the VTT's *Bio-CO*$_2$ project, more integrated CCU concepts will be screened, including concrete curing and plastics manufacturing as well as refining the analysis on formic acid production.

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