A preliminary study of the economics of a biomass to liquid fuel production in Iceland based on allo-thermal gasification and Fischer-Tropsch synthesis.

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Abstract

The economy of Fischer-Tropsh (FT) fuel production has been addressed by several investigators in the scientific literature. In all of these studies and at the few existing production sites, the production of the FT fuel is based on an auto-thermal concept, where little or no external energy is used. An allo-thermal FT process however, where external energy is introduced into the process, has some clear advantages over an auto-thermal process. In theory it allows for the production of fuel from a part of the feedstock that else is used to drive the gasification process.

Using clean external energy in an allo thermal process is also beneficial with respect to the CO_2 balance of the overall BTL production process, resulting in less greenhouse gas emission than can be expected in an auto-thermal production. However, the short supply and the cost of energy to drive an allo thermal process is a short coming of this concept. Thus the allo-thermal process has generated limited interest in the literature.

The aim of the present study was to investigate the economics of a large scale allo thermal BTL plant erected in Iceland and compare the results to economy studies published in the literature.

The results indicate that introducing external energy into the gasification process as apposed to combusting a part of the feedstock for elevating the temperature in the gasifier, has positive influence on the economics of the fuel production. In none of the cases investigated though, were the break even prices for the liquid fuel as low as current fossil fuel prices from refineries. The break even price for the BTL production is however, in all cases ($1.35\,\$/l$, $0.84\,\$/l$ and $0.83\,\$/l$ for modes 1, 2 and 3 respectively) lower than current at the pump prices in Iceland (approximately $1.5\,\$/l$).

Given these results, further investigations into the the economics of biomass to liquid (BTL) fuel production in Iceland is recommended. It could be one of the alternatives to consider with respect to making the country less dependent on foreign oil.

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1 Introduction

The economy of Fischer-Tropsh (FT) fuel production has been addressed by several investigators in the scientific literature (eg. Steynberg et al. (1999), Espinoza et al. (1999) and Tijmensen et al. (2002)). Steynberg et al. (1999) and Espinoza et al. (1999) studied the economy of FT fuel production of the Sasol plants in South-Africa but Tijmensen et al. (2002) explored the concept of producing Fischer-Tropsh liquids and power via biomass gasification. In the economical part of their biomass to liquid (BTL) study, Tijmensen et al. (2002) assumed that the feedstock (poplar wood) would be used to produce FT-liquids and the tail gas could be used to produce power using gas engine generators. This is similar to the process concept of the recently erected Choren β-plant in Freiberg in Germany.

The Freiberg complex is a part of ongoing research effort by German industry and government in an effort to make the country less depended on fossil fuels. This work has resulted in detailed economy studies for the purpose of attracting investors to finance commercial scale BTL complexes within German borders. The results of this work has been gathered in a report published by Deutsche Energie-Agentur GmbH (2006). In this report the economics of different BTL production concepts at five different location within Germany were investigated (Gelsenkirchen, Heilbronn, Leuna, Ludwigshafen and Wismar). The motivation for this work was to provide enough background information for investors to support discission making for the erection of a 1 million tonnes (equivalent dry weight) annual feedstock BTL complex. This report provides important information and insight into the future of BTL production since Germany is at the forefront in developing this technology.

In all of these studies and at the Choren site in Freiberg, the production of the FT fuel is based on an auto-thermal concept (figure 1), where little or no external energy is used. An allo-thermal FT process however, where external energy is introduced into the process, has some clear advantages over an auto-thermal process. In theory it allows for the production of fuel from a part of the feedstock that else is used to drive the gasification process. Using clean external energy in an allo thermal process is also beneficial with respect to the CO_2 balance of the overall BTL production process, resulting in less greenhouse gas emission than can be expected in an auto-thermal production. However, the short supply and the cost of energy to drive an allo thermal process is a short coming of this concept. Thus the allo-thermal process has received limited attention in the literature.

In countries where geothermal energy and hydropower electricity are available, an allo-thermal production of FT-fuels might be economically feasible.

The aim of the present study was to investigate the economics of a large scale allo thermal BTL plant erected in Iceland and compare the results to the economy study published by Deutsche Energie-Agentur GmbH (2006).

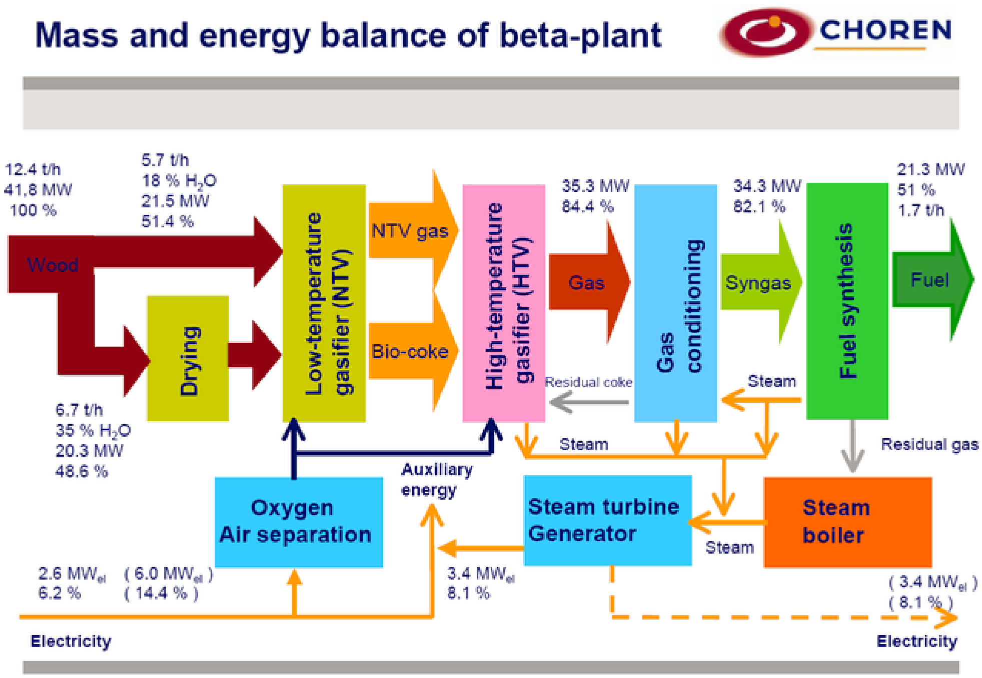

Fig. 1. Mass and energy balance for the Choren β-plant. The image is taken from www.greencarcongress.com/2008/09/norske-skogxyne.html.

2 Materials and methods

2.1 BTL process configuration

According to Tijmensen et al. (2002) and Deutsche Energie-Agentur GmbH (2006) several possible options exist for system configuration for a BTL production complex such as using direct vs. indirect, air blown vs. oxygen blown and atmospheric vs. pressurized gasifiers. In the present study a direct, oxygen blown, pressurized gasifying process was assumed. The benefit of using a direct gasification process rather than indirect is less problems with the presence of tar in the syngas (Tijmensen et al. (2002)). In accordance with the literature (eg. Tijmensen et al. (2002)) the FT synthesis in the present study is based on low temperature fluidized bed reactor in order to maximize the production of diesel.

One of the benefits of erecting a BTL production complex in Iceland would be the access to relatively inexpensive green energy, which could make the electrolysis of water for separating hydrogen and oxygen an option to be included in the gasification process. The electrolysis of water makes the use of oxygen blown gasification feasible which limits nitrogen dilution, but it should also enable the optimization of the H_2/CO-ratio in the syngas. This ratio should ideally be close to 2.

In the present study the inclusion of geothermal steam to transfer energy to the process and carry the feedstock is also considered. According to Tijmensen et al. (2002) gasification can take place at different temperatures. In the present study the gasifying temperature was assumed to be 1400°C which is similar to the gasifying temperature in the Choren β-plant. According to a Choren spokes person, gasification at such high temperatures atomizes the feedstock, therefore all molecular impurities, e.g. organic like tars or other polycyclic compounds are destroyed. The same applies for halogenous compounds. Elemental impurities however, cannot disappear by definition, and therefore have to be tackled specifically per element. Most metals stay in the vitrified slag as oxides, other compounds like sulphur (H_2S, COS) or acids (HCl) can be removed in a water scrubber. Standard syngas cleaning technologies can be applied in these cases but they are not investigated in detail in the present study.

The gasification process is energy demanding. In order to maximize the liquid output of the production, direct electrical heating is assumed to be included in the gasification in the present study.

The basic FT reaction for converting syngas to hydrocarbons has the form:

$$CO + 2H_2 \rightarrow -CH_{2-} + H_2O \quad (1)$$

with

$$\triangle H = -165\,\mathrm{KJ/mol} \quad (2)$$

The $-CH_{2-}$ is the basic building block for longer hydro carbon chains. When syngas passes through a FT reactor the liquid selectivity of the process depends on the chain growth probability (Tijmensen et al. (2002)). This describes the probability of a hydro carbon chain of given length being created in the FT reactor but producing long hydro carbon chains in the reactor is the goal of the FT synthesis. A portion of the syngas gets converted into diesel during the FT synthesis (straight run diesel) but a larger portion of the syngas is developed into long wax chains in the reactor (Tijmensen et al. (2002)). These chains are then developed into diesel and shorter hydro carbon chains by a process called hydrocracking.

The exact liquid selectivity and thus the ratios between long wax chains vs. shorter gas chains vs. naphta is difficult to determine a priori and would in the end have to be determined by in-depth process analysis and evt. by erecting pilot units. In the present study 10% of the carbon in the syngas (current 10 in figure 2) was assumed to be converted to short gas chains (average chain C_2H_6) that can be used to produce electricity (current 15). Another 10% of the carbon in the syngas was assumed to be converted into naphta (average chain C_8H_18) that is recycled in the process and burned in the gasifier to generate heat (current 13). Thus 80% of the carbon in the syngas was assumed to be converted into long wax chains with the average chain length similar to diesel (current 11). To be able to reach such a high utilization ratio for the syngas, a recycling loop (not included in the EES model) that would transfer unconverted gas upstream to the FT reactor, would have to be included in the final design of the production complex. The hydrocracking process downstream from the FT reactor is not modeled in the present study.

2.2 Mass and energy balance

Commercial software (EES vers. 8.201) was used for determining the mass and energy balance of the BTL system under investigation. The simplified EES model used for this purpose is illustrated in figure 2. Processes thought to have minor influence on the results of the economical comparison between process modes, such as water scrubbing for sulphur removal, were not included in the model. The temperature and pressure at individual nodes in the process were estimated based on similar studies in the literature (Tijmensen et al. (2002)). The feedstock was assumed to be in the form of 84 (wt%) cellulose ($C_5H_{10}O_5$), 13 (wt%) calcium carbonate ($CaCO_3$) and 3 (wt%) water (H_2O). Three different process modes were investigated:

Mode 1 Auto thermal process with minimal external energy used.
Mode 2 Allo thermal process with minimum electrolysis of water and maximum geothermal steam utilization.
Mode 3 Allo thermal process with maximum electrolysis of water and minimum geothermal steam utilization.

Mode 1 was included to allow for some comparison between the mass and energy balance of the existing auto thermal Freiberg process (figure 1) and the allo thermal processes (Modes 2 and 3).

2.3 *Economy*

Because the economy of scale is considerable in fuel production the present study was based on a large commercial scale factory with a feedstock input of 1 million tonnes pr. year, similar to the size of the factory studied by Tijmensen et al. (2002) and Deutsche Energie-Agentur GmbH (2006). This also allows for some direct comparison between the auto and allo thermal concepts. The basic cost data is gathered in table 1. Some clarification for the items in the table are given below. All cost data is presented in USD.

Production cost

The price of feedstock is uncertain to some degree since this market is not fully developed. Tijmensen et al. (2002) assumed a cost of $23 - 92\,\$/\mathrm{t}$ for the feedstock in their study but the price is probably closer to the upper limit for the current cost of feedstock. The cost of feedstock was estimated by Deutsche Energie-Agentur GmbH (2006) to be in the range of $21 - 180\,\mathrm{Euros/t}$ with most of the feedstock in Germany being sold at prices around $60\,\mathrm{Euros/t}$. It is also possible that this cost will to some extent correlate with oil price in the future, because carbon rich material will increasingly be used for producing fuel. Taken transport and storage into account the economics of the BTL complex were investigated for a feedstock cost of $70 - 130\,\mathrm{USD/t}$.

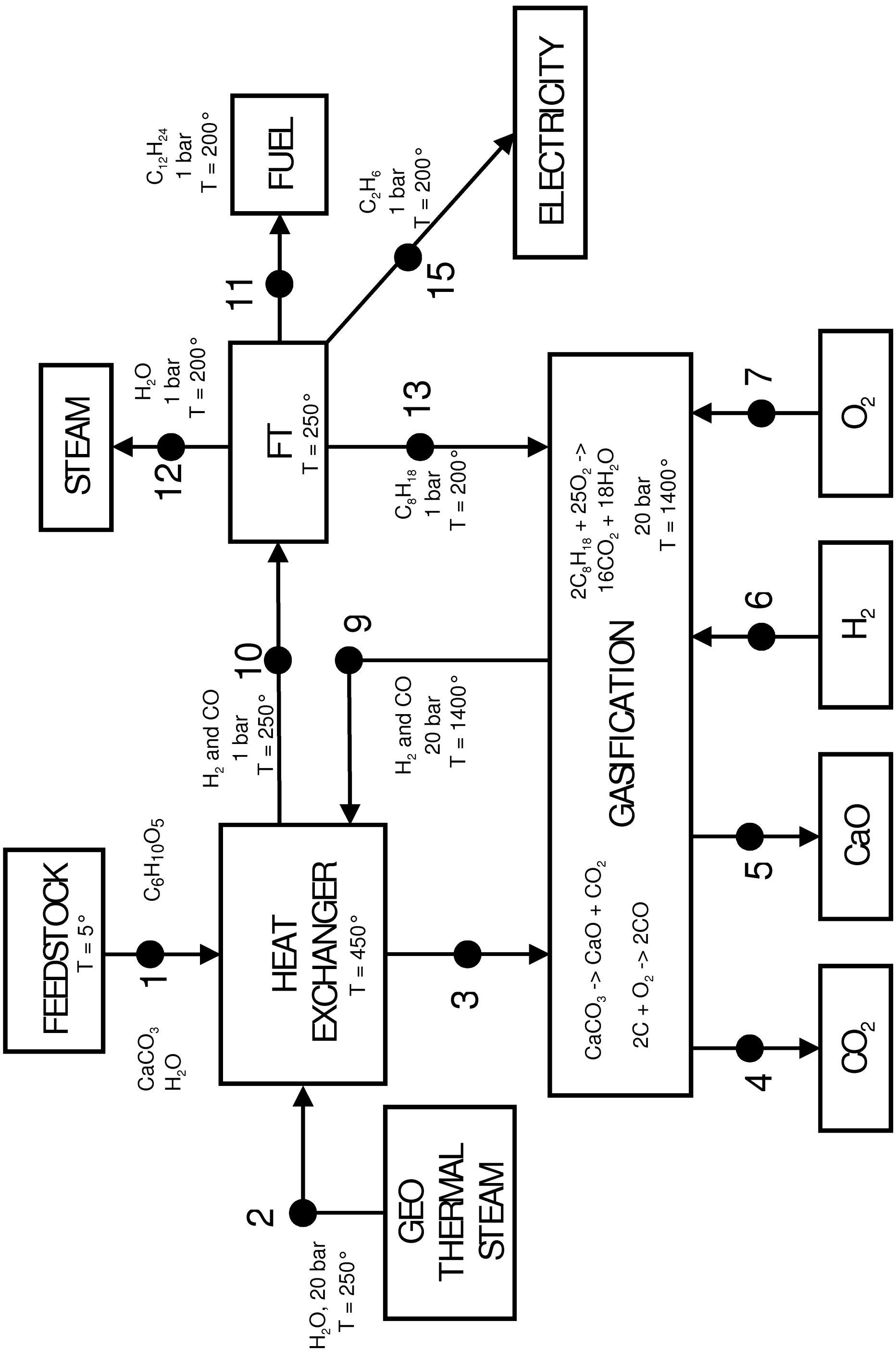

Fig. 2. Conceptual illustration of EES model used for mass and energy balance calculations.

The cost of electricity used directly in the gasification process and in electrolysis of water was assumed to be $0.03\,\$/\mathrm{kWh}$ which is considered realistic for heavy industry in Iceland. No electrolysis was assumed in the auto thermal process (Mode 1). Instead an air-to oxygen unit was assumed included in the process, producing oxygen at a cost of $0.08\,\$/\mathrm{m}^3$. Some electricity is also produced as a byproduct of the BTL conversion. The value of this electricity, which can either be used in the BTL process or sold back to the grid, was also assumed to be $0.03\,\$/\mathrm{kWh}$. The price for geothermal steam used is not well defined. The energy content of the steam as delivered to the site was estimated and the cost assumed to be $0.03\,\$/\mathrm{kWh}$.

Additionally, unspecified cost pr. tonne of feedstock was added to the production cost to account for uncertainties in the cost data. This cost was assumed to cover eg. the cost of manpower, feedstock preparation, gas cleaning and catalyst material used in the FT reactor. This unspecified cost was assumed to be $20\,\$/\mathrm{t}$ for the allo thermal modes but set to zero for the auto thermal mode to give a resulting production cost of approximately $1.29\,\$/\mathrm{l}$ ($0.88\,\mathrm{Euros/l}$), which was the baseline production cost estimated by Deutsche Energie-Agentur GmbH (2006).

Capital cost

Many of the process units needed for a BTL production have not yet been developed on a commercial scale and it is thus difficult to assess their cost. However, this was studied relatively detailed by Tijmensen et al. (2002) and taken economy of scale into consideration they estimated the capital cost to be approximately $400\,\mathrm{M\$}$ for a feedstock energy input of approximately $400\,\mathrm{MW}$ which is close to $1\,\mathrm{M\$/MW}$ of energy input. The same ratio for the much smaller ($43.9\,\mathrm{MW}$) Choren β-plant in Freiberg is closer to $3\,\mathrm{M\$/MW}$. The capital cost for a production complex of 1 million tonnes annual feedstock was estimated by Deutsche Energie-Agentur GmbH (2006) to be in the range of $772-956\,\mathrm{M\$}$ ($525-650\,\mathrm{MEuros}$) without detailed process optimization. This is be close to $2\,\mathrm{M\$/MW}$ of input energy. The capital cost pr. MW input energy is assumed to be smaller for the allo thermal options and is set to $1.5\,\mathrm{M\$/MW}$ for modes 2 and 3. The capital cost for mode 1 was set to $772\,\mathrm{M\$}$ in accordance with the study of Deutsche Energie-Agentur GmbH (2006). Interests on capital cost were set to 8% and the depreciation period was assumed to be 15 years.

The main product of the BTL complex is diesel with a cetene number considerably higher than currently needed in the transport sector. This product could thus perhaps be sold for the purpose of mixing it with low cetene diesel oil to produce fuel for transportation. The average annual price of diesel oil from refineries in the US is illustrated in figure 3. As can be seen on the graph the price of oil has changed considerably through the last 30 years. Predicting the future price of oil is difficult. Most analysts would tend to agree that the short term price of oil is expected to remain relatively low following the price drop after the economic crisis of 2008. However, future price of oil is expected to rice even as high or higher than it's peak in 2008. In the present study the influence of changes in oil price on the BTL complex economics was calculated by using the three different values for oil price ie. 30 year average, 5 year average and the average price of 2008.

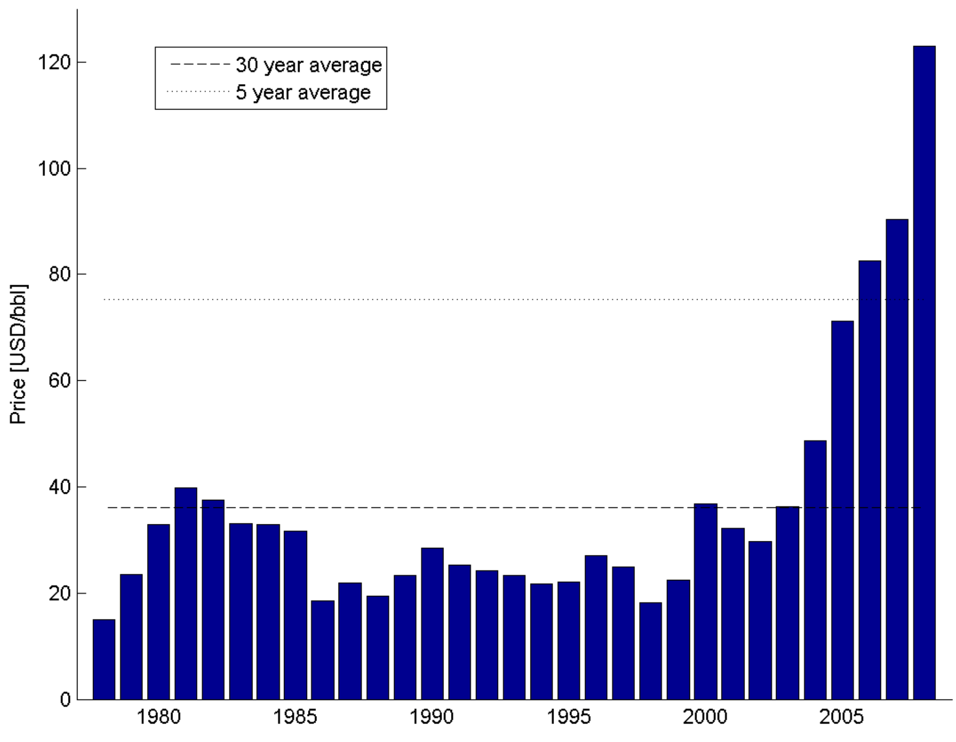

Fig. 3. Development of annual average diesel oil price from refineries in the US for resale (http://www.eia.doe.gov/). The 5 and 30 year averages are 76.4 $/bbl and 36.1 $/bbl respectively. In 2008 the average oil price reached 122.1 $/bbl.

The BTL complex also produces a large amount of low pressure steam (current 12 in figure 2) that can either be recycled in the gasification process or used to produce electricity. In the present study it was assumed to be used for producing electricity (see table 1) at a value of $0.03\,\$/\mathrm{kWh}$.

The electrolysis of water produces oxygen and hydrogen in a 1:2 mole ratio. The hydrogen deficiency of the feedstock means that all the hydrogen from the electrolysis is used to a adjust the H_2/CO-ratio of the syngas, thus leading to a considerable by-production of oxygen (see table 2). Since pure oxygen has a considerable value it is also featured among revenues at $0.1\,\$/\mathrm{m}^3$. The off gas from the FT synthesis was assumed to be used in a gas turbine to produce electricity at a value of $0.03\,\$/\mathrm{kWh}$.

Table 1
General cost data that applies for all the case studies.

Item	Price
Annual average oil price (peak in 2008)	$122.1\,\$/\mathrm{bbl}$
Annual average oil price (last 5 years)	$76.9\,\$/\mathrm{bbl}$
Annual average oil price (last 30 years)	$36.1\,\$/\mathrm{bbl}$
Value of of oxygen	$0.1\,\$/\mathrm{m}^3$
Cost/value of electricity in Iceland (heavy industry)	$0.03\,\$/\mathrm{kWh}$
Cost geothermal steam in Iceland (heavy industry)	$0.03\,\$/\mathrm{kWh}$
Cost of feedstock at site in Iceland	$70 - 130\,\$/\mathrm{ton}$
Other production cost (pr. tonnes feedstock)	$0 - 20\,\$/\mathrm{ton}$

2.4 Case studies

The price of feedstock and oil were identified as key input parameters for the economic study. The annual economic results for the BTL complex were thus analyzed with 6 different combination of feedstock and oil prices.

Case I Feedstock at 90 $/t and oil price at 56.3 $/bbl.
Case II Feedstock at 70 $/t and oil price at 36.1 $/bbl.
Case III Feedstock at 70 $/t and oil price at 76.4 $/bbl.
Case IV Feedstock at 130 $/t and oil price at 36.1 $/bbl.
Case V Feedstock at 130 $/t and oil price at 76.4 $/bbl.
Case VI Feedstock at 90 $/t and break even oil price.

Case I is based on feedstock cost of approximately 60 Euros/t which should cover a broad part of the feedstock sold in Germany according to Deutsche Energie-Agentur GmbH (2006) and the 5 year average oil prices. Cases II-V are based on combining the estimated extreme values for the key input parameters. Case VI was included determine the break even price of oil for the three different modes.

3 Results

3.1 Mass and energy balance

The results for the mass and energy balance are listed in table 2. Energy balance was not reached for Mode 1, as could be expected unless some of the unused energy in the FT syntheses is utilized for raising the temperature in the gasifier. This is due to oversimplification of the mass and energy balance model that does assume that all of the carbon is converted into syngas except for the carbon in the $CaCO_3$ that is split into CaO and CO_2 at a temperature of approximately 900°C. In reality some of the carbon in the auto thermal process is combusted without ever passing through the FT reactor. Energy balance was reached for the allo thermal processes (Modes 2 and 3) by introducing sufficient amount of electrical energy into the gasifier.

3.2 Economy

The production cost and revenues estimated for the six different combination of feedstock and oil price are listed in tables 3-5 for the three different process modes. The results of the economic analysis taking investment cost into account are listed in tables 6-8. A capital cost of 772 M$ was assumed for the auto thermal complex but 1158 M$ and 1186 M$ for the allo thermal modes 2 and 3 respectively. The resulting break even oil price for case VI was 1.35 $/l, 0.84 $/l and 0.83 $/l for modes 1, 2 and 3 respectively. This is

Table 2
Mass balance results for annual feedstock input of 1 million tonnes. Please refer to figure 2 for locating the individual nodes of the mass and energy balance model.

		Mode 1	Mode 2	Mode 3
	Node nr.	(Kt)	(Kt)	(Kt)
Feedstock	1	1000	1000	1000
Geothermal steam (H_2O)	2	0	176	0
Hydrogen (H_2)	6	0	47	66
Oxygen (O_2)	7	377	0	156
Carbon dioxide (CO_2)	4	882	194	194
Calcium monoxide (CaO)	5	73	73	73
Fuel/diesel ($C_{12}H_{24}$)	11	130	348	348
Steam (H_2O)	12	246	560	560
Naphta (C_8H_{18})	13	267	44	44
Gas (C_2H_6)	15	47	47	47

slightly less than the total cost. pr. liter according to tables 6-8 because revenues from by-products influence the break even oil price.

Table 3
Estimation of the production cost and annual revenues for the for six different combinations of feedstock and oil price for auto thermal production (Mode 1).

Mass and energy	**Case I**	**Case II**	**Case III**	**Case IV**	**Case V**	**Case VI**	**Unit**
FT diesel production	14.8	14.8	14.8	14.8	14.8	14.8	t/h
Energy (36 MJ/liter)	174	174	174	174	174	174	MW
Production cost							
Feedstock							
Total weight	114	114	114	114	114	114	t/h
Cost	90	70	70	130	130	90	$/t
Specific heat	11.55	11.55	11.55	11.55	11.55	11.55	KJ/kg
Energy	366	366	366	366	366	366	MW
Oxygen air separation							
Oxygen (current 7)	43.0	43.0	43.0	43.0	43.0	43.0	t/h
Oxygen (current 7)	33085	33085	33085	33085	33085	33085	m^3/h
Cost pr m^3	0.08	0.08	0.08	0.08	0.08	0.08	$/$m^3$
Electricity							
Energy	26.0	26.0	26.0	26.0	26.0	26.0	MW
Efficiency	0.9	0.9	0.9	0.9	0.9	0.9	
Cost pr. kWh	0.03	0.03	0.03	0.03	0.03	0.03	$
Other							
Total weight	114	114	114	114	114	114	t/h
Unspec. operational cost pr. ton feedstock	0	0	0	0	0	0	$/t
Feedstock	10274	7991	7991	14840	14840	10236	$/h
Oxygen	2647	2647	2647	2647	2647	2647	$/h
Electricity	867	867	867	867	867	867	$/h
Other unspecified cost	0	0	0	0	0	0	$/h
Total production cost pr. Hour	**13787**	**11504**	**11504**	**18354**	**18354**	**13750**	**$/h**
Total annual production cost	**121**	**101**	**101**	**161**	**161**	**120**	**M$**
Revenues							
Diesel							
Diesel barrel	159	159	159	159	159	159	L
Density	0.85	0.85	0.85	0.85	0.85	0.85	t/m^3
Number of barrels pr. hour	110	110	110	110	110	110	bbl/h
Value of diesel barrel	56.3	36.1	76.4	36.1	76.4	215.0	$/bbl
Value of diesel pr. Liter	0.35	0.23	0.48	0.23	0.48	1.35	**$/litre**
Steam							
Steam (current 12)	28	28	28	28	28	28	t/h
Efficiency	0.6	0.6	0.6	0.6	0.6	0.6	
Energy (100 MJ/t)	0.47	0.47	0.47	0.47	0.47	0.47	MW
Cost pr. kWh	0.03	0.03	0.03	0.03	0.03	0.03	$
Product revenues							
Diesel	6160	3954	8367	3954	8367	23546	$/h
Steam	14	14	14	14	14	14	$/h
Total revenues pr. hour	**6174**	**3968**	**8381**	**3968**	**8381**	**23560**	**$/h**
Total annual revenues	**54**	**35**	**73**	**35**	**73**	**206**	**M$**

4 Conclusions

The aim of the present study was to investigate the economics of a large scale allo thermal BTL plant erected in Iceland and compare the results to the economy study published by Deutsche Energie-Agentur GmbH (2006). The results indicate that introducing external energy into the gasification process (allo thermal mode) as apposed to combusting a part of the feedstock for elevating the temperature in the gasifier (auto thermal mode), has positive influence on the economics of the fuel production. In none of the cases investigated though, were the break even prices for the liquid fuel as

Table 4
Estimation of the production cost and annual revenues for the for six different combinations of feedstock and oil price for allo thermal production (Mode 2).

Mass and energy	**Case I**	**Case II**	**Case III**	**Case IV**	**Case V**	**Case VI**	**Unit**
FT diesel production	40	40	40	40	40	40	t/h
Energy (36 MJ/liter)	468	468	468	468	468	468	MW
Production cost							
Feedstock							
Total weight	114	114	114	114	114	114	t/h
Cost	90	70	70	130	130	90	$/t
Specific heat	11.55	11.55	11.55	11.55	11.55	11.55	KJ/kg
Energy	366	366	366	366	366	366	MW
Electricity (elecrolysis and direct)							
Efficiency	0.9	0.9	0.9	0.9	0.9	0.9	
Amount of energy needed in electrolysis	195	195	195	195	195	195	MW
Amount of energy needed into gasifier	250	250	250	250	250	250	MW
Cost pr. kW/h	0.03	0.03	0.03	0.03	0.03	0.03	$/h
Geothermal steam							
Amount of geothermal steam	20.1	20.1	20.1	20.1	20.1	20.1	t/h
Efficiency	0.5	0.5	0.5	0.5	0.5	0.5	
Energy (416 MJ/t)	4.64	4.64	4.64	4.64	4.64	4.64	MW
Cost pr. kWh	0.03	0.03	0.03	0.03	0.03	0.03	$
Other							
Total weight	114	114	114	114	114	114	t/h
Unspec. operational cost pr. ton feedstock	20	20	20	20	20	20	$/t
Feedstock	10274	7991	7991	14840	14840	10274	$/h
Electricity	13338	13338	13338	13338	13338	13338	$/h
Geothermal steam cost	139	139	139	139	139	139	$/h
Other unspecified cost	2283	2283	2283	2283	2283	2283	$/h
Total production cost pr. Hour	**26034**	**23751**	**23751**	**30601**	**30601**	**26034**	**$/h**
Total annual production cos	**228**	**208**	**208**	**268**	**268**	**228**	**M$**
		0.51					
Revenues							
Diesel							
Diesel barrel	159	159	159	159	159	159	L
Density	0.85	0.85	0.85	0.85	0.85	0.85	t/m^3
Number of barrels pr. hour	294	294	294	294	294	294	bbl/h
Value of diesel barrel	56.3	36.1	76.4	36.1	76.4	133.0	$/bbl
Value of diesel pr. Liter	0.35	0.23	0.48	0.23	0.48	0.84	**$/litre**
Steam							
Steam (current 12)	64	64	64	64	64	64	t/h
Efficiency	0.6	0.6	0.6	0.6	0.6	0.6	
Energy (100 MJ/t)	1.07	1.07	1.07	1.07	1.07	1.07	MW
Cost pr. kWh	0.03	0.03	0.03	0.03	0.03	0.03	$
Oxygen from electrolysis							
Oxygen (current 7)	0.0	0.0	0.0	0.0	0.0	0.0	t/h
Oxygen (current 7)	0	0	0	0	0	0	m^3/h
Value pr m^3	0.1	0.1	0.1	0.1	0.1	0.1	$\$/m^3$
Electricity							
Combustion energy of C_2H_6	1423	1423	1423	1423	1423	1423	kJ/mol
Efficiency	0.6	0.6	0.6	0.6	0.6	0.6	
Amount of energy in C_2H_6	42.1	42.1	42.1	42.1	42.1	42.1	MW
Value pr. kWh	0.03	0.03	0.03	0.03	0.03	0.03	$
Product revenues							
Diesel	16555	10625	22485	10625	22485	39143	$/h
Steam	32	32	32	32	32	32	$/h
Oxygen	0	0	0	0	0	0	$/h
Electricity	1264	1264	1264	1264	1264	1264	$/h
Total revenues pr. hour	**17851**	**11920**	**23781**	**11920**	**23781**	**40439**	**$/h**
Total annual revenues	**156**	**104**	**208**	**104**	**208**	**354**	**M$**

Table 5
Estimation of the production cost and annual revenues for the for six different combinations of feedstock and oil price for allo thermal production (Mode 3).

Mass and energy	**Case I**	**Case II**	**Case III**	**Case IV**	**Case V**	**Case VI**	**Unit**
FT diesel production	39.8	39.8	39.8	39.8	39.8	39.8	t/h
Energy (36 MJ/liter)	468	468	468	468	468	468	MW
Production cost							
Feedstock							
Total weight	114	114	114	114	114	114	t/h
Cost	90	70	70	130	130	90	$/t
Specific heat	11.55	11.55	11.55	11.55	11.55	11.55	KJ/kg
Energy	366	366	366	366	366	366	MW
Electricity (electrolysis and direct)							
Efficiency	0.9	0.9	0.9	0.9	0.9	0.9	
Amount of energy needed in electrolysis	276	276	276	276	276	276	MW
Amount of energy needed into gasifier	191	191	191	191	191	191	MW
Cost pr. kW/h	0.03	0.03	0.03	0.03	0.03	0.03	$/h
Geothermal steam							
Amount of geothermal steam	0.0	0.0	0.0	0.0	0.0	0.0	t/h
Efficiency	0.5	0.5	0.5	0.5	0.5	0.5	
Energy (416 MJ/t)	0.00	0.00	0.00	0.00	0.00	0.00	MW
Cost pr. kWh	0.03	0.03	0.03	0.03	0.03	0.03	$
Other							
Total weight	114	114	114	114	114	114	t/h
Unspec. operational cost pr. ton feedstock	20	20	20	20	20	20	$/t
Feedstock	10274	7991	7991	14840	14840	10274	$/h
Electricity	14019	14019	14019	14019	14019	14019	$/h
Geothermal steam cost	0	0	0	0	0	0	$/h
Other unspecified cost	2283	2283	2283	2283	2283	2283	$/h
Total production cost pr. Hour	**26576**	**24293**	**24293**	**31142**	**31142**	**26576**	**$/h**
Total annual production cost	**233**	**213**	**213**	**273**	**273**	**233**	**M$**
Revenues							
Diesel							
Diesel barrel	159	159	159	159	159	159	L
Density	0.85	0.85	0.85	0.85	0.85	0.85	t/m³
Number of barrels pr. hour	294	294	294	294	294	294	bbl/h
Value of diesel barrel	56.3	36.1	76.4	36.1	76.4	132	$/bbl
Value of diesel pr. Liter	0.35	0.23	0.48	0.23	0.48	0.83	**$/litre**
Steam							
Steam (current 12)	64	64	64	64	64	64	t/h
Efficiency	0.6	0.6	0.6	0.6	0.6	0.6	
Energy (100 MJ/t)	1.07	1.07	1.07	1.07	1.07	1.07	MW
Cost pr. kWh	0.03	0.03	0.03	0.03	0.03	0.03	$
Oxygen from electrolysis							
Oxygen (current 7)	17.8	17.8	17.8	17.8	17.8	17.8	t/h
Oxygen (current 7)	13685	13685	13685	13685	13685	13685	m³/h
Value pr m³	0.1	0.1	0.1	0.1	0.1	0.1	$/m³
Electricity							
Combustion energy of C_2H_6	1423	1423	1423	1423	1423	1423	kJ/mol
Efficiency	0.6	0.6	0.6	0.6	0.6	0.6	
Amount of energy in C_2H_6	42.1	42.1	42.1	42.1	42.1	42.1	MW
Value pr. kWh	0.03	0.03	0.03	0.03	0.03	0.03	$
Product revenues							
Diesel	16555	10625	22485	10625	22485	38849	$/h
Steam	32	32	32	32	32	32	$/h
Oxygen	1369	1369	1369	1369	1369	1369	$/h
Electricity	1264	1264	1264	1264	1264	1264	$/h
Total revenues pr. hour	**19219**	**13289**	**25149**	**13289**	**25149**	**41513**	**$/h**
Total annual revenues	**168**	**116**	**220**	**116**	**220**	**364**	**M$**

Table 6
Outcome of economic study for Mode 1. Capital cost is assumed 772 MUSD. Interest rates are set to 8%. Table values are MUSD annually except for cost pr. liter.

	Case I	Case II	Case III	Case IV	Case V	Case VI
Production cost	-121	-101	-101	-161	-161	-120
Revenues	54	35	73	35	73	206
Capital cost and interests	-86	-86	-86	-86	-86	-86
Total	-152	-152	-113	-212	-173	0
Cost pr. liter ($/l)	1.35	1.22	1.22	1.62	1.62	1.35

Table 7
Outcome of economic study for Mode 2. Capital cost is assumed 1158 MUSD. Interest rates are set to 8%. Table values are MUSD annually except for cost pr. liter.

	Case I	Case II	Case III	Case IV	Case V	Case VI
Production cost	-228	-208	-208	-268	-268	-228
Revenues	156	104	208	104	208	354
Capital cost and interests	-127	-127	-127	-127	-127	-127
Total	-198	-230	-126	-290	-186	0
Cost pr. liter ($/l)	0.87	0.82	0.82	0.96	0.96	0.87

Table 8
Outcome of economic study for Mode 3. Capital cost is assumed 1186 MUSD. Interest rates are set to 8%. Table values are MUSD annually except for cost pr. liter.

	Case I	Case II	Case III	Case IV	Case V	Case VI
Production cost	-234	-214	-214	-274	-274	-233
Revenues	168	116	220	116	220	364
Capital cost and interests	-130	-130	-130	-130	-130	-130
Total	-196	-228	-124	-288	-184	0
Cost pr. liter ($/l)	0.89	0.84	0.84	0.99	0.99	0.88

low as current fossil fuel prices from refineries. The break even price for the BTL production is however, in all cases ($1.35\,\$/l$, $0.84\,\$/l$ and $0.83\,\$/l$ for modes 1, 2 and 3 respectively) lower than current at the pump prices in Iceland (approximately $1.5\,\$/l$). This means that all the options investigated could be feasible if this type of green fuel production would be partially tax relieved. This can be justified due to reduced CO_2 emission from the production and burning of FT fuel compared to the burning of conventional fossil fuel.

The size of the BTL production complex in the present study was assumed to be 1 million tonnes of biomass input annually to include the effects of the economy of scale. The liquid fuel production of the complex would come close to completely cover the demand for liquid fuels of the country. The scale of this factory however, is such that if it were located in Iceland it would mean that the import of carbon rich feedstock would be necessary, or forestry on a large industrial scale. Given the positive outcome of the allo thermal options, a smaller complex that could be supplied by local feedstock in form of wood and municipal waste, could be considered as an alternative. With an annual feedstock input of $100 - 500\,\mathrm{kt}$ the liquid output could be used to drive the fishing fleet and aircrafts of the country. The rest of the transport sector could slowly be converted to run on electricity or other types of green energy supplied locally. Scaling the complex down to this size would still mean that forestry on large scale would be needed to supply the plant with enough feedstock. With an estimated annual harvest of $25\,\mathrm{t/ha}$ of wood, a forrest land of $40\,\mathrm{km}^2$ would be needed for each $100\,\mathrm{kt}$ of annual feedstock.

The results of this study cannot be interpreted without addressing some of the obvious limitations of this work. Studying the economics of a technology that has not been fully developed at least not on this scale, does bare with it the risk of large underestimation of cost. We have however, attempted to estimate cost and revenues conservatively and eg. not taken into account the possible optimization of processes that were mentioned in the report by Deutsche Energie-Agentur GmbH (2006). We estimate that the biggest technological risk in this project is the scaling up of current electrical heater technology for the inclusion of large amount of electricity in the gasification process. Addressing the technological aspects of the FT process in detail is however outside the scope of this study.

Given these results it is clear that further investigations into the the economics of biomass derived fuel production in Iceland can be recommended. We believe that the focus of future studies should be on the possibility of supplying a scaled down allo thermal BTL complex with local feedstock and further optimization of the mass and energy balance of the process. We consider the production of biomass to liquid fuels, based on gasification and FT syntheses, to be a realistic option to be considered for supplying the country with CO_2 neutral energy and even more importantly, make Iceland independent of foreign oil.

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