RETROL VISION: PRELIMINARY TECHNO-ECONOMICAL ANALYSIS

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Introduction

One of the leading power companies in Denmark, Elsam Kraft A/S, has proposed a vision of the Danish energy sector (end of 2004), with a working title ''From petrol to REtrol'' (originally ''From benzin to VEnzin'', vedvarende = renewable, in Danish). The vision points to changes in the energy sector from being based on combined production of electricity and heat to one based on combined production of electricity, heat and liquid fuels. This combination introduces a new liquid fuel called REtrol, produced by blending ordinary gasoline with ethanol and methanol, both of which should be produced mainly from the renewable sources.

Description of the REtrol vision

The REtrol vision assumes that blend of ethanol, methanol and gasoline, called REtrol, should be produced from wind, biomass, solar energy and recirculated CO_2. REtrol production is schematically represented on Figure 1.

Ethanol is imagined to be produced by enzymatic hydrolysis and fermentation of ligno-cellulosic biomass. The main raw material should be secondary biomass (ligno-cellulosic wheat straw), which is obtained after wheat harvest. In the future, different kind of waste should be included in this process. The basis for this process will be IBUS process (Integrated Biomass Utilization System), which is an EU project with considerable participation of Danish companies. The IBUS process will also yield certain amount of non-fermentable residues (mainly lignin), which can be used in the gasification process or combusted in a CHP (combined power and heat) plant.

Methanol production process could be based on the conventional production from synthesis gas (CO, CO_2, H_2). The CO_2 could be obtained by separation from the flue gas from central CHP plants, while the H_2 may be obtained from electrolysis of water. Additional amount of CO and H_2 could be obtained from gasification of non-fermentable biomass residues and from synthesis gas produced by reforming of natural gas. At the beginning, the methanol could be produced by using steam reforming of natural gas, which is known and proven technology, and later the share of the renewable energy could be increased step-wise (by using H_2 from electrolysis or synthesis gas from gasification).

Central CHP plants are the largest generators of CO_2. Consequently, the CO_2 removal could be performed at the central CHP plants, which mostly burn coal or biomass.

The electrolysis of water is going to use electricity generated by wind turbines, in order to produce oxygen and hydrogen. Oxygen will be further used in process of gasification of non-fermentable biomass residues, while hydrogen is used for methanol synthesis.

Finally, gasoline, produced from crude oil in oil refineries, is blended with ethanol and methanol, in order to obtain REtrol liquid fuel. The share of the renewable energy in the REtrol fuel should be increased gradually.

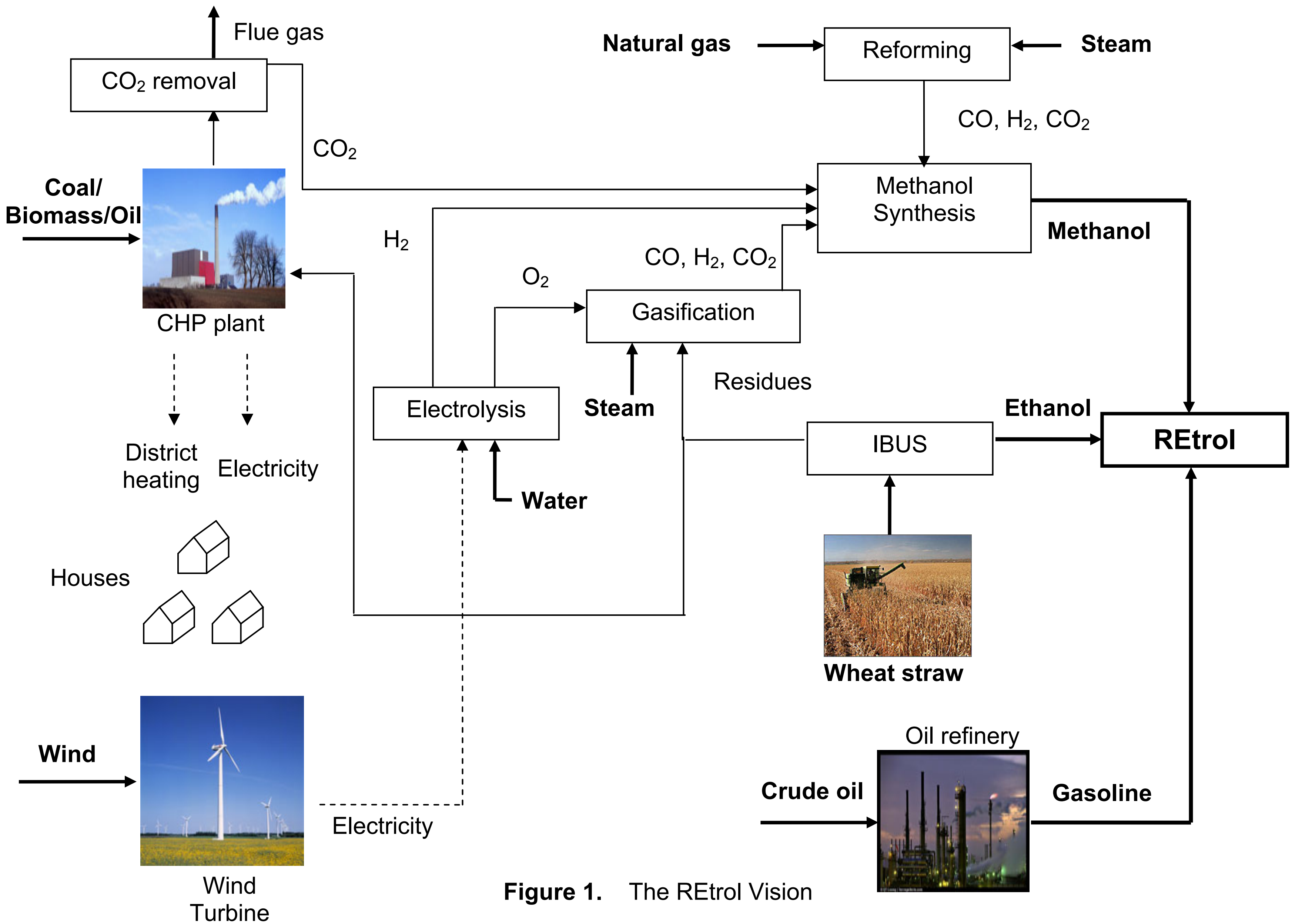

Figure 1. The REtrol Vision

The description of the REtrol vision is based on the concept of sustainability, adopted by Elsam A/S, which intends to balance the social responsibility, environmental performance and financial profitability. Implementation of the REtrol vision in the transport sector should offer environmental advantages, such as: lowering CO_2 emissions from CHP plants and car exhaust pipes, integration of the large amount of wind electricity into Danish electricity system, utilization of the large amounts of the low value biomass and waste, conversion of wheat straw residues to incineration residues, reduction of NO_x emissions by utilizing O_2 in the gasification or combustion process, etc. It will be of great importance to reduce the almost total dependence of gasoline in the transport sector, which is present today in almost all developed countries. The REtrol vision is beneficial to many different Danish companies, from different areas (Elsam, Haldor Topsøe, Novozymes, wind turbine industry, agriculture sector) and on a longer perspective to developers of methanol fuel cells and cells for electrolysis. In the case of crude oil shortage and an increased price of gasoline, the content of the renewable energy will reduce the negative economic balance, if Denmark would be an energy importing country. In the case of Denmark being an energy exporting country, the REtrol content will allow a larger amount of oil for export. Finally, the integration of CO_2 removal, electrolysis, fermentation and gasification requires large demands in the CHP plants and considerable expertise to complete this task of integration.

Preliminary techno-economical analysis

In this study, a preliminary techno-economical analysis is performed in order to initially assess the proposed REtrol vision, i.e. to evaluate the combined production of electricity, heat and renewable transport fuel REtrol, at the CHP plants. The major objective of this analysis is to investigate the influence of the integration of different processes for production of methanol and ethanol, with the CHP plant. This is done first by generating different scenarios of REtrol production, each representing one process alternative. The process alternatives are subsequently evaluated in the terms of energetic efficiencies, basic economic results and environmental impact (mainly CO_2 emission).

CHP plant Studstrupværket, located at the East part of the Jylland, Denmark, is used as the base-case CHP plant in the REtrol production analysis. Studstrupværket has the ability to produce simultaneously electricity and heat in two units, each of which produces 274 MW of electricity together with 506 MJ/s of district heating (DH). Fuel is consisted mainly of coal, but also wheat straw, heavy and light oil.

Table 1. Electricity and DH production at the Studstrupværket CHP plant (B4 block)

Fuel input [MW]	875.5
Electricity, net [MW]	273.9
DH [MJ/s]	505.6
Electricity efficiency [%]	31.3
DH efficiency [%]	57.7
Total efficiency [%]	89

The scale at which renewable fraction of the REtrol is produced, is selected based on the availability of the biomass in this area. Since at the Studstrupværket CHP plant is burned

215 ton of straw, for the daily production of electricity and heat, this amount is chosen as the amount that is available for the use in the IBUS process, for production of ethanol. However, this implies reduced output from the CHP plant that must be compensated in order to maintain the constant electricity and district heating production. Therefore, it is assumed that the difference in the CHP plant output is compensated by the use of additional coal, which is also reflected on CO_2 emission and process economy. This CHP plant, that uses additional coal without straw, is used as the base-case CHP plant in the evaluation (it produces 6572 MWh of electricity and 12133 MWh of DH).

Furthermore, it is assumed that the REtrol composition is based on the volumes of methanol and ethanol that can be used today in the car engine, without making any changes on it - methanol 3 vol% and ethanol 10 vol%, blended with 87 vol% of gasoline. Since the IBUS process produces 32 ton of ethanol from the 215 ton of straw, this determines the amount of the REtrol constituents that can be produced on a daily basis:

Table 2. Daily production of REtrol

	Composition [vol%]	Density [kg/m^3]	Mass [t]	Volume [m^3]
Methanol	3	794	10	12
Ethanol	10	792	32	40
Gasoline	87	779	273	350
REtrol	100	781	315	402

In this analysis, it is only considered the production of renewable part of the REtrol-methanol and ethanol.

In order to evaluate the combined production of electricity, heat and renewable part of REtrol (methanol and ethanol), 9 different scenarios are created. In the first 4 scenarios (1a-4a) it is assumed that the electricity and steam (that are consumed or produced in the separate processes) for production of methanol and ethanol are completely supplied or exported across the border of the plant, i.e. the methanol and ethanol production is not integrated with the CHP plant. In the next 4 scenarios (1b-4b) it is assumed that electricity is supplied or exported from/to the power plant, while the steam is either supplied or exported from/to the power plant or it is produced in one separate process and consumed in another. This means that the production of ethanol and methanol is integrated with the CHP plant.

In all above scenarios, the daily production of electricity and heat from the CHP plant is kept at almost the same level as the for the base-case CHP plant (6572 MWh of electricity and 12133 MWh of DH). In all scenarios including production of hydrogen by electrolysis, the electricity for this process is supplied from the wind turbines. In addition, it is assumed that ethanol and methanol are in the fixed ratio in REtrol (10% and 3%, respectively). In the final Scenario 5 it is assumed that the ratio of methanol in the REtrol is significantly higher than ethanol and the size of the methanol plant is based on a real industrial plant. In this case, ethanol fraction in REtrol is not at a considerable level.

It is important to emphasize that the conversion of the synthesis gas (obtained from the steam reforming of natural gas or gasification of biomass) is low due to the thermodynamic limitations and that unconverted reactants have to be recycled and mixed with the make-up gas. By this, approximately 99 % of the carbon contained in the feed make-up gas can be converted in to the methanol. Furthermore, there are certain requirements in respect to the synthesis gas composition: the amount of CO_2 in the make up gas should not be higher than the 14% (others 2-10%), the stoichiometric number R is 1.9-3.2 and the ratio CO/CO_2 can vary from 0.8-14, the stoichiometric number in the make-up gas is desirable to be slightly above 2 and the ratio CO_2/CO relatively low and the ratio H_2/CO should be at least 2. Since, on the other side, it is desired to capture as much as possible of the fossil CO_2 from the CHP plant, the composition of synthesis gas (molar ratio) make-up is chosen as follows: H_2 = 70%, CO = 20% and CO_2 = 10%. This composition is stoichiometric (R = 2) and it will give ratios of H_2/CO equal to 3.5, CO_2/CO equal to 0.5 and CO/CO_2 ratio equal to 2.

In the economic analysis, the total costs of methanol and ethanol production are divided in to operating costs and capital costs. The operating costs include costs of the feedstock, utilities (electricity, steam, cooling water) and operation and maintenance (O&M). The capital costs include the cost of equipment and building. The capital costs are simply calculated by assuming the lifetime of 16.5 years for all separate plants included in methanol and ethanol production. The interest rate and scale factors are not used in this simple analysis. The profit bound is determined as the difference between the total income and the operating costs.

In order to compare different scenarios, several definitions are introduced: a) <u>energy ratio (ER)</u> - the ratio between the energy content of the fuel obtained (methanol, ethanol and residual biomass) and feedstock energy content (straw and/or natural gas); b) <u>efficiency</u> – the ratio of the energy content of the methanol, ethanol and residual biomass over the energy content of the feedstock (straw, natural gas), natural gas (fuel), electricity and steam used for liquid fuels production; c) <u>efficiency (liquid fuels only)</u> - the ratio of the energy content of the liquid fuels (methanol and ethanol) over the energy content of the feedstock (straw, natural gas), natural gas (fuel), electricity and steam used for liquid fuels production; d) <u>fraction in fuel energy</u> – the ratio between the energy content of the electricity and steam used for liquid fuels production and energy content of the methanol and ethanol; e) <u>wind electricity</u>- the fraction of the electricity from wind turbines in the total electricity consumption; f) <u>renewable energy</u> - the ratio between the renewable energy consumed (straw and renewable electricity) and the total energy consumed (straw, electricity, steam, natural gas), assuming that the whole energy coming from the CHP plant is of fossil origin.

In the economic analysis, the following prices of the products are used: methanol 230 €/ton, ethanol 620 €/ton, coal 22 €/ton and vinasse 30 €/ton. In addition, all cost estimates are based on electricity price of 30 €/MWh, cooling water price of 0.037 €/m^3 (or 3.3 €/MWh assuming $\Delta T=10^oC$), steam price of 16.8 €/MWh (simplified as the same price for all pressure levels) and process steam price of 5.1 €/ton (low pressure steam for steam reforming). When the plant exports the electricity and steam, the credit is calculated based on the prices used for consumption. When considering the integration with the CHP plant, the price of the steam and electricity supplied from the power plant is 0 €/MWh, but it expressed through the cost of increased coal consumption, which is needed to maintain the constant production of electricity and heat. The price of electricity from wind turbines is in all cases 30 €/MWh.

In the considerations regarding the environmental impact, the CO_2 emissions from the a) combined methanol and ethanol plant alone, b) CHP plant alone and c) from the combined methanol and ethanol plant, integrated with the CHP plant, are compared in respect to the total emissions (fossil + renewable) and only fossil CO_2 emissions, e.g. emissions without CO_2 obtained from the combustion of straw or biomass, which are assumed renewable. Also, these emissions are compared with the emissions from the base-case CHP plant.

The main results of the preliminary techno-economical analysis

The results of this analysis indicate the energy ratio is roughly between 0.7-0.8, which suggests that the efficiency of converting the straw in to the methanol, ethanol and residual biomass is relatively high in the combined production of methanol and ethanol. The energy ratio is the same in the cases with and without integration with the CHP plant (except Scenario 5), since the same amounts of methanol, ethanol and residual biomass are produced from the same amount of straw. The energy ratio for the Scenario 5 is the highest (0.82), and it produces significantly higher amount of methanol, than other scenarios.

The efficiency of 50-57 %, suggests that the high amount of electricity and steam needs to be employed for production of methanol and ethanol and this is why the energy ratio ER is higher than efficiency. In the scenarios where combined production of methanol and ethanol is integrated with the CHP plant, the efficiency is slightly higher (52–58 %), while for Scenario 5 is the highest (85 %), due to the fact that high amount of the steam is exported to the CHP plant.

If the efficiency is expressed without residual biomass energy content, then 24-26 % of the total energy input is converted in to the liquid fuels methanol and ethanol. This indicates that almost half of the energy content of the products is in the residual biomass from the IBUS process. When methanol and ethanol production is integrated with the CHP plant, the liquid fuel efficiency is slightly increased to 25-27 %. For Scenario 5, this efficiency is much higher (82 %).

The fraction in the fuel energy suggests that all scenarios consume slightly more energy (electricity and steam, export is subtracted) than it is found in the produced methanol and ethanol (1.03-1.19). In the case of integration with the CHP plant, the fraction in the fuel energy is lower (0.98-1.14) and it shows that the energy content of the liquid fuels is, approximately, equal to the energy used to produce it (electricity and steam). Scenario 5 is again exception, where the energy content of the liquid fuels is much higher (-0.04, the negative sign indicates that more steam is exported than electricity is imported from the CHP plant).

If scenario includes the production of hydrogen by water electrolysis, the fraction of the wind electricity in the total electricity consumption is around 67-71 % (when integrated with CHP 59-64 %).

Furthermore, the fraction of renewable energy in the total energy consumed (68-73 %) shows why the REtrol constituents, methanol and ethanol, obtained by the combined production, are considered renewable. When integrated with the CHP plant, fraction of the renewable energy in the total energy consumed is from 69-74 %. Scenario 5 has the lowest value of 7 %, since it utilizes high fraction of fossil energy (natural gas) to produce methanol.

The integration of the combined methanol and ethanol plant with the CHP plant provides reduction of the total cost. This is mainly because the operating costs are reduced (from 28 500 – 32 000 to 22 600- 24 200 €/day), since the steam and electricity are imported from the CHP plant at zero costs (but with increased coal consumption). In addition, the capital costs are also somewhat lower, also because they exclude the price of the separate electricity generating steam turbine (33.5- 35.5 million € decreased to 33.4- 35.3 million €). For Scenario 5 the operating and capital costs (134 077 €/day and 119.7 million €, respectively) are much higher than in other scenarios, since it assumes high level of methanol production. Finally, the profit bound (the difference between total income and operating cost) is showing the economic effect of integrating the production of the liquid fuels methanol and ethanol, with the CHP plant (Scenario 5 yields 284 000 €/day):

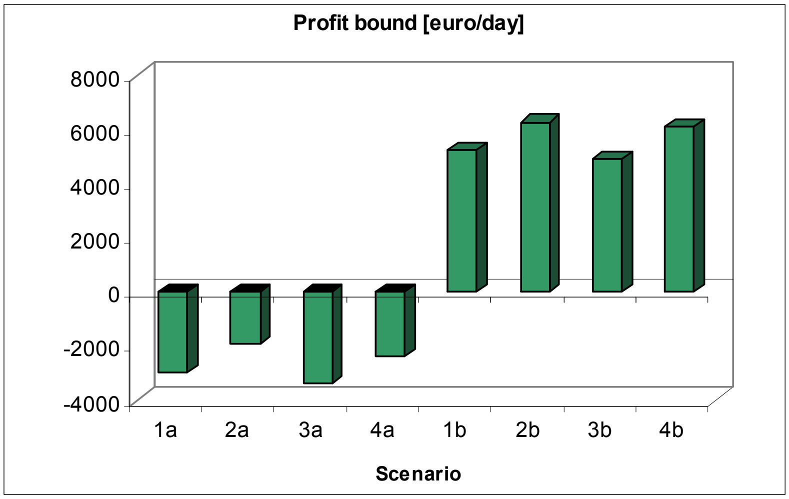

Figure 2. Profit bound for different scenarios of methanol and ethanol production, without (1a-4a) and with (1b-4b) integration with CHP plant

When the profit it calculated as a difference between the total income and the total costs (operational and capital), all scenarios except Scenario 5, yield negative value. If it does not assume integration with the CHP plant, the profit is in the range of -7 600 to -9 200 €/day, while in the case of integration, it ranges from -6 500 to -5 100 €/day (for Scenario 5 is positive, e.g. 260 000 €/day).

It is somewhat difficult to compare the environmental impacts of different scenarios and base-case CHP plant, due to slightly different electricity production. One way of making this comparison is to express the fossil CO_2 emission over the MWh of produced electricity:

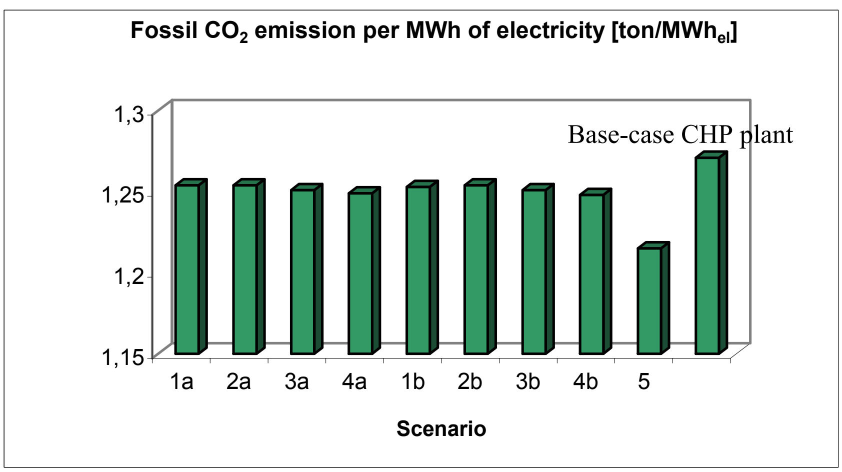

Figure 3. Emission of fossil CO_2 per MWh of produced electricity. Comparison of base-case CHP plant with different scenarios, without (1a-4a) and with (1b-4b and 5) integration with CHP plant

In almost all cases were combined plant is integrated with the CHP plant, slightly lower emission of fossil CO_2 per MWh of electricity is obtained. In addition, these emissions are lower than the emission of fossil CO_2 per MWh of electricity from the base-case CHP plant, which is 1.271 ton$_{CO2}$/MWh$_{el}$. This could indicate, that the combined production of methanol,

ethanol and biomass, with or even without integration with the CHP plant, provides improved environmental impact (fossil CO_2 emission), in respect to the base case plant.

To conclude, if the certain conditions are fulfilled, as it is discussed comprehensively in this work, the combined production of liquid fuels methanol and ethanol could be feasible. There is a variety of possible improvements of the economy of this complex production process, to mention only: utilization of the low-cost wind electricity (during long periods of strong wind) and off-peak periods of cheaper electricity and steam (night, summer, availability of cheap electricity from Norway), increased green tax for CO_2 emission, governmental subsidies, utilization of oxygen produced from electrolysis, etc. In addition, the production process itself can be improved substantially, by, for example, utilization of advanced oxy-firing concept in the CHP plant, improvement of design of pressurized bubbling fluidized bed or entrained flow gasifiers, design of more efficient CO_2 capture process, development of process for production of methanol only from H_2 and CO_2, improving efficiency of electrolysis and, integrating wind turbine directly with the electrolysis, etc.

Furthermore, one of the main possibilities for improvements lay in the ethanol production from the ligno-cellulosic biomass, e.g. the wheat straw, since the IBUS process has the highest contribution to the total costs of the REtrol production process. Thus, the biggest challenge is in reduction of the capital costs in the pre-treatment and enzymatic hydrolysis step of this process, but also in decreasing the price of the straw and especially, enzymes.

Conclusion

The combined production of the electricity, heat and liquid fuels, described by the REtrol vision is evaluated in this work, by the means of the preliminary techno-economical analysis. As it seen, the large scale combined production of liquid fuels methanol and ethanol, integrated with the CHP plant producing electricity and heat, could be feasible in the near future, if the certain conditions in relation to the process design and development are fulfilled, together with the favorable political frame.

The current technologies used for the separate processes in the combined production are presented and discussed, with respect to the maturity of the technology for use in the REtrol vision. It is seen that the most of the technologies that should be involved in this production are already available, but also that the further process development is required.

Finally, it is shown that the integration of the combined methanol and ethanol production with the CHP plant offers advantage with respect to the energy efficiency, process economy and environment, and that this benefit could be further increased.

One of the processes that has the strongest impact on the REtrol production efficiency and economy, is the production of ethanol from the ligno-cellulosic biomass by utilization of the cellulose degrading enzymes.

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