# FLEXIBLE HYBRID PROCESS FOR COMBINED PRODUCTION OF HEAT, POWER AND RENEWABLE FEEDSTOCK FOR REFINERIES

Esa Kurkela, Sanna Tuomi, Minna Kurkela & Ilkka Hiltunen
VTT Technical Research Centre of Finland Ltd, P.O. Box 1000, FI-02044 VTT, Finland,
Tel. +358 405 026 231, e-mail:esa.kurkela@vtt.fi

ABSTRACT: A flexible combined heat, power and fuel production concept, FLEXCHX, is being developed for managing the seasonal mismatch between solar energy supply and demand for heat and power that is highly pronounced particularly in the Northern and Central Europe. This process produces heat, power and an intermediate energy carrier (Fischer-Tropsch hydrocarbon product), which can be refined to transportation fuels using existing oil refining equipment. The FLEXCHX process can be integrated to various combined heat and power production systems, both industrial CHPs and communal district heating units. In the summer season, renewable fuels are produced from biomass and hydrogen; the hydrogen is produced from water via electrolysis that is driven by low-cost excess electricity from the grid. In the dark winter season, the plant is operated only with biomass in order to maximize the production of the much needed heat, electricity and FT hydrocarbons. Most of the invested plant components are in full use throughout the year, only the electrolysis unit is operated seasonally.
Keywords: biomass, gasification, reforming, biofuels, Fischer-Tropsch

## 1 INTRODUCTION

Combined Heat and Power (CHP) production technologies using various wood residues and agro biomasses are commercially available at different sizes ranging from very small gasifier-engine plants to large-scale fluidized-bed boiler plants. Power production efficiencies in CHP operation are usually below 30 %, while the overall efficiency to power and heat can exceed 85 %. CHP plants based on direct combustion and conventional steam cycle are not highly flexible and their operation is usually limited to the heating season as the efficiency in condensing (power alone) mode is low. The state-of-the-art CHP technologies have become under severe financial stress in a number of European markets characterized by a rapid addition of VRE (variable renewable energy) capacity and stagnating electricity demand. Consequently, many new thermal generators are currently designed to produce only hot water for heating purposes instead of CHP (this is also the case in Finland where CHP has been the common standard so far). As a result, there is a clear need for new flexible district heating and combined heat and power production solutions in Europe that can maintain economic feasibility under increasing VRE penetration.

On the other hand, the production of advanced transportation biofuels (based on the coupling of biomass gasification and synthesis technologies) has been the focus of intensive development for over ten years, but industrial deployment has been postponed time and again. One fundamental reason for this is the attempt to reach satisfactory economics by exploiting economies of scale, which leads to extremely large-scale plant concepts (> 300 MW) that are eventually deemed too risky by the investors. Large-scale gasification/synthesis plants also suffer from incomplete utilization of by-product heat, as it is difficult to find such large heat consumers that could exploit the heat supply to a large degree. Thus, the biomass utilization efficiency of stand-alone plants rarely exceeds 55 % (LHV) even with the best available technologies [1]. In addition, the common chemical engineering principle of the economies of scale does not apply to biomass logistics.

In response to the growing share of solar and wind power in the energy systems and consequent need for converting surplus electricity into storable form, Power-to-Gas (P2G) and Power-to-Liquids (P2L) concepts have recently been suggested for managing the temporal mismatch between solar energy supply and heat and power demand. However, the simple P2G and P2L concepts producing e.g. synthetic natural gas (SNG) or methanol from excess electricity and $CO_2$ suffer from poor round-trip efficiency (typically <40 %) when the final product after storage is once again converted to electricity. In addition, annual operation times for these plants, including fuel synthesis, are low especially in the Northern European countries, typically only ca. 2000 hours/yr. These limitations result in prohibitively high production costs making conventional P2G and P2L concepts economically unattractive.

The FLEXCHX concept and technologies constitute a complete rethinking of how combined heat and power should be produced in VRE dominated power grids, and how the use of excess solar and wind energy can be combined with effective utilization of biomass residues. The novel and ground-breaking approach of FLEXCHX is the idea to combine power-to-fuels principle with combined heat and power plants and existing oil refineries, thus relying on existing assets instead of heavy new investments that are required by conventional power-to-fuels concepts or large Biomass-to-Liquids (BTL) plants.

## 2 FLEXCHX CONCEPT

The key idea of FLEXCHX is shown in Fig.1, which illustrates the operation principle of the process under two distinctly different seasons. The FLEXCHX process combines several innovative elements into a cost-effective and highly flexible conversion plant that can be economically realized already at small-to-medium-scale of 5-50 MW feedstock input. Biomass residues are gasified in a two-stage pressurized fixed-bed reactor, which can be operated with flexible mixtures of oxygen, air, steam and $CO_2$ as the gasification agents. The raw gas leaving the gasifier is filtered in a hot filter unit, where robust novel metal filters are used. After filtration, the raw gas is led into a catalytic reformer, where tars and light hydrocarbon gases are reformed to increase the yield of $H_2$ and CO. After final gas cleaning, syngas is utilized in a highly efficient and compact Fischer-Tropsch (FT) process.

A unique design feature of the process is that in spring and summer, “in the solar energy season”, the syngas composition can be tailored by recycling $CO_2$ to the gasification process to replace gasification steam. In this operation mode, the molar ratio of $H_2$ and CO after the reformer is low, typically < 1, which creates space for adding electrolysis-$H_2$ so that the optimal $H_2$/CO ratio of 1.8-2 is achieved and the yield of FT wax is maximized.

In winter, during the “dark heating season”, the same plant is operated by biomass alone using enriched air and steam as the gasification agents. This will result in maximized total conversion of biomass to FT hydrocarbons and heat.

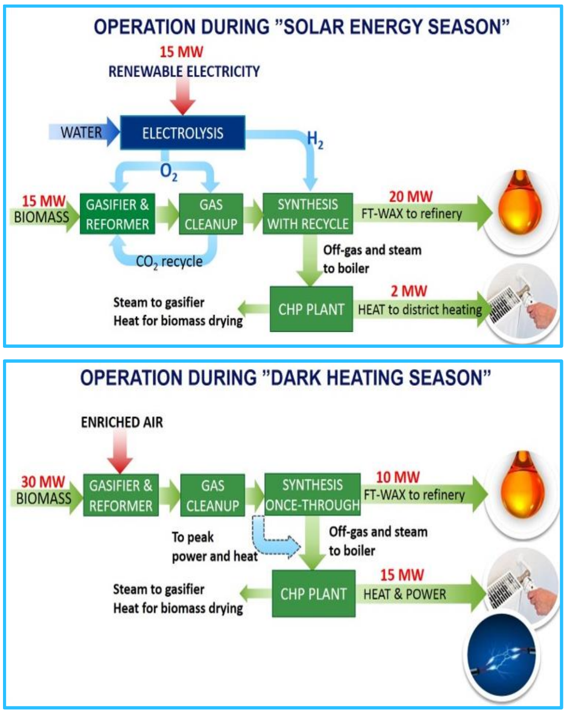


**Figure 1:** Principal idea of the FLEXCHX concept.

## 3 CONCEPT DEVELOPMENT STUDIES

### 3.1 Operation during different seasons

The operation principle of the FLEXCHX process during the dark heating season and under the solar energy season is illustrated in Fig. 2 and Fig. 3, respectively.

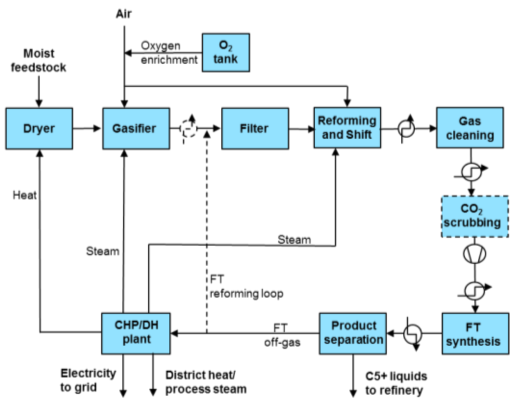


**Figure 2:** FLEXCHX process operated with biomass-alone during heating season.

During winter, or more generally at periods when the electricity price is high, FLEXCHX process is operated with biomass as the only feedstock. At first, biomass is dried from the initial moisture content (typically 40-60%) to 10-15 % moisture. Then, dry biomass is fed through a lock-hopper system to the staged fixed-bed gasifier, where it is gasified with a mixture or air, oxygen and steam to raw synthesis gas. Raw gas is filtered and led into the staged catalytic reformer, where tars and $C_2$-hydrocarbon gases and part of methane are reformed to hydrogen and carbon monoxide. In the last stage of the reformer, main gas components (CO, $CO_2$, $H_2$ and $H_2O$) approach the equilibrium of water gas shift reaction. Reformed product gas is cleaned from sulphur compounds and other potential catalyst poisons by a sorbent-based gas cleaning system using activated carbon and zinc based sorbents. Finally, part of $CO_2$ may be removed by pressure water scrubbing, in order to lower the inert gas content of the syngas entering the FT synthesis.

In the basic version of this operation mode, defined as Case A1 in Table 1, gasification is carried out with enriched air with 25 wt% enrichment with oxygen ($O_2$ content of gasification air 42.4%). This oxygen is considered to be taken from the excess production during the “solar energy season”. In this case, 60 % of $CO_2$ is removed and vented in order to keep the inert gas content at a reasonable level. The FT off-gas is led to the boiler unit, where it is combusted to generate heat and power. Due to the higher inert gas content of syngas and due to the fact that off-gases are not recycled in Case A1, the FT efficiency to $C_{5+}$ hydrocarbon products is lower than in other operation cases.

Biomass-alone operation can also be realized as pure steam-oxygen gasification, if the plant has a separate oxygen production unit. Case A2 represents an optimal design for maximized yield of FT liquids and waxes with biomass-alone operation. In this case, pure oxygen and steam are used both in the gasifier and in the reformer, 80 % $CO_2$ is removed and the off-gases of the FT unit are recycled back to the gasification process. This design can be considered for plants, which will be operated throughout the year without electrolysis.

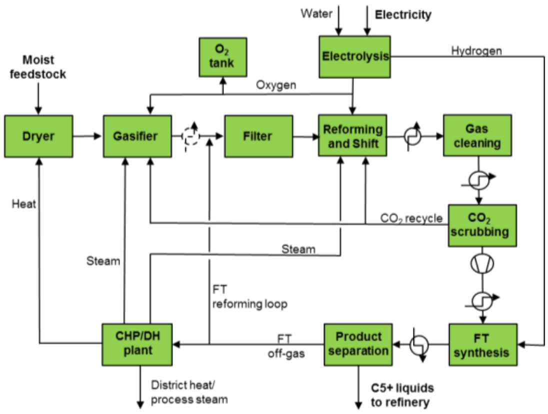


**Figure 3:** FLEXCHX process with electrolysis boosting and FT off-gas recycling.

During the solar energy season, as illustrated in Figure 3, the gasifier and the reformer are operated with pure oxygen diluted by recycled $CO_2$ and smaller amount of steam. In the ideal Case B1 of this operation mode, 80 % of $CO_2$ is removed from the synthesis gas and all separated $CO_2$ is recycled back to gasifier and the reformer. As a result, the char gasification reactions in the gasifier are dominated by $CO_2$ gasification and the role of dry reforming by $CO_2$ also plays an important role in the reformer. The homogenous shift reaction pushes the gas composition towards high CO content and as a result, the molar ratio of $H_2$ and CO is clearly below 1. This creates space for the additional hydrogen input provided by electrolysis of water. In this operation mode, it is essential to maximize the yield of C5+ hydrocarbons as the value of by-product heat is low and there is no need for electricity production.

3.2 Estimated process performances

The key design parameters and the results of preliminary process evaluation studies are presented in Table I. Case A1 corresponds to biomass-alone operation during a period, when the values of heat and power are high, and the gasifier and the reformer are operated with enriched air. Case A2 presents the performance of biomass-alone operation in an ideal case, where the process design is optimized to maximize the yield of FT liquids and waxes, and pure oxygen is used both in gasification and reforming. Case A3 shows the estimated performances for the same process as Case A2, but now with conservative assumptions for the achieved gasification and reforming efficiencies. Cases B1 and B2 describe the estimated operation conditions and efficiencies during electrolysis-assisted operation. B1 is the ideal or target case, while B2 is calculated with more conservative assumptions concerning the front-end gasification process.

In all cases, the initial moisture content of biomass is 50%, moisture content after dryer is 12% and the energy efficiency of drying is 55%. Gasifier pressure is 10 bar and carbon conversion to gas and tars 99.5 %. The filter unit is operated without a gas cooler, which is considered realistic with clean woody biomass feedstocks. In the case of high-alkali agro-biomass or waste-derived fuels, raw gas must be cooled to ca. 600 °C in order to remove vapor-phase trace metals and chlorine before the reformer. The FT process is not simulated in detail, but the effects of syngas gas composition (inert gas content) is qualitatively taken into account by using lower per-pass CO conversion efficiency for the cases where the inert gas concentration of syngas is high.

**Table I:** Estimated characteristics of different operation cases of the FLEXCHX process.

| Case | A1 | A2 | A3 | B1 | B2 |
|---|---|---|---|---|---|
| Gasifier parameters | | | | | |
| Outlet temperature, °C | 830 | 830 | 850 | 830 | 850 |
| $O_2$ in air streams, wt% | 42.4 | 100 | 84.6 | 100 | 100 |
| Steam/(air+$O_2$), w/w | 0.75 | 2.5 | 2.2 | 0.15 | 0.15 |
| $CO_2$/(air+$O_2$), w/w | 0 | 0 | 0 | 2.3 | 2.3 |
| Reformer performance: | | | | | |
| Outlet temperature, °C | 850 | 850 | 880 | 850 | 880 |
| Steam/(air+$O_2$), w/w | 0.5 | 1 | 1 | 1 | 1 |
| $CO_2$/(air+$O_2$), w/w | 0 | 0 | 0 | 0 | 0 |
| $CH_4$ conversion, % | 80 | 80 | 50 | 80 | 50 |
| $CO_2$ removal, % | 60 | 80 | 80 | 50 | 50 |
| Electrolysis | | | | | |
| Energy efficiency % | - | - | - | 75 | 75 |
| Hydrogen to FT, MW | - | - | - | 18.5 | 18.5 |
| Total inlet gas to FT: | | | | | |
| Energy input, MW | 40.4 | 53.9 | 51.2 | 49.8 | 52.0 |
| $H_2$/CO ratio, mol/mol | 1.82 | 1.95 | 1.98 | 1.8 | 1.8 |
| Inert gas content, % vol | 37.4 | 8.5 | 26.6 | 15.7 | 18.0 |
| FT performance: | | | | | |
| CO conversion, % | 60 | 70 | 70 | 70 | 70 |
| $C_{5+}$ selectivity, % | 91 | 91 | 91 | 91 | 91 |
| Off-gas recycle % | 0 | 85 | 72 | 85 | 85 |
| Recycled off-gas, MW | 0 | 15.8 | 15.5 | 12.8 | 15.5 |
| Power plant parameters | | | | | |
| Off-gas to steam eff. % | 90 | 90 | 90 | 90 | 90 |
| Steam-to-power eff. % | 35 | 35 | 32.5 | 0 | 0 |
| Overall energy balance: | | | | | |
| Biomass input, MW | 46.1 | 46.1 | 46.1 | 23.0 | 23.0 |
| Electricity input, MW | 0 | 0 | 0 | 27.0 | 27.1 |
| $C_{5+}$ products, MW | 18.6 | 27.6 | 23.2 | 27.1 | 26.4 |
| Heat production, MW | 12.8 | 7.1 | 9.7 | 11.0 | 11.9 |
| Net Power to grid, MW | 2.3 | 0.8 | 0 | 0 | 0 |
| Efficiencies (LHV), % of input energy | | | | | |
| - $C_{5+}$ products | 40.3 | 58.9 | 50.4 | 54.2 | 52.6 |
| - Heat production | 27.8 | 15.1 | 21.0 | 22.0 | 23.8 |
| - Net Power to grid | 5.0 | 1.7 | 0 | 0 | 0 |

3.3 Conclusions of the preliminary process design studies

The following conclusions were made based on the preliminary process design studies:

(1) High energy conversion efficiencies to $C_{5+}$ hydrocarbon FT products can theoretically be reached both in biomass-alone operation and in the integrated operation of biomass gasification and electrolysis. However, in biomass-alone case this will necessitate the use of high purity oxygen as gasification agent instead of enriched air, and consequently a separate oxygen plant is needed.

(2) When maximized efficiency to $C_{5+}$ hydrocarbon products is targeted, the tail gases of FT synthesis must be recycled somehow. One interesting way is to recycle the tail gas back to the raw gas line before the filter or before the reformer. In this case, the hydrocarbon gases will be reformed and the recycled $CO_2$ is partly used for reforming reactions and partly removed in gas scrubbing. Already moderate recycle ratios result in high FT product yields.

(3) The product gas cooling and the cooling of FT unit always produce by-product heat. Thus, a suitable heat sink would be required also during the “summer mode” to reach high overall efficiency.

(4) The FLEXCHX process can be realized by very many different design and operation principles. As the gasification process as well as the whole concept is rather novel, there are still rather many open

questions to be studied in the experimental work packages of the project. A powerful simulation tool based on Aspen Plus will also be developed and used in the project to assess and guide these developments.

## 4 EXPERIMENTAL DEVELOPMENT AND VALIDATION TESTS

### 4.1 SXB gasification pilot plant

The process development activities of the project are focused on the five key enabling technologies - gasification, filtration, reforming, final gas cleaning, and compact FT synthesis, which essentially form the backbone of the flexible production concept. The experimental development culminates to extended-time tests using the 1 MW (biomass input) pressurized fixed-bed gasification pilot plant located at VTT's piloting centre Bioruukki (Fig. 4).

The patented staged fixed-bed gasifier (SXB) developed at VTT is a combination of a well-proven updraft gasification principle and a highly innovative catalytic step integrated within the gasifier. The lower gasification stage is operated as a counter-current reactor resulting in complete carbon conversion and fully oxidized ash. Major part of tars and $C_2$-$C_5$ hydrocarbon gases are decomposed in the secondary catalytic gasification zone. This innovative gasifier is a result of VTT's continuous efforts to advance biomass gasification technologies. In the 1980's, VTT developed a simple and robust updraft gasifier (producing tar-containing fuel gas), which has been in industrial use since the mid-1980's [2]. In the late 1990's, the first version of two-stage operation was developed, and the idea of forced fuel feeding was applied to broaden the feedstock basis and to produce gas that could be cleaned for gas engines [3, 4]. The main idea of the present invention is to integrate tar decomposition unit directly within the fixed-bed gasifier. In the FLEXCHX project, a Fischer-Tropsch compatible version of the gasification process (operated with $O_2$/steam/$CO_2$) is developed (to TRL5).

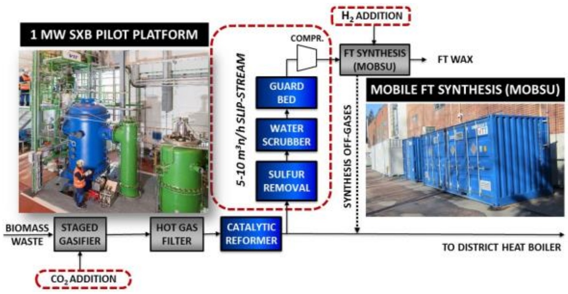


**Figure 4:** Pilot-scale experimental facilities used for validating the key enabling technologies.

### 4.2 Gas cleaning and FT synthesis

Gas filtration and tar control play a key role in many gasification applications. The innovative concept realised in the FLEXCHX process is based on having initial tar control already in the gasifier so that the produced gas can be filtered at 500-800 °C without soot formation or problems caused by tar condensation. The filter design of VTT and Grönmark is specifically tailored for the pressurised fixed-bed gasifier, and new robust corrosion-resistant metal alloy filters (modified Iron-Chromium-Aluminium) are applied.

In the FLEXCHX project, the extensive know-how of VTT on catalytic reforming technology [5] is combined with the catalyst know-how and new innovations of Johnson Matthey (JM). It is especially important to be able to avoid the use of nickel-based catalysts, because they are difficult to operate during start-up and shutdown periods. With nickel-catalysts, the start-up and shutdown procedures have to be designed properly to avoid overheating on one hand and the formation of very hazardous emissions of nickel carbonyls on the other hand. The PGM (Platinum Group) catalysts of JM have been successfully tested at VTT in fluidised-bed gasifier applications and they are easier to operate. In the FLEXCHX project, JM will focus on further development of their catalyst materials towards increased tolerance against impurities, needed to move from clean wood to more challenging RDF (refuse-derived fuel), and when designing simpler concepts without gas cooling between the gasification and filtration process.

Commercial Fischer-Tropsch synthesis reactors, based on slurry bubble column or fixed-bed reactor technologies, are available for large production units having annual capacities > 50 ktoe/a (corresponding to gasifier capacities > 150 MW). In the FLEXCHX project, a cost-effective process for capacities in the range 3-10 ktoe/a will be developed. For this purpose, the innovative compact synthesis of INERATEC is a perfect match with the flexible fixed-bed gasification process. FT synthesis will be conducted in innovative chemical reactors of INERATEC that intensify the chemical reactions by micro process technology.

## 5 INTEGRATION STUDIES

The process development and validation activities are complemented by studies on potential feedstocks, electrolysis technology options, CHP integration, and by designing of an appropriate control system for the integrated FLEXCHX plant. CHP integration options include existing or new district heating plants and networks as well as industrial CHP systems. On the other hand, an optimized strategy for introducing FT hydrocarbons to large refineries with minimal modifications to existing infrastructures, and maximal added-value to local FT wax suppliers and back-end fuel/chemical producers is studied in the project by Neste Engineering Solutions.

## 6 REFERENCES

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## 8 LOGO SPACE

The project is realized by a consortium of ten partners: VTT, Enerstena, INERATEC, DLR, HELEN, Kauno Energija, Lithuanian Energy Institute, NESTE Engineering Solutions, Johnson Matthey and Grönmark. More information about the FLEXCHX project can be found at www.flexchx.eu.