Process concept for flexible production of renewable transportation fuels and heat

Results for the pilot scale process validation tests

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ISBN 978-951-38-8747-6

VTT Technology 387

ISSN-L 2242-1211
ISSN 2242-122X (Online)
DOI: 10.32040/2242-122X.2021.T387

JULKAISIJA – PUBLISHER

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Cover image: VTT

Preface

This report summarizes the research results of the Work Package 6 of the EU-funded research project **FLEXCHX** - “Flexible combined production of power, heat and transport fuels from renewable energy sources”. This Work Package was focused on the pilot-scale validation of the FLEXCHX process, consisting of a pressurized fixed bed gasifier, hot filter, catalytic reformer, final gas cleaning unit, and the Fischer Tropsch synthesis.

The authors would like to acknowledge the EU “FLEXCHX” project for the financial support. The FLEXCHX project has received funding from the European Union’s Horizon 2020 research and innovation program under Grant Agreement No. 763919.

Espoo, April 2021

Authors

The FLEXCHX Consortium

Project website: http://www.flexchx.eu/index.htm

Contents

List of symbols

Daf	Dry and ash free
FID	Flame Ionization Detector
FLEXCHX	Flexible Production of Combined Heat, Power, and Fuels
FT	Fischer-Tropsch
GHSV	Gas Hourly Space Velocity
KPI	Key Performance Indicator
LHV	Lower Heating Value
MOBSU	Mobile Synthesis Unit
Nm^3	Standard cubic meter (at 273,15 K, 101,35 kPa)
RHC	Renewable Heating and Cooling
RIA	Research and Innovation Action
SXB	Staged Fixed Bed
UC5	Ultra Cleaning Unit - version 5
VRE	Variable Renewable Energy

1. Introduction

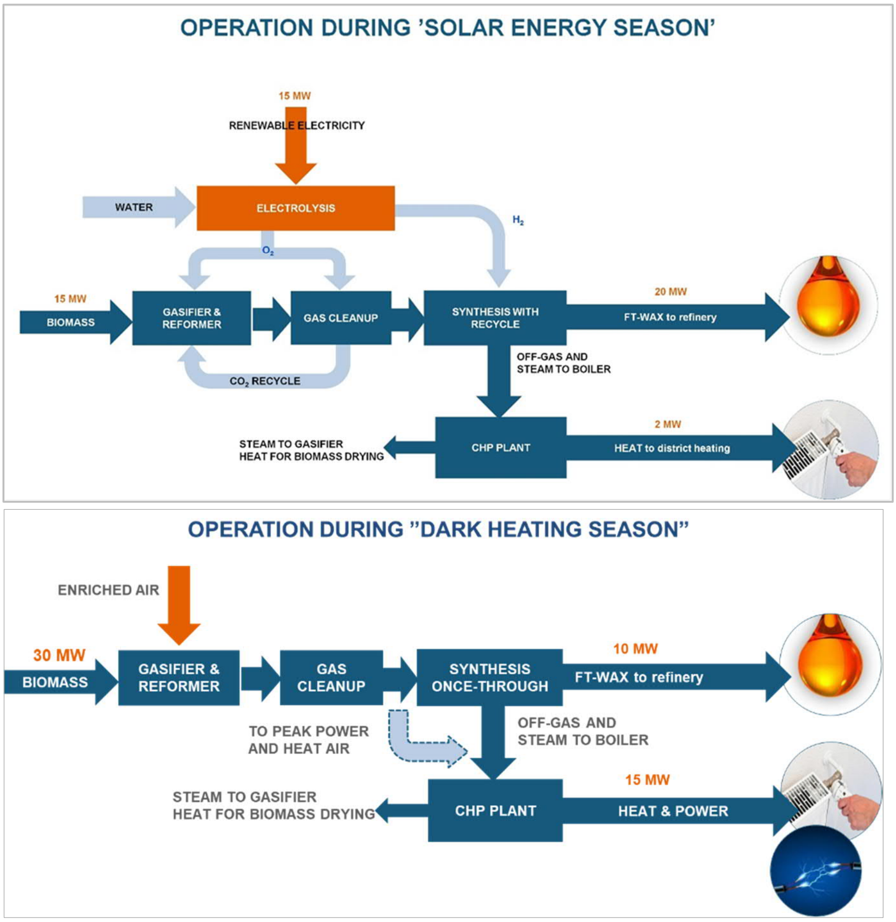
The EU Horizon 2020 project, FLEXCHX, realized in 2018-21, was focused on the development of a flexible process for the production of renewable transport fuels and heat. The developed hybrid production concept, FLEXCHX, combines the use of biomass residues and intermittently available low-cost renewable electricity in a novel and flexible way. According to the Renewable Heating and Cooling Platform (RHC), almost 50% of the total energy consumed in Europe is used for heat generation, either domestic or industrial purposes [1]. The heating and cooling sector is expected to play a key role in achieving targets set to renewable energy (Renewable Energy Directive (2009/28/EC) and greenhouse gas reductions by 2050 [2]. The increasing role of variable renewable energy (VRE) supply in the grid puts extreme technical and financial pressure on existing generators that were originally designed to operate as baseload units. The retirement of such pre-existing generation capacity raises the important question of how to best maintain the stability and reliability of the future energy grid. As a result, there exists a clear need for new low-GHG technologies that can mediate the temporal differences between energy supply and demand. In the future energy system, biomass will play an increasing role in managing fluctuations of VRE-dominated energy systems.

The FLEXCHX project is targeted at creating a method for managing the seasonal mismatch between solar energy supply and energy (heat and power) demand that is highly pronounced, particularly in Northern and Central Europe. Plenty of solutions already exists for managing short-term (from split seconds to diurnal) variation in the energy system, but there is a clear need for new technologies that can reconcile the seasonal mismatch of abundant solar supply (summer) with peak energy demand during the dark winter months. In addition to these challenges, Europe also has to decarbonize the transport sector to meet its CO_2 reduction targets. While electric vehicles are becoming a viable solution for light-duty and city transport, there is still a huge demand for renewable fuels in the heavy road, maritime, and commercial aviation sectors. Advanced biofuels are expected to play a key role in these “difficult-to-electrify” sectors, as described in the report prepared by the European Industrial Biofuels Initiative [3].

The key idea of FLEXCHX is shown in Figure1, 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 a 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 roughly 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 the maximized total conversion of biomass to FT hydrocarbons and heat.

The operating principles of the FLEXCHX process are described in more detail in [4], and detailed results for the development of key enabling technologies are described previously in [5], [6], [7], and will be further presented in several reports and articles, which are under preparation in spring 2021. Preliminary studies on the conversion efficiencies were presented also in [4] and will be further published in 2021.

This report summarizes the results of the process validation tests and presents preliminary ideas for follow-on industrial demonstration activities. In the validation tests, the gasifier, hot filter, and catalytic reformer were tested on a pilot scale and the slipstream of gas was further cleaned in the bench-scale final gas cleaning unit. Finally, the clean syngas was compressed and utilized in the Fischer-Tropsch (FT) synthesis.


OPERATION DURING 'SOLAR ENERGY SEASON'

OPERATION DURING "DARK HEATING SEASON"

Figure 1. Principal idea of the FLEXCHX concept [4].

2. Description of the experimental set-up

2.1 SXB pilot plant

The schematic process diagram of the Staged Fixed Bed (SXB) pilot plant is shown in Figure 2, while a more detailed plant description is presented in [5] and [6]. In the SXB-gasifier, biomass is fed to the top of stage 1 and a fixed-bed is created from the biomass charcoal and ash at the bottom of the reactor. Primary gasification agents, mixtures of air, O_2, steam, and/or CO_2, are fed to the bottom of the bed. The gasification and pyrolysis gases produced in the primary stage flow to the second stage of the gasifier, where secondary gasification gases are introduced through a catalytic distributor system. A high proportion of tars and light hydrocarbon gases produced in the primary updraft gasifier stage are decomposed in the second stage, and gas temperature is raised from 300-600 °C to the target outlet temperature of 750-900 °C.

Two different designs for separating the primary and secondary gasification stages were tested. Originally, the two stages were separated by a thick plate, which had four holes, each 40 mm in diameter. These holes led the primary raw gas from the lower updraft bed into the secondary gasification zone so that the raw gas entered directly into the first distributor level of the secondary gasification agent. The last test run (SXB 20/24) was carried out with a larger central opening of 400 x 400 mm, as the aim was to study whether this division plate has a major role in gasifier performance [6], [8].

After leaving the gasifier, the raw gas is led via the first gas cooler into the filter unit. Dust containing raw gas is entering into the lower part of the filter, where it meets the outer surfaces of 12 one-meter-long metal candle filter elements. The filter elements are divided into four clusters and the accumulated dust is removed from the filter surface by periodic reverse pulsing with nitrogen. The filtered gas flows through the porous filter elements and enters the upper clean gas side of the filter unit. The lower and upper sides of the filter unit are separated by the tube sheet, in which the filter elements are mounted using special gaskets and securing methods. A mixture of fine sand and dolomite is fed as additional dust into the first gas cooler to create a suitable dust cake, as the raw gas of the SXB gasifier has a very low initial dust content, and thus a sticky cake of tars and soot could build up.

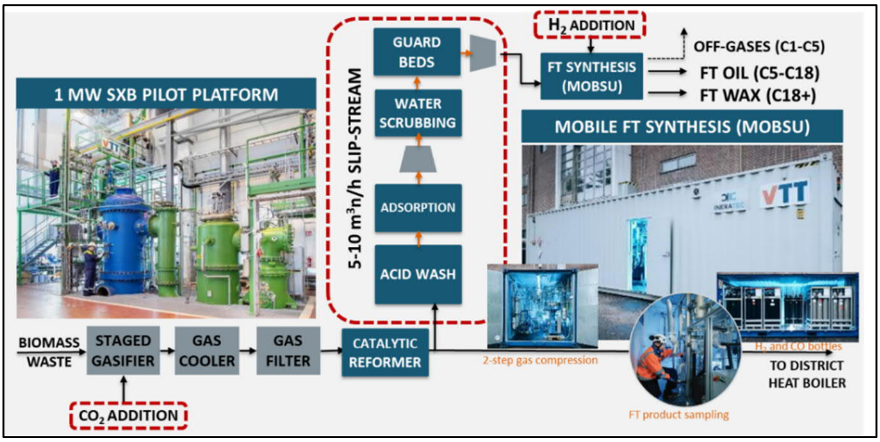


Figure 2. VTT's SXB gasification pilot plant and the main experimental facilities used in the validation tests.

From the filter unit, the raw gas flows into the reformer, where the filtered gas is reformed in a two-stage catalytic reformer. Both stages are realized with fixed beds filled with granular catalyst material. The reformer is operated autothermally, and the required heat for the endothermic reforming reactions is provided by oxidation reactions. Mixtures of oxygen, nitrogen, and CO_2 are fed to both reformer stages. In the present pilot test campaigns realized at the SXB gasification plant, different catalyst loadings, provided by Johnson Matthey (JM), were tested. The reformer is described in more detail in [5]. Three different reformer loadings used in the SXB tests are illustrated in Figure 3.

After the reformer, the gas flows through the second gas cooler, where the temperature is lowered from 800-900 °C to the range of 200-400 °C. Then, gas pressure is reduced close to ambient in a pressure let-down valve. A slipstream of the reformed gas is taken after the pressure let-down valve for the final gas cleaning process (called UC5), where ammonia, sulfur compounds, and remaining traces of tars are removed. Finally, the clean syngas is compressed and led into the Fischer-Tropsch (FT) unit MOBSU (Mobile Synthesis Unit). The main part of the produced syngas is led directly from the second gas cooler into the hot water boiler, which is connected to the existing district heating network in the City of Espoo, Finland.

The concentrations of main gas components (CO, H_2, CO_2, CH_4, and O_2) were analyzed by online gas analyzers. These results were used for real-time process monitoring and control. Micro-GC was used to analyze permanent gases as well as light hydrocarbon gases C_1-C_4H_y in a fully qualitative and reliable way. This data was used in the evaluation of the result, as described in [8]. In the ultra cleaning process, several offline analytical methods (e.g. Dräger tubes) were in use [7].

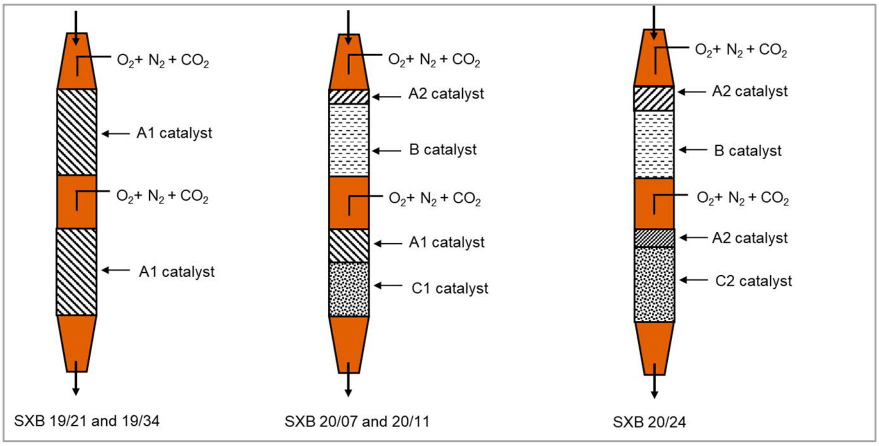


Figure 3. Illustration of the three tested reformer loadings.

2.2 Slip-stream final gas cleaning unit UC5 at the SXB pilot tests

The final gas cleaning from sulfur compounds, trace halides, ammonia, and HCN, as well as from residual tars and benzene, was realized using the slipstream gas cleaning unit, called “UC5”, illustrated in Figure 4. It is a novel low- to medium-temperature final gas cleaning process based on adsorption and organic solvent-free scrubbing. This final gas cleaning process is intended to replace the capital-intensive wet-scrubbing processes which are optimized for syngas purification at a larger scale of hundreds of MW fuel input.

The final gas cleaning process UC5 was originally constructed and used for cleaning syngas from an atmospheric fluidized-bed gasifier [7], and it involves a two-stage compression system from 1 to 5 bar and from 5 to 30 bar (see photographs in Figure 5). A heated gas line was constructed to connect the SXB gasifier to the final gas cleaning train. The slipstream was connected after the SXB pressure reducer, and atmospheric pressure syngas was fed to the process. The decision to feed atmospheric syngas to the final gas cleaning does not change the nature of the tests in a meaningful way compared to a fully pressurized system as applied in the FLEXCHX concepts. The gas composition was analyzed very carefully using continuous analytical methods, employing FTIR (NH_3, Benzene) and FPD-GC (H_2S, COS) and a micro GC (O_2). Non-continuous methods included Dräger colorimetric tubes for HCN and HCl analysis.

The process is divided into the operations involving purification steps, which are located inside the gasification hall in Bioruukki, and the compression steps, which are in a container structure outside the building. The unit operations of the UC5 gas cleaning unit are briefly described in the following. More detailed information is given in [9].

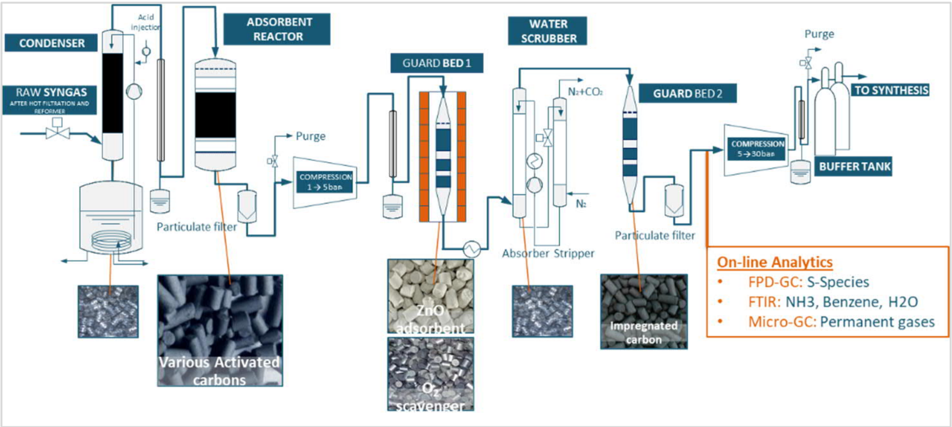


Figure 4. A schematic of the slip-stream final gas cleaning system UC5 [7].

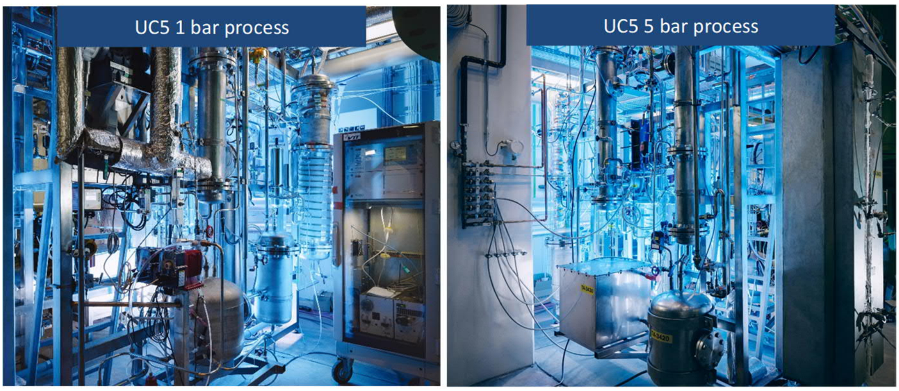


Figure 5. Photographs of UC5.

Condenser and ammonia removal

In the condenser, the 150–300 °C wet syngas is cooled down to room temperature, and NH_3 is simultaneously removed by dissolving it in acidic water. In the SXB campaigns, formic acid was used to lower circulating water pH to around 3.

Adsorbent reactor

The bulk of the H_2S is removed in a room temperature AC reactor filled with various activated carbons. Residual tars and benzene are also adsorbed by the carbons. The first bed of activated carbon consists of carbons intended for the physical adsorption of hydrocarbons. The second bed, filled with microporous activated carbon, is intended for H_2S removal by oxidation. For this, air (oxygen) is injected into the gas stream prior to the adsorbent reactor at 0.2 Ndm^3/min rate. The activated carbon surface acts as a medium for facilitating the oxidation reaction, which would not otherwise occur, thus the activated carbon does feature certain catalytic properties. As a final precautionary layer, the AC reactor utilized, in the campaigns SXB 20/07 and 20/11, a small bed of highly efficient caustic impregnated carbon.

Pressurized Water Scrubber

The water scrubber is intended as a simple solution for partial CO_2 removal from syngas. A closed water loop is employed with a pressure-swing of around 5 bars between absorption and desorption columns. A heat exchanger is used to cool the water loop to improve CO_2 solubility in water.

Guard beds

There are two guard beds in the process. One is at 200 °C temperature to facilitate catalytic reactions and the other at room temperature to act as a final polishing step. The warm guard bed is a pressurized reactor placed in a furnace with a preheater. The two uppermost beds were packed with ZnO with Al_2O_3 support. The zinc oxide adsorbent pellets are not only used for H_2S capture but also COS and HCN hydrolysis through the Al_2O_3 support.

The second guard bed is utilizing high-performance carbons acting as a final step to polish the gas from any impurities with acid/basic affinity, namely NH_3, H_2S, and HCl. It is actively removing NH_3 if there is HCN hydrolyzed in the warm guard bed step. Otherwise, it acts as a precautionary step to prevent accidental or one-off high impurity concentrations from entering the downstream catalyst and poisoning it. A high-performance, doped, activated carbon for H_2S removal was utilized in the upper bed as well.

2.3 Fischer-Tropsch unit MOBSU

The Fischer-Tropsch (FT) synthesis unit, called MOBSU (Mobile Synthesis Unit), was coupled to the gasifier-gas cleaning process train. The process was constructed by Ineratec, and it utilized Ineratec's microchannel reactor technology. The unit is designed for 5 – 6 Nm^3/h syngas input. After the final gas cleaning, the syngas was fed to a small buffer tank, and gas was fed to the FT process with a mass flow controller. The syngas feeding rate depended on the final gas cleaning compressor capacities. The FT process block diagram is presented in Figure 6.

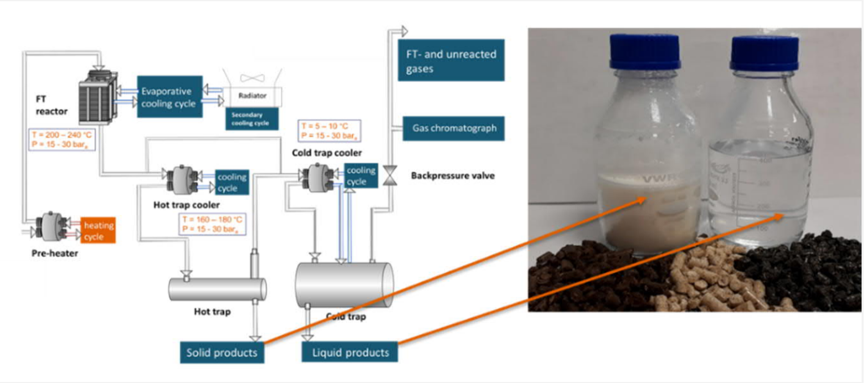


Figure 6. Mobile synthesis unit FT process block diagram.

In the FT process, pre-heated syngas is fed to the compact microstructured water-evaporation-cooled reactor. The catalyst was a Co-based commercial particulate catalyst. The product gas was cooled in two stages: in the first stage, the effluent was cooled and condensed to the hot trap at slightly below the reaction temperature to achieve separation of a heavy hydrocarbon fraction; the lighter hydrocarbon fraction and water phase were condensed in the second cooling step below room temperature to the cold trap. In the FLEXCHX validation campaigns, the syngas feeding was at times fed with bottled hydrogen to simulate the conceptual electrolysis hydrogen boosting during specific seasonal operating modes. The gases before the FT unit and after the cold trap were analyzed using a Shimadzu gas chromatograph with a TCD and flame ionization detector (FID) for permanent gases and hydrocarbons.

In the campaigns SXB 20/07 and 20/11, the operation was carried out on-site by Ineratec. In the third campaign, SXB 20/24, guest visits were not possible due to the COVID-19 situation, and remote monitoring of the FT process was introduced with success.

3. Results of the process validation tests

3.1 Gasifier feedstocks

Table 1 presents the average results for the proximate and ultimate analyses of the feedstocks used in the SXB tests campaigns. The test campaigns were realized using different wood-based feedstocks and sunflower husks, which represented agricultural residues. Pellets of 8-10 mm in diameter were used at most of the setpoints and one set point was realized with crushed wood chips. Wood and bark pellets were hard, while the softer sunflower pellets were partly crushed in the live-bottom silos and the screw feeders. Sunflower husk pellets were delivered to VTT by Lithuanian partners (Kauno Energija AB and Lithuanian Energy Institute). Other feedstocks were derived from Finnish pellet producer Vapo. Wood and bark pellets were produced from sawmill residues.

Table 1. Feedstock analyses as used in the gasification campaigns of the SXB pilot plant.

Test run	**SXB 20/11**	**SXB 20/07** **SXB 20/11**	**SXB 20/07**	**SXB 20/11** **SXB 20/24**
Feedstock	**Wood pellets**	**Bark pellets**	**Wood chips**	**Sunflower husk pellets**
Photograph of the used feedstock				
Particle size, mm	10-20	8	< 10	8
LHV MJ/kg d.b.	18.4	18.8	18.1	18.4
HHV, MJ/kg (d.b.)	19.8	20.1	19.5	19.6
Moisture (avg), wt%	7.4	9.2	10.0	10.3
Proximate analysis, wt% d.b.				
Volatile matter	82.5	72.2	85.7	75.0
Fixed carbon d.b.	17.1	23.5	13.9	22.1
Ash, wt% d.b.	0.4	4.3	0.4	2.8
Ultimate analysis, wt% d.b.				
C	49.8	51.7	48.6	52.1
H	6.3	6.1	6.5	5.8
N	0.13	0.5	0.1	0.7
Cl	< 0.005	0,01	0.004	0.06
S	0.01	0.03	0.01	0.14
O as difference	43.7	41.7	44.4	38.6
Ash	0.4	4.3	0.37	2.8

A mixture of fine sand and dolomite/MgO was fed into the raw gas at the gasifier exit to assist in building up an effective dust cake on the filters. This was necessary because the original dust content of the raw gas from the SXB gasifier is very low, which would result in deposition problems caused by tars and sticky fine particles.

3.2 Test campaigns

The validation tests were realized between March and June 2020 as three test weeks, including 58-85 hours of continuous operation under gasification conditions. The validation tests campaigns of WP6 were carried out using the complete SXB pilot plant process, the slipstream final gas cleaning unit, and the MOBSU synthesis unit, as is illustrated in Figure 2. The gasification test campaigns are briefly summarized in Table 2. In all test runs, the plant was operated continuously without interruptions. Measurements were carried out in periods that were 2-24 hours long (setpoints), during which the mass flow rates of the input streams were kept as constant as possible. Elemental mass balances and performance indicators of the gasification process were calculated for the setpoint periods based on average measuring results [8].

The primary target of the SXB test campaigns was to validate the entire process chain from biomass gasification up to FT liquids production. Also, one target was to verify that the process could be operated with and without additional hydrogen and CO_2 feeding.

Table 2. Realized process validation tests.

Year/ week	Goals	Feedstocks	Operation time
20/07	• Commissioning of the entire process concept: SXB gasifier + UC5 + FT process (MOBSU) • To demonstrate the production of FT-products	Bark pellets Wood Chips	On gasification: 58 h UC5 operation: 42 h FT on bio-syngas: 38,5 h FT with bottle gases: 38 h
20/11	• Testing of the entire process concept • To demonstrate the production of FT-products • To simulate both operation modes of the process	Wood pellets Bark pellets Sunflower husk	On gasification: 70 h UC5 operation: 63 h FT on bio-syngas: 61 h
20/24	• The entire process concept: SXB gasifier + UC5 + FT process (MOBSU) was in use • Increased operation pressure in the gasifier • To study the effect of division plate on the gasifier performance • To test another reformer loading • Test UC5 with smaller bed sizes	Wood pellets Sunflower husk	On gasification: 85 h UC5 operation: 75 h (syngas used in the EU REDIFUEL project with different FT catalyst)

The test program could be realized according to the plan, and no major problems were met despite the great novelty of the individual processing steps as an integrated operation of rather many unit operations. A good basis for this success was made already in 2019 and at the beginning of 2020, when the gasification process was tested independently from the synthesis and the FT unit was operated with bottled gases. In addition, the UC5 and MOBSU had been successfully utilized in the previous tests of the COMSYN projects, where these units were connected to a fluidized-bed bed gasification process [7].

3.3 Gasification and hot gas filtration

3.3.1 Gasification results

Key results and main conclusions concerning the SXB gasifier and hot filtration are summarized in this chapter, while detailed results are presented in [6] and [8]. Table 3 shows the key operating condition and calculated performances for the gasifier, filter, and reformer during selected setpoints.

Figure 7 shows the gasifier temperatures and the filter outlet temperature during the test weeks (week 20/11). During this test week, the primary gasifier stage was operated with ca. 500 °C temperature at the top of the primary stage (T-414), and this temperature, together with gas analysis, was used to control the fuel feeding. The gas temperature was then raised to 800-870 °C in the secondary gasification zone. After the gasifier, the raw gas was cooled to 500-600 °C before filtration.

One of the key aims of the gasifier development was to convert the tar-containing updraft gas to a similar kind of raw gas as produced in fluidized-bed gasifiers. Consequently, similar filtration and catalytic reforming methods can be utilized as having been previously developed and tested for fluidized-bed gasifiers [10], [11]. Figure 8 illustrates the measured tar and benzene contents of raw gas measured in different set points of the SXB tests. The setpoints of the last test runs (SXB 20/24) are shown separately as this test run was realized with the open structure between the primary and secondary zone. In all previous tests, the gasifier stages were separated by the division plate where the raw gas had to flow through the four smaller hoes directly towards the first distributor basket of the secondary gasification zone. It can be seen from the tar results, that the use of the division plate improved tar decomposition to some degree. The achieved tar contents of 2-12 g/m3n are comparable to those measured for steam-oxygen blown fluidized-bed gasifiers [12].

In Figure 9, the equilibrium coefficients of the shift reaction ($CO + H_2O \Leftrightarrow H_2 + CO_2$) calculated from the actual wet gas composition are compared to theoretical values calculated with the formula presented in [13]. It can be noticed that under the conditions of the SXB gasifier shift-equilibrium is not approached, and part of the steam seems to pass through the gasifier unreacted. However, the gas composition after the reformer is closer to equilibrium.

In biomass gasification, a large share of feedstock nitrogen is usually converted into ammonia [14]. Figure 10 shows the measured ammonia concentrations before and after the reformer defined for different feedstocks. In the SXB gasifier, the fuel nitrogen conversion to ammonia was in the range of 40-70%, which is slightly lower than usually determined for fluidized-bed gasifiers.

Table 3. Main operating conditions of the gasifier and the reformer in selected set points [6].

Set point	**20/11A**	**20/11B**	**20/24D**	**20/24F**	**20/11D**	**20/11E**	**20/24E**
Feedstock	**wood**	**wood**	**wood**	**wood**	**bark**	**sunflower**	**sunflower**
Feed rate, g/s	11.7	11.7	11.9	11.9	10.6	10.5	13.6
Pressure at gasifier top, bar	2.5	2.5	2.0	2.0	2.5	2.5	2.0
Temperature at top of stage 1, °C	523	535	588	453	552	526	461
Average Temp. of 2nd stage, °C	847	848	857	834	850	852	819
O_2 feed, % of stoich.combustion	29.9	28.7	29.8	27.9	30.6	30.0	23.7
Steam to fuel ratio, kg/kg-daf	0.83	0.42	0.87	0.71	0.88	0.97	0.74
CO_2-feed to fuel ratio, kg/kg-daf	0.18	0.74	0.27	0.23	0.34	0.25	0.21
Filtration temperature, °C	533	542	512	480	551	482	492
Feed of sand/dolomite to filter, g/s	0.6	0.6	0.7	0.7	0.6	0.6	0.7
Particulate content in filter inlet, g/m3n	14.5	14.5	13.4	12.2	14.5	14.5	12.8
Filter face velocity, cm/s	1.6	1.5	2.1	1.8	1.5	1.4	2.1
Filter pressure drop, mbar	55	49	49	252	63	126	252
Dry gas analysis after filter, % vol							
CO	19.5	23.2	19.3	19.3	16.7	15.4	17.0
CO_2	30.3	41.5	31.0	32.4	36.0	36.1	33.1
H_2	19.7	14.8	17.7	17.4	18.0	19.5	19.9
N_2 (as difference)	22.6	13.5	24.0	22.5	21.8	20.3	21.2
CH4	6.62	5.89	6.47	6.85	6.26	7.28	6.69
C_2H_2	0.03	0.03	0.07	0.05	0.03	0.04	0.05
C_2H_4	1.00	0.83	1.30	1.27	0.95	1.23	1.60
C_2H_6	0.23	0.17	0.16	0.25	0.20	0.23	0.38
C_3-C_5Hy	0.00	0.00	0.00	0.01	0.00	0.00	0.02
Benzene content, g/m3n dry gas	11.2	10.3	12.9	13.1	13.1	14.1	13.2
Tar content, g/m3n dry gas	6.1	5.7	10.8	12.1	8.2	8.1	12.2
Wet gas flow rate, m3n/h	111	98	116	106	102	104	118
Carbon loss in fly ash, % of feed C	1.1	0.5	0.7	0.6	0.7	1.2	0.7
Carbon balance closure (out/in)	1.03	0.98	1.03	0.98	0.96	1.02	0.93
Oxygen balance closure (out/in)	1.00	1.00	1.01	0.97	1.00	1.00	0.99
Wet gas H_2O content, % vol							
determined from tar samples	41.0	31.5	43.0	39.8	42.5	44.9	39.4
calculated from H_2 balance	42.9	31.6	43.5	40.3	43.3	42.3	39.1
O_2 feed to reformer (stage 1 & 2), g/s	1.8	1.6	2.3	2.6	1.6	1.6	2.5
N_2 feed to reformer (stage 1 & 2), g/s	3.2	3.2	4.3	4.9	2.8	2.8	4.6
Reformer stage 1 outlet temperature, °C	752	757	765	802	770	769	803
Reformer stage 2 outlet temperature, °C	751	755	808	836	781	786	836
GHSV - stage 1 (satp)	3430	3050	3800	3490	3140	3230	3890
GHSV - stage 2 (satp)	3500	3100	4760	4400	3120	3140	4690
Dry gas analysis after reformer, % vol							
CO	14.9	20.5	14.8	16.9	14.3	12.9	16.0
CO_2	28.1	34.0	28.6	25.7	31.3	32.2	26.5
H_2	30.7	24.5	28.8	27.3	26.7	26.2	26.8
N_2 (as difference)	25.2	20.2	27.7	29.7	26.2	25.7	28.8
CH_4	1.09	0.77	0.09	0.37	1.51	3.11	1.77
C_2H_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C_2H_4	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C_2H_6	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C_3-C_5Hy	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Benzene content, mg/m3n dry gas	492	292	215	229	1340	4570	3940
Tar content, mg/m3n dry gas	2.7	1.0	2.9	1.1	6.0	204	254
Wet gas flow rate after reformer, m3n/h	133	118	145	134	119	120	143
Wet gas H_2O content, % vol							
determined from tar samples	29.3	23.2	34.0	33.3	32.0	35.9	35.7
calculated from H_2 balance	30.3	23.5	30.5	29.3	34.2	34.6	31.0

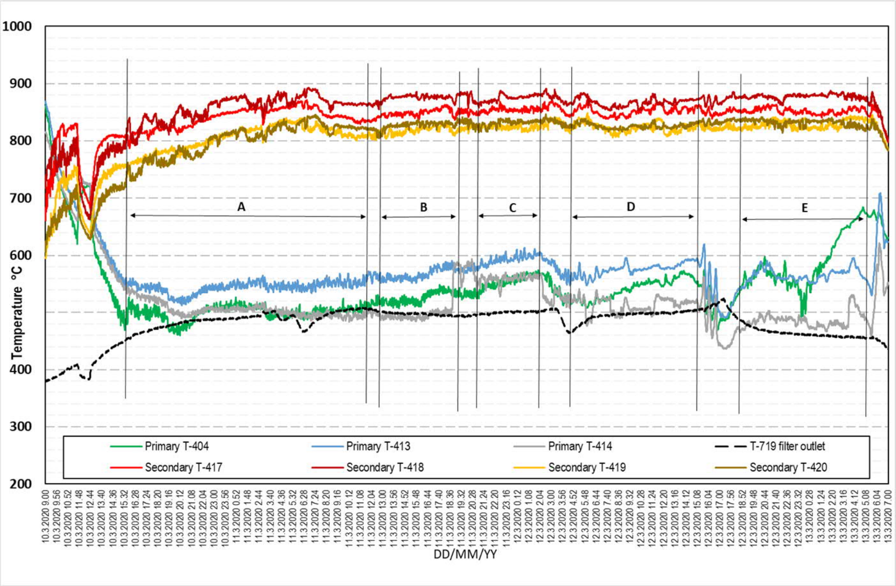


Figure 7. Temperatures in the gasifier (lower and upper parts) in the test run SXB 20/11.

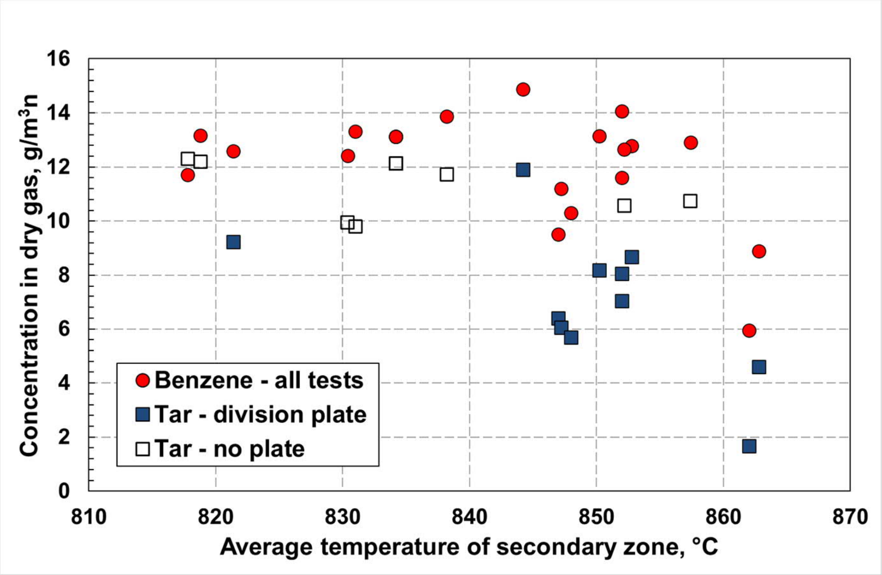


Figure 8. Tar and benzene concentrations after the filter [6].

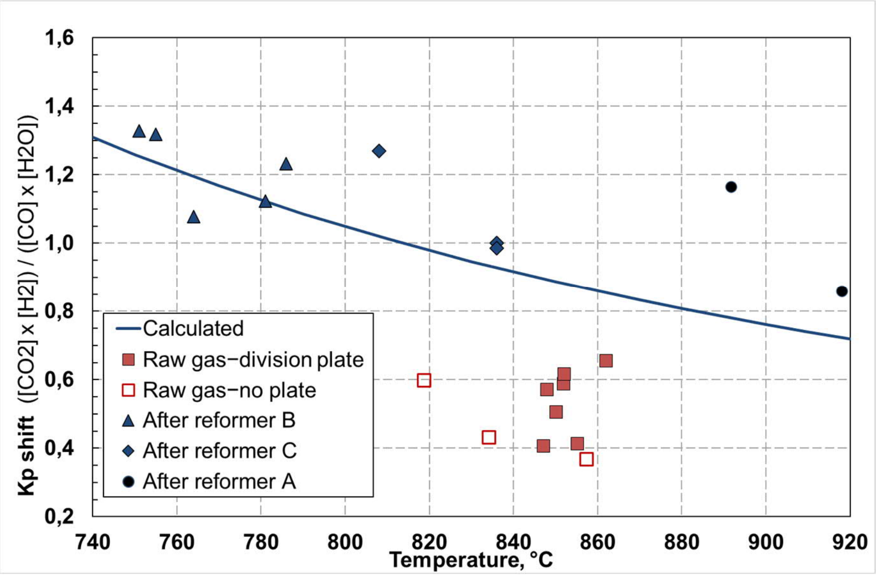


Figure 9. Comparison of the measured and calculated equilibrium coefficients of shift reaction [8].

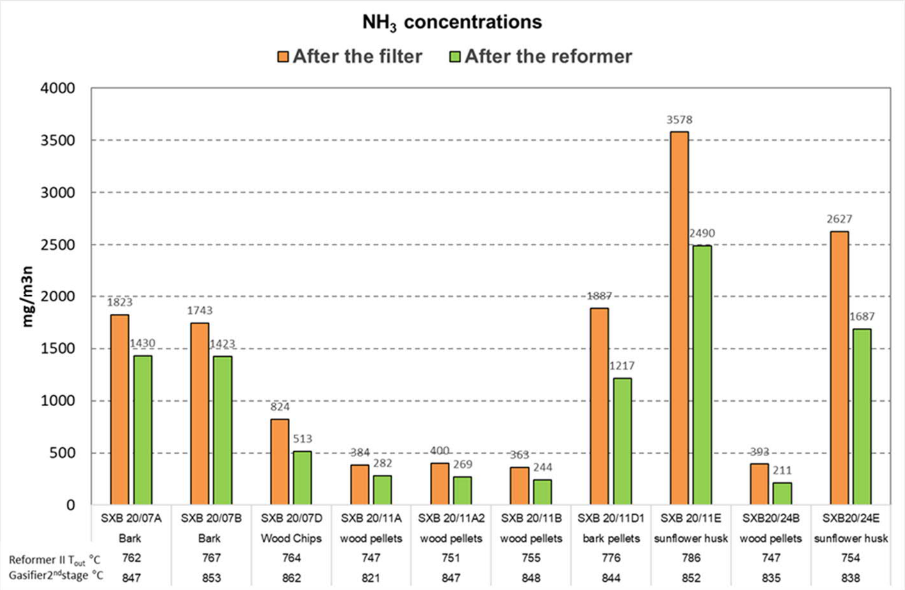


Figure 10. Measured ammonia concentrations (in dry gas) in selected set points realized with different biomass feedstocks.

3.3.2 Filtration

In the tests of this report, the raw gas was filtered using 12 one-meter-long metal candle filter elements that were organized into four clusters (3 elements in each cluster). Figure 11 illustrates the cumulative number of operation hours and the filtration temperatures during operation under gasification conditions. In addition to this operation time, the filter elements were exposed to the preheating and cooling periods. Preheating was realized by operating the gasifier as a biomass combustor. The same set of filters were also used in the previous test run SXB 19/34, carried out in WP3. The filter unit was operated in the temperature range of 500-600 °C in the tests. Additional dust (sand/MgO/dolomite) was fed into the raw gas at the top of the gas cooler.

The filters were pulse cleaned with nitrogen at regular intervals to detach the accumulated filter dust. Examples of filter pressured drop curves are presented in Figure 12 and 13.

Filter operation was smooth - stable pressure drop was achieved at all set points except part of the set points of the last test runs SXB 20/24, where the raw gas tar content was higher than in the previous test runs. There were no signs of dust penetration through the filter unit. No signs of filter breakage or leakages in the gaskets between the elements and the tube sheet were noticed

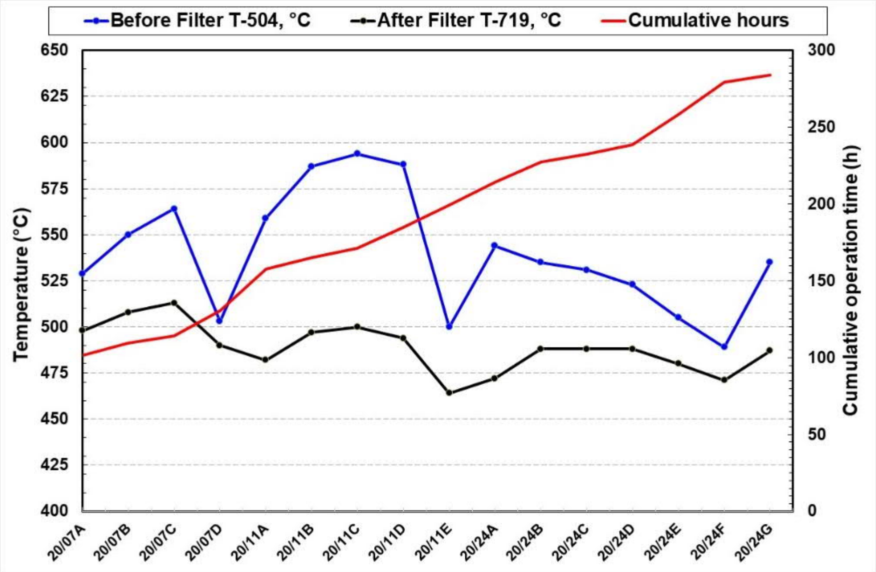


Figure 11. Operating temperatures and cumulative operation time of the filters in the SXB test runs [8].

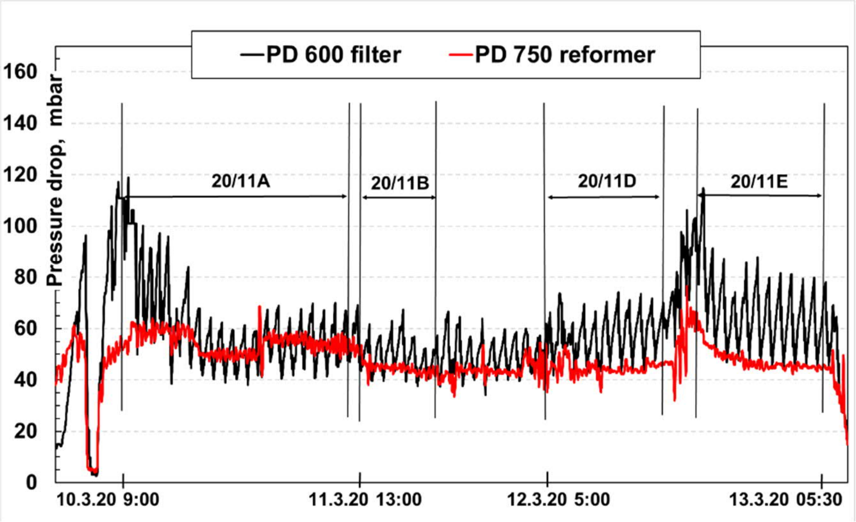


Figure 12. Pressure drops of the filter and the reformer in the test run SXB 20/11 [6].

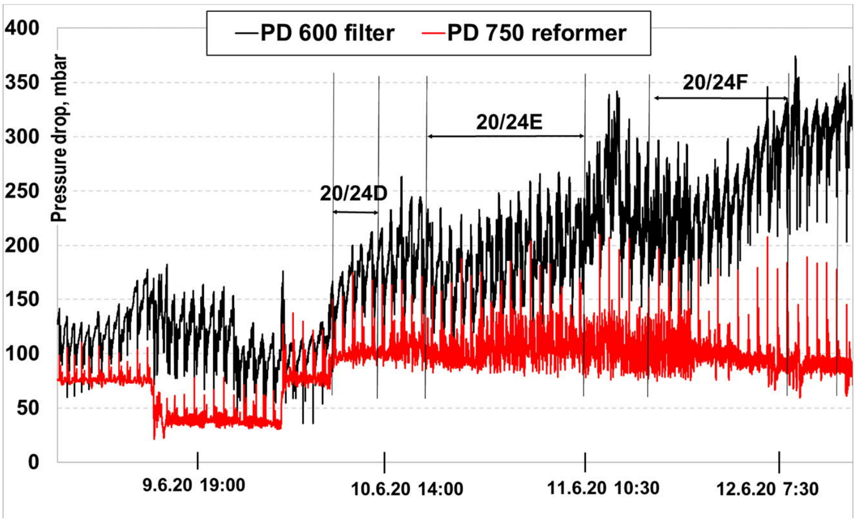


Figure 13. Pressure drops of the filter and the reformer in test run SXB 20/24 [6].

After the final test run, the 12 filter elements were removed from the filter vessel, and two elements were sent by Grönmark to the filter manufacturer GKN Sinter Metals Filters. GKN characterized the used filter elements as part of their tasks within the EU COMSYN project. One of the elements was used for making samples for microscopic studies of the cross-sections. As can be noticed from Figure 14, the elements contained some relatively sticky dust, which was not removed during the shutdown procedure and final pulse cleaning cycles. This is typical of filtration of biomass gasification gases, but in this case, the amount of residual dust soot cake was probably higher than after other SXB test runs, as the tar content was higher and an increasing pressure drop tendency was noticed in the last test run.

The conclusions from the post-mortal characterization work of GKN were as follows:

- The filter media was in good condition, there were no signs of severe corrosion or mechanical wear
- Soot/dust layer was detected on parts of the filter surfaces, but the porous inner structure was clean and showed no accumulation of dust or soot - targeted principle of surface filtration was achieved
- Generally, the inspected filter elements were in good shape after these tests and 11 of the 12 elements (together with one new element) will be used in other projects of VTT (to gain more operation hours).

Figure 14. Photographs of the used filter elements after the last test run SXB 20/24.

3.3.3 Summary of the gasifier and filter testing

In Table 4, the achieved results are compared to the original targets of the project. The main findings of the gasification and filtration tests can be summarized as follows:

- The gasifier was operated mainly with various pelletized biomass residues, but the successful operation was also achieved with crushed wood chips, which had a lower bulk density. Feeding from the biomass hoppers into the gasifier was stable, and the used control principle worked well.
- Validation tests of WP6 were successfully realized with four biomass qualities: clean sawdust pellets, wood chips, bark pellets, and sunflower husk pellets. Carbon conversion targets could be reached, while the tar content after the gasifier was typically in the range of 2-10 g/Nm3 depending

on the operating conditions. With the first version of the gasifier design, the tar decomposition targets were reached, and the gas could be filtered easily without problems.

- Hot filter operated in each test run with the following target KPIs: dust content < 5 mg/m^{3}n, the content of vapor-phase alkalis and heavy metals < 0.1 ppm-wt, stable pressure drop < 100 mbar achieved.

Table 4. Comparison of the achieved results and original targets.

KPI - Gasifier	Minimum target	Ideal target	Means of verification	Status at the end of the project
Design and operation concept for pressurized operation created	5 bar	25 bar	Tests at 2-5 bar Design for 10-25 bar	Pilot tests 2-4 bar. Design of a 10 MW plant made.
Design for 10-50 MW scale			Dimensions for 10-50 MW plants and preliminary design	The excel-based dimensioning tool has been used to estimate the dimensions of 5 MW demo and 50 MW industrial plants
Feedstock flexible gasifier	Various woody residues	+ straw + wastes	Pilot tests	Four different wood feedstocks and one agro residue gasified.
Flexibility concerning feed gas - various shares of O_2, air, steam and CO_2	40 % replace of steam by CO_2	90 % replace of steam	Pilot tests and gasifier modeling	Minimum flexibility targets were reached in WP6 tests and higher shares were also briefly tested.
Carbon conversion to gas and tars	> 97 %	> 99.5 %	pilot tests	Target reached.
Tar content at gasifier exit (heavier than C_6H_6)	< 15 g/m3n	< 5 g/m3n	pilot tests	Measured contents varied in the range 5-10 g/m3n, which meets the overall objective that the gas can be filtered and reformed without soot formation problems.
KPI - Filter	Minimum target	Ideal target	Means of verification	Status at the end of the project
Robust and efficient filtration	stable operation at > 500 °C	stable operation without gas cooling	pilot tests; pressure drop, dust removal, filter operability	Stable filtration with target performance verified at 500-600 °C.

3.4 Reforming

Following filtration, the particulate-free gas was introduced into a two-stage catalytic reformer that was operated autothermally, using a mixture of oxygen and nitrogen. In the reformer, the tars and hydrocarbons were catalytically reformed to carbon monoxide and hydrogen at elevated temperatures in the range of 750–950 °C. In the performed test campaigns, Johnson Matthey's developmental catalysts, as well as commercial nickel catalysts, were loaded in the reformer as was illustrated in Figure 3. The initial gasification tests of 2019 were performed using only commercial nickel catalysts, while all the tests of WP6 were realized with JM catalysts.

Detailed results for the reformer development and testing are presented in [5] and [6]. Key results, obtained with different catalyst loadings, are presented in Figure 15. It can be concluded that low outlet tar concentrations could be achieved with JM catalyst already at ca. 100 °C lower outlet temperature than was required with the commercial nickel catalysts. The pilot tests were carried out with four different feedstocks: bark and wood pellets, wood chips, and sunflower husk pellets. From the reformer's point of view, the main difference between the feedstocks was the sulfur content. The sulfur content of wood and bark pellets is low (0.01-0.03 wt-%), while the sunflower husk contained much more sulfur (0.14 wt-%).

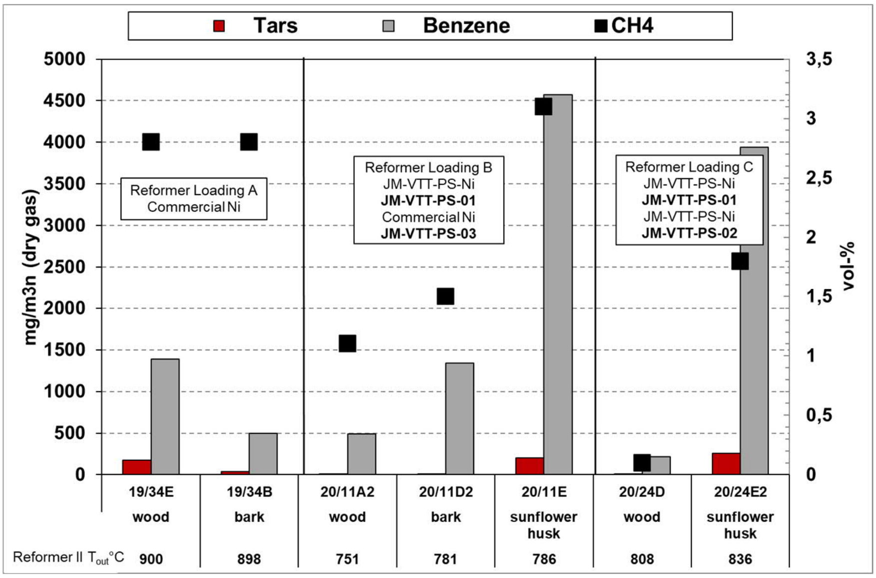


Figure 15. Measured concentrations of methane, benzene, and tars after the catalytic reformer at selected set points realized with different catalyst loadings.

The great importance of catalytic reforming for the overall energy conversion efficiency of the SXB gasification process can be seen by comparing the contribution of different components to the energy content of the gasification gas before and after reforming (Figure 16). Tars and hydrocarbon gases represent roughly half of the energy content of the raw gas, while the efficiency of syngas components (CO and H_2) is significantly increased in the reformer. Also, the main gas components approach the equilibrium of water gas shift reactions, which is essential for the flexible operation targets of the FlexCHX process. It should be mentioned that these results are obtained at the pilot plant, which has higher heat losses than industrial plants. Consequently, the energy efficiencies at industrial plants would be higher [6].

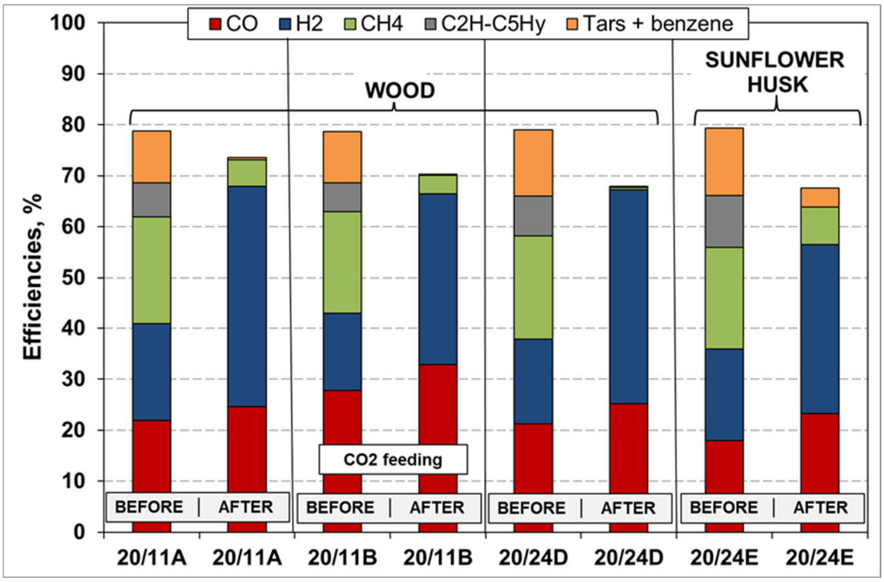


Figure 16. The energy conversion efficiency of biomass to different gas constituents before and after reforming (LHV based) [6].

The catalyst loadings used in the validation tests were not active for catalyzing ammonia decomposition, as can be seen from the results shown in Figure 10. Thus, the ammonia concentration mainly depends on the nitrogen content of the feedstock. The highest ammonia concentrations were obtained with sunflower husks and the lowest with clean wood. Ammonia was then efficiently removed in the scrubber cooler of the slipstream gas-cleaning unit.

The following conclusions can be drawn from the operation of the reformer:

- The smooth operation of the reformer could be validated with all feedstocks and with all operation modes of the process. The catalytic reformer operated very efficiently and the pressure drop remained constant during all tests. No signs of soot formation were detected. Heavy tars and C_2-hydrocarbons were completely decomposed.

- When the reformer was operated at higher temperatures in the last tests (SXB 20/24), satisfactory reformer conversions were also achieved with sunflower husks.
- The gasification, filtration, and reforming process produced a raw gas that could be cleaned by the final gas-cleaning train to a clean syngas, meeting the requirements of the FT synthesis.
- With a high-sulfur biomass addition of a third stage, operating at an 80-100 °C higher temperature would probably improve the conversions to similar levels as were achieved with wood fuels.

3.5 Final gas cleaning and FT synthesis operation

3.5.1 Final gas cleaning UC5

The final gas-cleaning process UC5 was first time coupled to the SXB gasifier in campaign SXB 20/07 and later used in campaigns SXB 20/11 and SXB 20/24. The FT synthesis was coupled to the process for the FLEXCHX context in the first two campaigns. Table 5 shows the total UC5 runtimes in each campaign. The results of the final gas-cleaning studies are summarized in the following table and will be presented in more detail in [9].

Table 5. SXB 20/07 and SXB 20/11 campaign UC5 details.

Campaign	**SXB 20/07**	**SXB 20/11**	**SXB 20/24**
UC5 runtime in syngas (h)	42	63	75
FT synthesis on-stream (h)	38.5	61	-
Avg.Flowrate to synthesis (Ndm^3/min)	50	50	-

In the campaign SXB 20/07, the total ultra cleaning runtime was 42 h. There were no interruptions in the campaign, which was considered a major success for a first-of-its-kind experiment. The synthesis total runtime with syngas was 38.5 h. The SXB 20/11 total runtime was for the ultra cleaning part was a bit longer, 63 h, and the FT unit was operated with gasification syngas 61 h. In the final campaign SXB 20/24, the FT synthesis was utilized in another project (with another type of catalyst). The total runtime for UC5 was 75 h.

In conclusion, in the two coupled campaigns, SXB 20/07 and SXB 20/11, the final gas cleaning process “UC5” produced ultraclean gas to synthesis. Several biomass types were gasified with different gas impurity concentrations, and the gas cleaning managed to remove impurities in all these conditions. Campaign SXB 20/07 was the first time the fixed-bed gasifier - UC5-MOBSU coupled process train was ever tested; thus, the success of the coupled operation is an excellent achievement. In SXB 20/11, more advanced analytics were employed to observe impurities removal, and the goal for the final gas cleaning in campaign SXB 20/24 was to use smaller bed sizes and learn more about the removal location of the impurities by extensive multipoint analysis. Furthermore, in SXB 20/24 high concentration COS removal could be tested and a multipoint analysis of HCN was performed.

The process units of UC5 were validated, and the following conclusions could be drawn from the FLEXCHX campaigns in terms of the removal of harmful impurities:

- **Condenser:** Sufficient for full condensing and cooling of MOBSU-required gas quantity. Acid-injected water at pH 3 was sufficient to likely remove 100 % of the gas ammonia.
- **Adsorbent Reactor:** The multiple activated carbons packed reactor removed all H_2S, most COS, and also hydrocarbons. Oxidative H_2S removal was employed, but the contribution to removal was not established, since a control run without O_2 was not possible. Surprisingly, COS was majority removed by virgin activated carbons, even at 100 ppmv concentrations. The beds were oversized on purpose in the FT-coupled campaigns. With smaller beds in the final campaign, a benzene breakthrough in the sunflower husk syngas was detected at the end.
- **Guard Bed 1**: ZnO partially removed COS, which was not removed by earlier steps. It was not sufficient to completely hydrolyze COS. In the final campaign, a dedicated alumina catalyst for COS hydrolysis did not achieve full conversion either. Oxygen removal by Cu-based catalyst worked well for the small AC reactor injected quantity, with slight but controlled over-temperatures due to the exothermicity of the reaction.
- **Pressurized Water Scrubber:** Almost 50 % removal of CO_2 was achieved, which is lower than the set target, but still acceptable. Important operating parameters that affect CO_2 removal could be established.
- **Guard Bed 2:** It was established in post-run deoxygenation catalyst characterization that the gas purity was very high already before the cold guard bed step, which could indicate that this step is redundant and the process could be simplified

The impurities concentration ranges before UC5 and the continuously measured concentration ranges for the coupled-run campaigns SXB 20/07 & 11 are summarized in Table 6.

Table 6. Syngas impurities concentration ranges in campaigns SXB20/07&11 before and after gas ultra cleaning UC5.

Species	**Before UC5**	***Breakthrough limit***	**After UC5**
H2S (ppm)	15 -200	*0.1*	0.0
COS (ppm)	2 - 12		0.0 - 0.1
NH3 (ppm)	300 - 3300	*0.1*	0
HCN (ppm)[a]	0.5 - 3		0
HCl (ppm)[a]	n.a	*0.1*	0
O2 (%)	0	*0.01*	0
Benzene (ppm)	50 - 1500	*10*	0
CO2 (%)	25 - 35	-	16-22

[a]Non-continuous measurement

The gas purity goals stated in the table were used in the campaigns to decouple the downstream synthesis unit in case the breakthrough limit was achieved. Impurities concentrations from literature sources were adapted for the limitations in detection of the analyzers employed in this study. High purity levels were achieved, with continuous measurement of impurities below detection limits.

3.5.2 FT synthesis unit MOBSU

The FT synthesis test rig MOBSU was operated with the biomass-derived cleaned syngas in the gasification campaigns SXB 20/07 and SXB 20/11. MOBSU was started in bottled gas mode before switching to gasification syngas. Reference set points with bottled gases were realized before and after both test runs. The operating conditions of these reference set points, BG1 and BG2, are shown in Table 7. BG1 was realized with a lower gas flow rate and BG2 represented a higher syngas flow rate.

Table 7. The reference setpoints of MOBSU realized with bottled gases.

	T °C	**P bar**	**SV $Ndm^3/g_{cat}*h$**	**H_2 Ndm^3/min**	**CO Ndm^3/min**	**Total Ndm^3/min**
BG1	217 - 219	20	5.65	39	21	80
BG2	219 - 222	20	8.83	70	35	125

Just before coupling the FT unit to the gasification process, the MOBSU was operated with a lower flow rate and gas composition that matched the syngas feed rate and gas composition, BG1. The real syngas flow rate depended on the final gas cleaning compressor capacity, which fluctuated a little during operation, and therefore small adjustments in the MOBSU feed rate had to be made.

Table 8 and 9 summarize the results from the FT synthesis with gas analysis results and liquid and solid productivities from the cold and hot trap, respectively. In these test runs, the FT unit was operated at a temperature range of 216-219 °C and with a syngas flow rate of 50-55 Ndm^3/min. The flow rate was lower than the synthesis maximum capacity due to limitations in the upstream compression step. The H2-to-CO molar ratio of syngas in the different set points varied in the range of 1.7-2.1. To simulate the other FLEXCHX operating mode of 'solar energy season' also at FT synthesis, additional hydrogen was fed into the syngas at set point B in the test run SXB 20/07 and in set point B of SXB 20/11. High conversions, partly attributed to the relatively low SV, and good product distributions were achieved. The CO conversion achieved with once-through operation varied in the range 65-80 % and the estimated selectivities of C5+ hydrocarbons were in the range 80-88 %.

The SF-α, the FT chain growth probability, is iterated to match the carbon molar balance from the gas analysis results so that the outlet equals inlet carbon molar flow. The H_2 and CO conversions are setpoint average values. The C5+ selectivity is calculated from one representative sample for each setpoint. Only the productivities from the syngas-fed SXB setpoints were included. The theoretical productivity is calculated with the setpoint average conversions and C5+ selectivity and SF-α are calculated from the gas analysis data as explained earlier.

The total productivity of solid and liquid products was in the range of 400 - 600 g/h. The comparison of measured total liquid and solids productivity to theoretical productivity is in relatively good agreement. However, the sampling of especially the hot trap for waxes is very difficult to fully empty and therefore shorter setpoints experience higher deviations from expected productivity. The theoretical ASF distribution predicts higher C5+ selectivities but does not take into account olefin and alcohol production.

In general, it could be concluded that the FT unit could be smoothly operated with the biomass-derived syngas, and the changes in operating modes of the gasification process could be easily followed. Intra-week catalyst deactivation could not be observed, however, the runtime is too short to determine any catalyst deactivation. The extensive gas impurities analysis and post-run catalyst/adsorbent characterisation in the upstream final gas cleaning gives high confidence that gas quality was suitable for FT synthesis purposes. The results in the table show for the reference bottle gas set points diminishing performance as time progresses. This is mainly attributed to natural decay of catalyst performance from high activity freshly reduced catalyst. Also deactivation caused by the startup and shutdown procedures (inter-week deactivation) was observed. This has been shown to be partly-reversible by a catalyst reduction procedure.

Table 8. Summary of the MOBSU results of the test run SXB 20/07.

	BG1	**SP A**	**SP B**	**SP C**	**SP D**	BG1	BG2
T (°C)	218	219	217	217	217	217	217
Syngas (Ndm^3/min)		50	50	50	55		
H2 (Ndm^3/min)			3.5				
H_2/CO-ratio	1.9	1.8	1.8	1.7	2.0	1.9	2.0
Gas analysis results							
X(H_2) %	63	86	80	81	82	54	42
X(CO) %	55	81	65	83	81	46	38
C5+ selectivity, wt%	84	80	83	80	80	84	82
Productivities							
Oil & water, (g/h)[a]		340	400		360		
Wax, (g/h)[a]		86	110		90		
Total, (g/h)[a]		430	509		450		
Theoretical, total (g/h)		490	C: 470 B: 530		460		

[a] determined based on product sampling and weighing

Table 9. Summary of the MOBSU results of the test run SXB 20/11.

	BG2	BG1	**SP A**	**SP B**	**SP C**	**SP D**	**SP E**	BG1
T (°C)	222	218	218	218	217	216	216	219
Syngas (Ndm^3/min)			55-65	50	50	50	50	
H2 (Ndm^3/min)				7				
H_2/CO-ratio	2.0	1.86	2.1	1.95	2.2	1.9	2.0	1.86
Gas analysis results								
X(H_2) %	44	55	80	76	82	80	82	50
X(CO) %	39	48	78	67	77	73	80	44
C5+ select. wt%	82	85	85	85	83	88	80	84
Productivities								
Oil & water, g/h[a]			460		450	310	350	
Wax, g/h[a]			133		120	80	90	
Total, g/h[a]			529		580	390	430	
Theoretical total, g/h			A: 562 B:548		550	510	450	

[a] determined based on product sampling and weighing

3.6 Testing of the flexibility of the gasification process

During set point SXB 20/11B, more primary gasification steam was replaced by CO_2 (see Figure 17) simulating the shift from the biomass-alone operation to the mode where CO_2 is recycled in the gasification process and additional hydrogen is fed into the inlet gas of FT synthesis. The fuel feed rate and the primary oxygen feed were kept at the same values as in the earlier setpoint 20/11A. During this period additional hydrogen was fed into the syngas before the FT synthesis and this set point simulated the FLEXHX operation under "summer season".

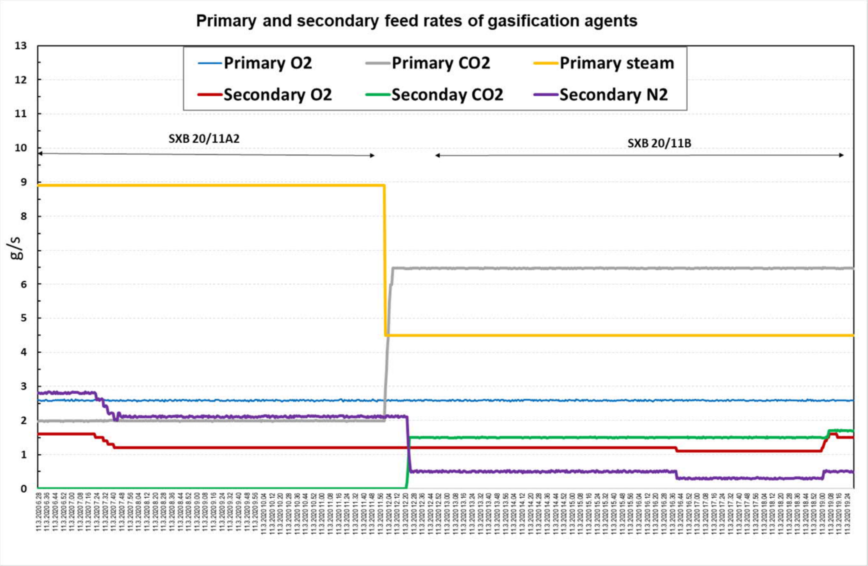


Figure 17. Primary and secondary feed rates of gasification agents in SXB 20/11B.

The temperatures of the gasifier and the reformer are presented in Figure 18. Reformer temperatures and the temperature of the secondary gasification zone were controlled by the oxygen feed rates. The temperatures of the primary gasification zone (T-404) were gradually increasing even though the mass balance calculations indicate that the bed inventory was slowly increasing. Evidently, the decreased steam feed affected the bed temperatures.

The setpoint B was rather stable until the last hour (18:30) when the feeding of air into the space between the two gasifier stages had to be stopped (due to measuring problems related to air feeding). This caused a change in gas analysis, which is seen at the end of this set point.

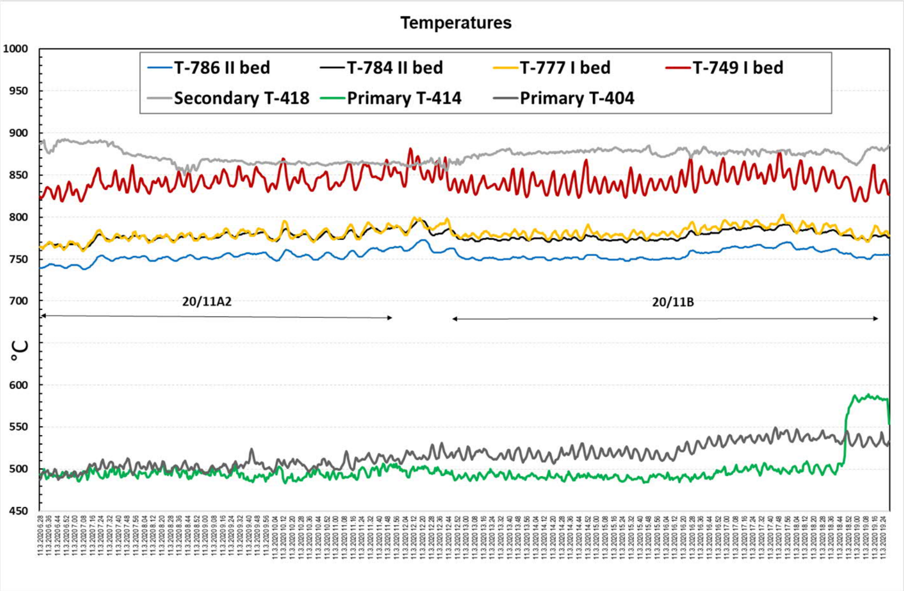


Figure 18. Gasifier and reformer temperatures in SXB 20/11B.

The change from steam/O_2 operation to a higher share of CO_2 can be seen in the gas composition (Figure 19). It took about 20 minutes after the mass flow rates of gasification agents were changed to reach stable gas composition representing the new operating conditions. This can be considered to be the typical time span for the gasification process. The final gas cleaning unit and the MOBSU FT synthesis could easily follow these changes as their time spans are smaller. Stabilizing the conditions of the massive charcoal bed of the gasifier and the catalyst beds of the reformer takes several minutes. A fluidized-bed gasifier would probably respond to the changes more rapidly than this fixed bed gasifier.

Figure 20 presents the K values of the homogeneous water gas shift reaction ($CO + H_2O \Leftrightarrow CO_2 + H_2$). The red columns are calculated equilibrium values at the average temperature of the 2nd stage of the gasifier and the outlet temperature of the second reformer bed. The blue columns are calculated from the measured wet gas analysis. It can be noticed that the water gas shift reaction does not approach the equilibrium in the gasifier, while the gas composition after the reformer can be estimated to be in equilibrium. This seems to be the case in both operation modes. This is important for the whole FLEXCHX concept, as the key idea is that recycled CO_2 will push the gas composition towards higher CO and lower H_2 contents. This may also indicate that CO_2 is consumed in the reformer by dry reforming reactions.

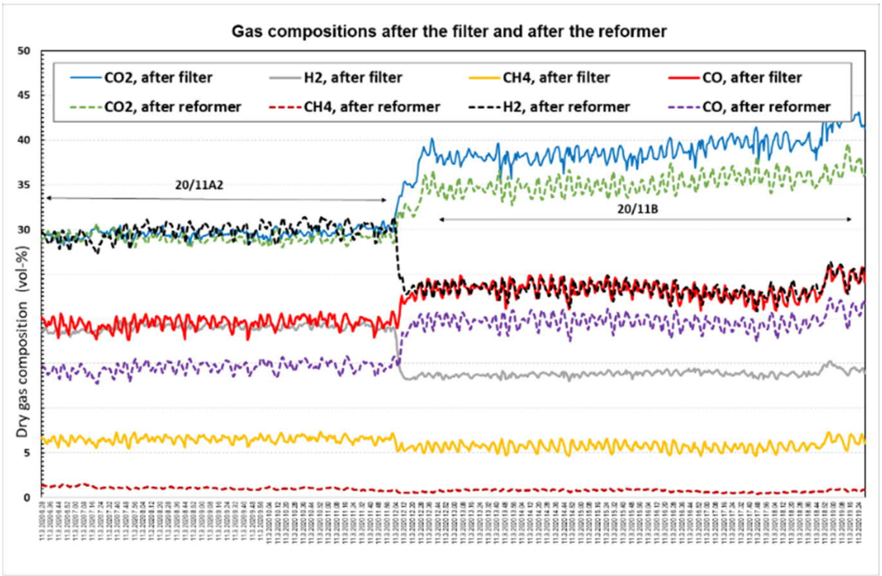


Figure 19. Concentrations of the main gas components before and after the reformer in SXB 20/11B.

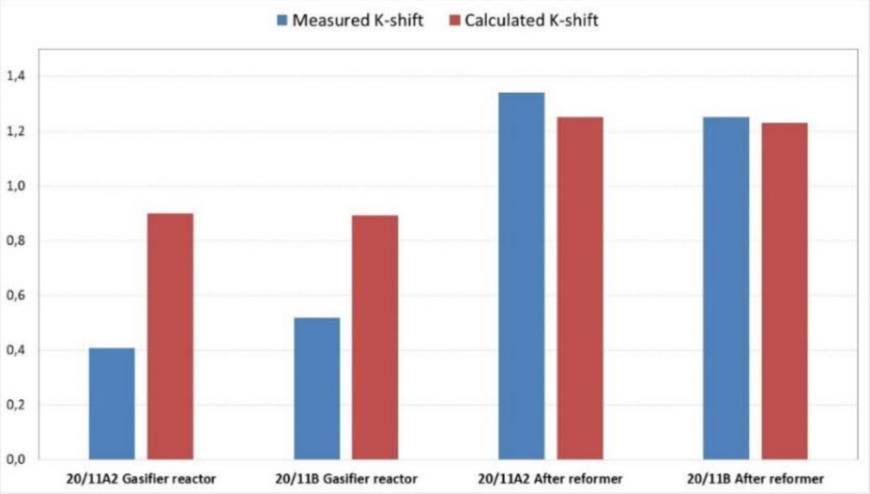


Figure 20. The measured and calculated K-shifts at set points SXB 20/11A2 and B.

4. Preliminary ideas for a follow-on demonstration

The FlexCHX concept and its key enabling technologies have been developed and validated to TRL5 in this Research and Innovation Action of Horizon 2020 program. Figure 21 illustrates the general road map towards industrial utilization of the developed technologies. Typical minimum costs of the follow-on industrial demonstration project are estimated to be in the range of 12-16 M€, while the cost of the flagship production unit is 60-100 M€. The required minimum time frame is also illustrated in the figure. In reality, the required time is longer as the financing and contracting will take additional time.

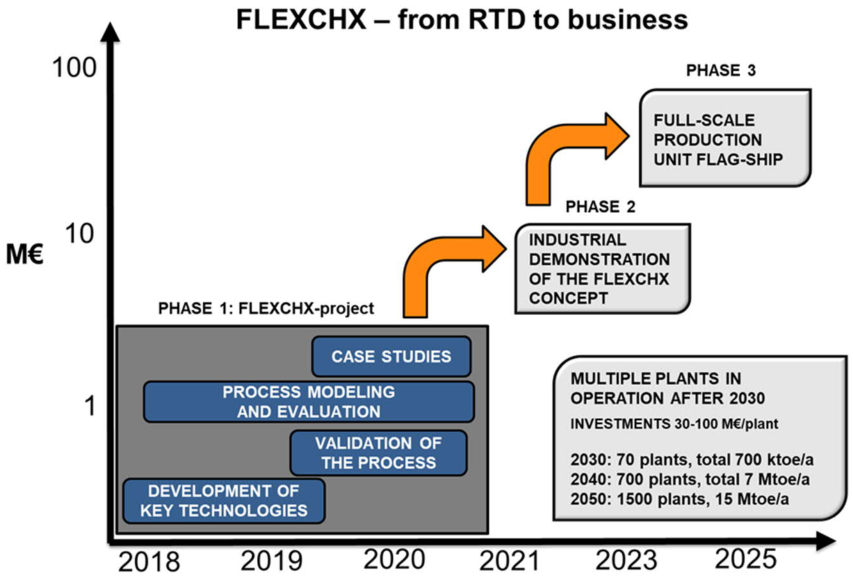


Figure 21. General road map from this RIA project to industrial projects.

The FlexCHX project can be considered to include two types of main achievements:

a) Developing and testing the production concept, which integrates the use of renewable electricity and biomass to produce flexible energy for heating and the production of renewable transport fuels.
b) The following individual key technologies have been developed to TRL 5 in the project:
    a. Pressurized staged fixed-bed gasifier aiming to 5-50 MW feedstock capacities
    b. Hot filtration system applying robust metal filters
    c. Catalytic reformer technology and highly active catalysts

d. A sorbent-based final gas cleaning system
e. Compact and flexible FT-synthesis technology suitable for 1-50 MW syngas capacities

Consequently, various types of demonstration pathways can be planned in addition to demonstrating the whole process scheme developed in this project. In principle, the FlexCHX-concept can be realized with different combinations of individual technologies, which opens possibilities for organizing the demonstration also at larger-scale fluidized-bed gasification sites, as well as in projects focusing on the production of other end-products, such as synthetic methane or methanol. In addition, the developed new technologies can also be applied separately in many alternative applications, which opens several promising possibilities for industrial demonstration.

5. Conclusions

The key enabling technologies of the FlexCHX process were successfully validated during three test weeks, realized at the SXB gasification pilot plant of VTT. The individual process steps, the gasifier, the filter, the reformer, the final gas cleaning unit, and the FT synthesis could all be operated so that at least the minimum performance targets, defined as the KPIs, were reached. The integrated operation was also demonstrated in two test weeks, during which the purified synthesis gas was used in the FT unit MOBSU for ca. 100 hours and producing roughly 115 kg of FT hydrocarbons.

The two operation modes of the FlexCHX process were also simulated by feeding additional CO_2 to the gasification process and hydrogen to the syngas before the FT unit. This demonstrated that the process can be used flexibly under both the summer and winter modes, and it took less than 30 min after changing the gasifier feeds gas composition to reach the new equilibrium gas composition.

Several ideas for further improvement of the technologies were identified, but generally, the whole process, as well as its key enabling technologies, can be considered to have reached the targeted TRL5 and are technically ready for follow-on demonstration.

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Series title and number
VTT Technology 387

Title	**Process concept for flexible production of renewable transportation fuels and heat** Results for the pilot scale process validation tests
Author(s)	Esa Kurkela, Minna Kurkela, Christian Frilund, Ilkka Hiltunen & Sanna Tuomi
Abstract	This publication summarizes the results of the process validation tests carried out in the EU-funded research project FLEXCHX "Flexible combined production of power, heat and transport fuels from renewable energy sources". The validation tests were realized between March and June 2020 as three test weeks, including a total of 180 hours of gasification operation. The validation tests were performed using the pressurized Staged Fixed Bed (SXB) gasifier, followed by the hot filter unit and the two-stage catalytic reformer. Different woody residues and sunflower husks were used as the gasifier feedstocks. A smaller slipstream of the reformed syngas was cleaned in the final gas cleaning unit, compressed, and utilized in the Fischer-Tropsch synthesis. The major part of the produced syngas was combusted in the hot water boiler connected to the district heating network of Espoo (Finland). All test facilities are located at the Bioruukki Piloting Centre of VTT. Generally, the tests were very successful despite the challenging surrounding conditions caused by the COVID-19 pandemic, which hindered the planned participation of other project partners in the final test runs on-site at VTT and thus created additional challenges for VTT personnel. Based on these tests, it can be concluded that the whole process, as well as its key enabling technologies, have been developed to the targeted Technology Readiness Level of TRL5 and are technically ready for follow-on demonstration. Preliminary ideas for the realization of follow-on demonstration are also presented at the end of this report.
ISBN, ISSN, URN	ISBN 978-951-38-8747-6 ISSN-L 2242-1211 ISSN 2242-122X (Online) DOI: 10.32040/2242-122X.2021.T387
Date	April 2021
Language	English
Pages	39 p.
Name of the project	FLEXCHX Grant agreement ID: 763919
Commissioned by	
Keywords	gasification, biomass, fixed-bed, biofuels, syngas, Fischer-Tropsch synthesis
Publisher	VTT Technical Research Centre of Finland Ltd P.O. Box 1000, FI-02044 VTT, Finland, Tel. 020 722 111, https://www.vttresearch.com

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ISBN 978-951-38-8747-6
ISSN-L 2242-1211
ISSN 2242-122X (Online)
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