



# FlexSNG

## Deliverable D7.2

# Definition of the FlexSNG process configurations

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1.1	01/06/2022	Revised draft	Sanna Tuomi (VTT)

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## Abbreviations and acronyms

SNG	Synthetic Natural Gas
BCFB	Bubbling Fluidized-bed Gasifier
CFB	Circulating Fluidized-Bed Gasifier
BFB	Bubbling Fluidized-Bed Gasifier
MSW	Municipal Solid Waste
OTM	Oxygen Transport Membrane
AC	Activated Carbon
LHV	Lower Heating Value
WP	Work Package

## 1 Executive summary

The present deliverable D7.2 defines the overall process configuration of the FlexSNG concept and sets an initial design and operational framework for each component of the proposed value chain.

The FlexSNG gasification concept is designed to flexibly switch between co-production of biomethane, biochar and heat, and maximised production of biomethane and heat. This deliverable outlines the details concerning the whole FlexSNG process that entails the following key technologies:

- Low-cost oxygen production via oxygen transport membranes (OTMs)
- Feedstock-flexible steam/oxygen-blown gasification process tailored for both operation modes
- Hot gas filtration to remove particulates, alkali and heavy metals and most of chlorine
- Catalytic reforming of tars and light hydrocarbons with minimal conversion of methane
- Gas cooling followed by a scrubber cooler unit that removes syngas moisture, ammonia and traces of chlorine
- Sorbent-based removal of sulphur compounds ( $H_2S$ ,  $COS$ ) and other residual impurities
- VESTA catalytic methanation developed by WOOD where carbon oxides are hydrogenated into biomethane, and  $CO_2$  is separated from the effluent stream after methanation

The FlexSNG concept introduces some significant advances and innovative technologies in the conversion process that are expected to result in CAPEX savings compared to state-of-the-art biomass-to-SNG plant designs. These design changes and new technologies are:

- Oxygen consumption in gasification minimized and the capital-intensive oxygen production (based on cryogenic air separation) replaced with OTM technology
- A separate shift conversion unit eliminated:  $H_2/CO$  molar ratio can be adjusted already in the reforming step; VESTA methanation unit does not require strict control of  $H_2/CO$  ratio and has an integrated sweet shift unit
- Capital-intensive wet acid gas removal process (e.g. Rectisol®) replaced with sorbent-based sulphur removal concept using activated carbon and ZnO
- VESTA methanation technology adopted: simplified approach with no need for gas recycling and  $CO_2$  can be separated downstream methanation

One of the important elements of the FlexSNG concept is also feedstock flexibility. Owing to this feature, the FlexSNG plant can be tailored for both rural conditions to

## D7.2 Definition of the FlexSNG process configuration



process a variety of biomass residues available from forestry, forest industry or agriculture (biorefinery), but also for urban environments where the feedstock base is more dominated by waste-derived materials (cityrefinery). The gasification/synthesis process can also be coupled with electrolysis (hybrid plant) that will allow exploiting the surplus low-cost electricity available in the grid and increasing the biomethane output of the plant by hydrogen boosting. The biorefinery, cityrefinery and hybrid configurations that are considered as the three potential FlexSNG plant schemes are also briefly described in this deliverable.

## 2 Introduction

The overall objective of the FlexSNG project is to develop and validate a flexible and cost-effective gasification-based process for the production of pipeline-quality biomethane (bio-based synthetic natural gas, bio-SNG), high-value biochar and renewable heat from a wide variety of low-quality biomass residues and biogenic waste feedstocks. The combination of gasification process development and feedstock supply chain optimization is expected to lead to significant cost reductions that allow lowering biomethane production costs by more than 30% compared to state-of-the-art biomass-to-SNG technologies. The FlexSNG concept and the primary development goals of the project in general are illustrated in Figure 1.

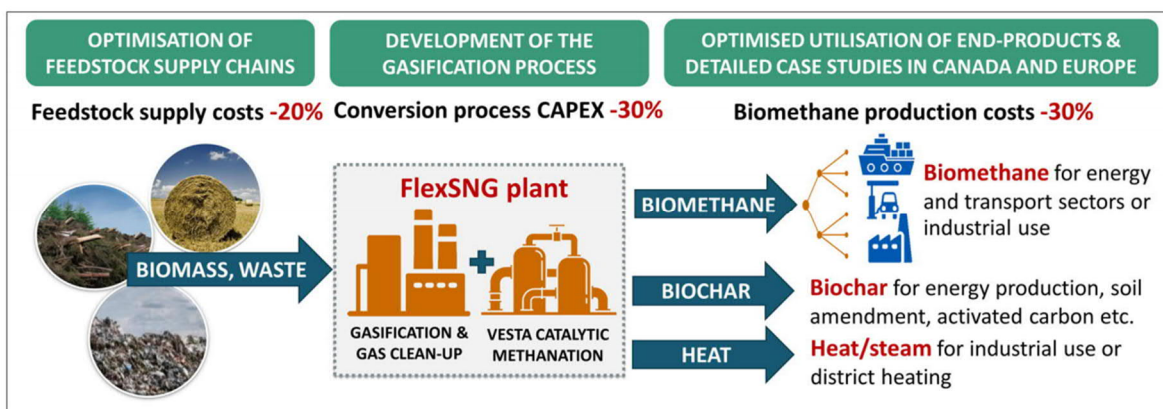


Figure 1. FlexSNG concept - Flexible production of intermediate bioenergy carriers (biomethane and biochar) and heat.

This deliverable is related to Task 7.2 "Design and modelling of complete process configuration". Taking into consideration the selected KPI targets in Task 7.1, the main process configurations will be developed and refined in this task. Based on the semi-empirical sub-model for gasification that will be developed by VTT, and in collaboration with other partners (WOOD, SFW, DTU), CERTH will develop a simulation model for the complete FlexSNG process. The preliminary version of the process simulation model has already been set up in Aspen Plus® by CERTH. The first round of calculations that base on experimental results obtained from technology development WPs (WP3-5) and particularly from validation test campaigns of Task 5.2 will be reported in D.7.3 (in M30).

The results from this task (as reported in deliverables D7.2 and D7.3) will be transferred to Task 7.3 and Task 7.4, where they will be used as a basis for scale-up, design and cost estimation of the industrial scale FlexSNG plant.



### 3 FlexSNG concept description

#### 3.1 The two operation modes of the FlexSNG plant

The FlexSNG gasification concept is based on “one plant, two modes” approach as shown in Figure 2, where the plant can switch between:

- co-production of biomethane, biochar and heat, and
- maximised production of biomethane and heat.

The key idea was that the single plant can adapt to changes in market conditions (e.g. demand of biochar) or feedstock availability and price by switching operation mode - thereby maximising plant revenue year round.

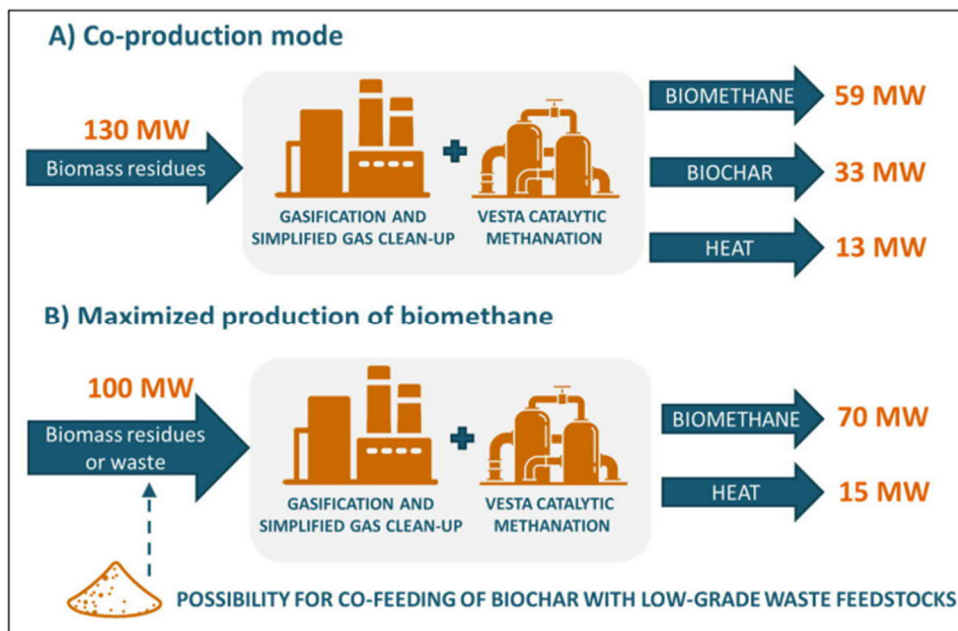


Figure 2. Two production modes of FlexSNG.

The main pillar of the FlexSNG plant is the flexible gasifier that depending on the conditions either co-produces biochar and syngas or maximises syngas production. Feedstock is converted to raw syngas (and biochar) in the gasifier using a mixture of oxygen and steam as fluidising gases. The biochar that is formed as a by-product in gasification is recovered from the bottom of the gasifier and/or captured as fly ash from the filter unit, and the raw gasification gas is subsequently cleaned up to remove the harmful contaminants prior to methanation.

The gas clean-up process involves the following steps:

- filtration to remove particulates, alkali and heavy metals and most of chlorine,
- catalytic reforming of tars and light hydrocarbons,

- gas cooling followed by water scrubbing to remove ammonia, syngas moisture and traces of chlorine,
- gas compression to synthesis pressure, and finally
- sorbent-based removal of sulphur compounds (primarily H<sub>2</sub>S and COS) and other residual impurities.

After purification, the gas is routed to a compact VESTA catalytic methanation unit developed by WOOD where carbon oxides are hydrogenated into biomethane, and CO<sub>2</sub> is separated from the effluent stream after methanation. The biomethane product, with a methane content of 96-98%, is suitable as such for injection into the natural gas network. The by-product heat that is recovered from the gasification/synthesis process is either used for district heating or supplied to industries as process steam.

Transitioning from one operation mode to another will require adjusting the gasification conditions, while the downstream processing steps remain the same and only adapt to the changes in gas composition. The two intermediate bioenergy carriers, biomethane and biochar, produced at the plant can be used widely in the energy system in transport and energy production and industries, while biochar also has wide markets in material use. The aim is to obtain maximum market value for the products, taking into consideration the country-specific markets and other characteristic features of the given region. These will be assessed as part of the case studies in WP8.

The operation approaches applied in FlexSNG gasification are described in the following sections.

### 3.1.1 Co-production of biomethane, biochar and heat

In co-production mode, the aim in gasification is to restrict the feedstock carbon conversion into gas to a level of 70-80% in order to produce solid biochar alongside synthesis-quality gas. This is accomplished by supplying less oxygen to the gasifier and lowering the gasification temperature to below 800 °C. In this mode, the gasification reaction rate is governed by the rate of biomass devolatilisation, which is an order of magnitude higher than that of charcoal gasification reactions. This is expected to facilitate 30% higher biomass throughput (in comparison to producing only biomethane), which makes possible to maintain high biomethane output also in co-generation mode. Around 20% of the feedstock carbon (mass basis) is converted to biochar, while the rest of the feedstock is turned into gas and subsequently cleaned-up and synthesized into high-quality biomethane. The biochar product is recovered as fly ash from the filter unit and/or as bottom ash from the bottom of the gasifier.

The two key advantages of the low-temperature gasification approach are:

- reduced demand of oxygen and consequently lower production costs, and
- extended feedstock base as now even the more challenging high-alkali biomass feedstocks (e.g. straw) become suitable feeds for gasification.

Approximately 45% of the feedstock energy (LHV-based) is converted to biomethane, 25% to biochar and 10% to usable heat in co-production mode. Eligible raw materials for biochar co-production include biomass residues available from the forest industry or agriculture as well as certain waste wood fractions. More contaminated wastes (e.g. municipal solid waste) are not eligible due to the high amount of impurities present in the feedstock that are transferred to the char product (especially when used in applications like soil amendment).

### 3.1.2 Production of biomethane and heat with maximal efficiency

In this production mode, feedstock conversion into syngas is maximized (carbon losses minimized) in the gasifier to reach high conversion efficiency to biomethane. This is achieved by increasing the gasification temperature to ca. 850-900 °C and lowering the biomass throughput of the plant so that also the biomass charcoal is gasified. Upon exiting the gasifier, the raw gasification gas is conditioned similarly as in co-production mode and afterwards converted to biomethane in the VESTA methanation unit.

In this mode, the target is to reach 70% conversion to biomethane (LHV basis) with additional 15% of heat production. Eligible feedstocks include various woody residues and waste wood that can be gasified alone. Lower-grade waste feedstocks (e.g. municipal solid waste, industrial/municipal sludges) need to be co-processed with biochar where the biochar co-feed is intended to induce tar decomposition and prevent ash sintering in the gasifier.

## 3.2 Biorefinery/cityrefinery/hybrid FlexSNG plant

One of the important elements of the FlexSNG concept is feedstock flexibility. Owing to this feature, the FlexSNG plant can be tailored for both rural conditions to process a variety of biomass residues available from forestry, forest industry or agriculture (biorefinery), but also for urban environments where the feedstock base is more dominated by waste-derived materials (cityrefinery). The gasification/synthesis process can also be coupled with electrolysis (hybrid plant) that will allow exploiting the surplus low-cost electricity available in the grid (typically in the summer season) and increasing the biomethane output of the plant by hydrogen boosting. Figure 3 shows a schematic representation of the three potential FlexSNG processing plants that are considered in the project: the biorefinery, the cityrefinery and the hybrid plant.

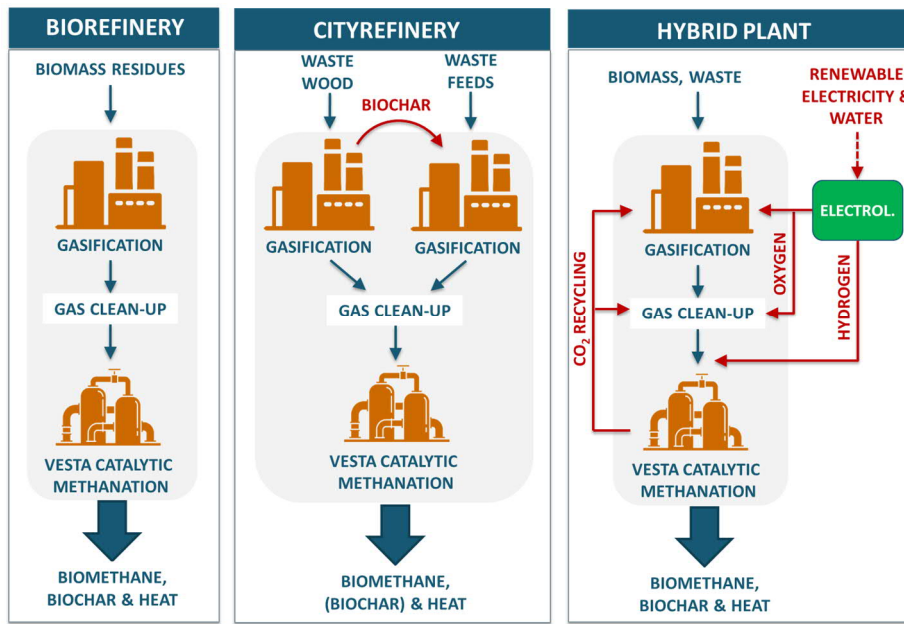


Figure 3. A schematic representation of the biorefinery, cityrefinery and hybrid FlexSNG plants.

### 3.2.1 Biorefinery

Biorefinery plants (Figure 4) can be integrated with existing forest industries (e.g. pulp mill, saw mill) or agricultural sites using the sidestreams as feedstock and supplying steam for industrial use. Such feedstocks are expected to produce biochar of good-quality that can be applied also for more demanding applications, such as soil amendment.

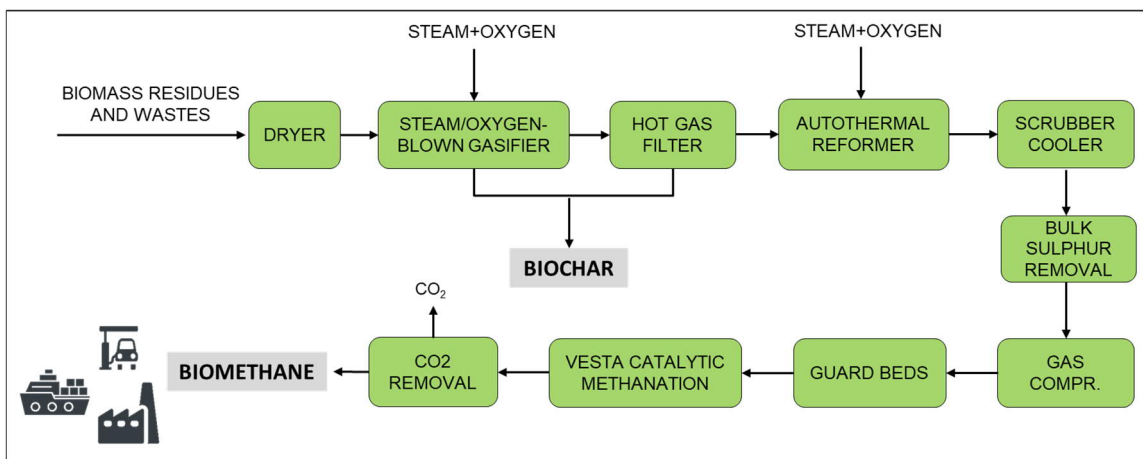


Figure 4. Biorefinery - FlexSNG concept process configuration.

### 3.2.2 Cityrefinery

Cityrefinery plants (Figure 5) can be used to convert urban waste and biomass residues into high-value products in support of cities' circular economy strategies. This feedstock potential in city areas consists of materials that are often difficult to recycle

and thus poorly utilized, e.g. municipal solid waste (MSW), demolition wood, combustible fraction of construction wastes, residues from parks and horticulture as well as certain waste fractions from the surrounding industries and municipalities.

Cityrefinery plants feature two parallel gasification lines: the first is operated with woody residues or good-quality waste wood in order to produce biochar and syngas, while the second gasification line uses wastes mixed with the wood-derived biochar as feedstock. If biochar production is not possible at the same site, it can also be procured from a nearby biorefinery plant. The two gasification lines have a joint gas cleaning and conditioning process after filtration.

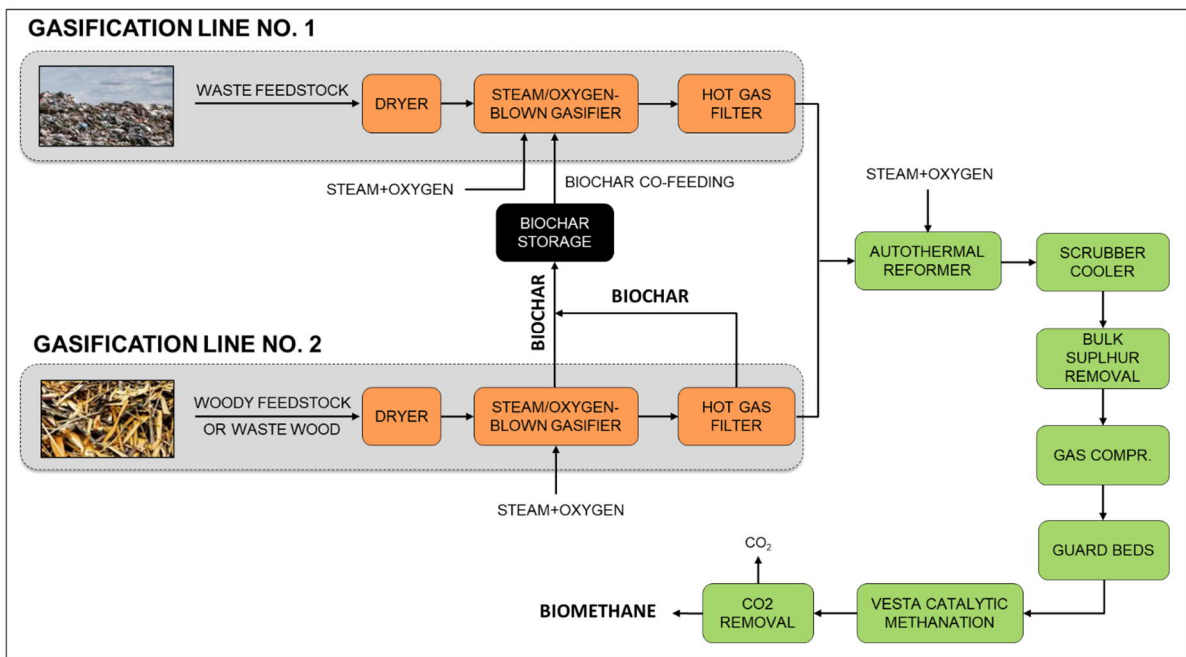


Figure 5. Cityrefinery - FlexSNG concept process configuration.

### 3.2.3 Hybrid plant

In hybrid plants (Figure 6), electrolytic hydrogen can be used to boost biomethane production when low-cost electricity is accessible. Hydrogen enhancement allows more than doubling biomethane production and substantially increasing the carbon utilisation in the process. In biomass-alone production, more than 50% of carbon remains unutilised in the form of CO<sub>2</sub>. In hybrid plants the carbon utilisation can easily exceed 90% as now also part of CO<sub>2</sub> can be synthesised into biomethane [1]. In the FlexSNG hybrid plant:

- The electrolysis unit that is driven with renewable electricity generates hydrogen and oxygen. Syngas is boosted with electrolytic H<sub>2</sub> and hydrogen production is adjusted in order to reach H<sub>2</sub>/CO molar ratio equal to 3 in the gas prior to methanation. The by-product oxygen is supplied to gasification and reforming.

- Part of the captured CO<sub>2</sub> can also be recycled back to the gasifier (or the reformer) to replace part of the fluidising steam and shift the gas composition towards higher concentration of CO, thus making more room for hydrogen addition.

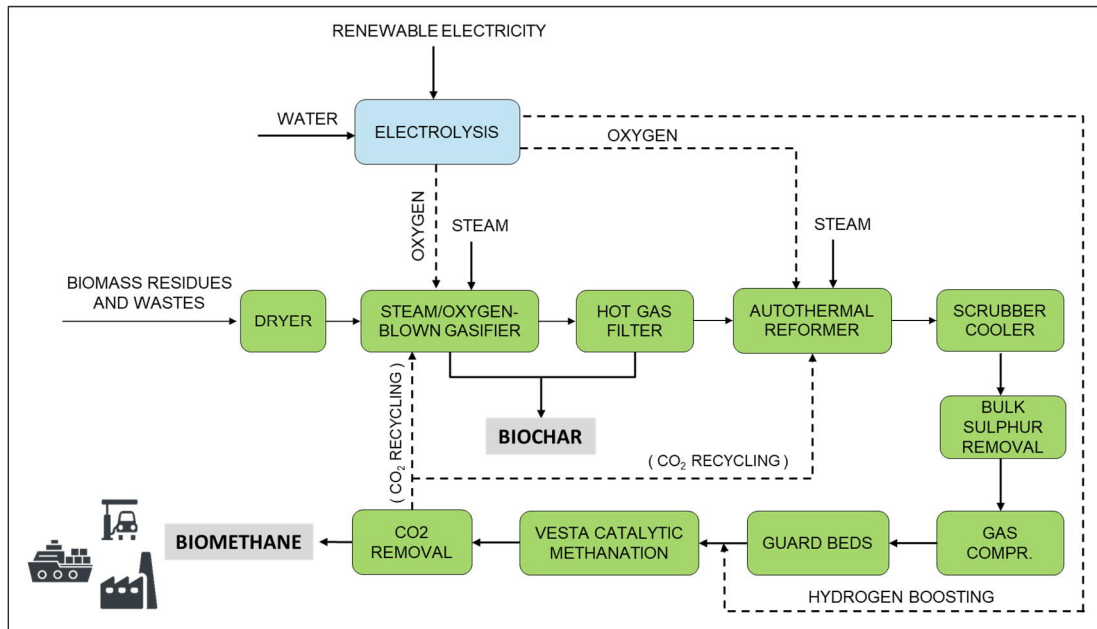


Figure 6. Hybrid plant - FlexSNG concept process configuration.

The implementation potential of electrolysis integration will be assessed in the project particularly in Central European conditions that are considered as potential early markets for the hybrid concept.

In the next steps of the project implementation, all these potential scenarios will be examined and presented in detail.

#### 4 FlexSNG concept and its main unit operations

The FlexSNG concept introduces some significant advances and innovative technologies in the conversion process that are expected to result in up to 30% CAPEX savings compared to state-of-the-art biomass-to-SNG plant design. These design changes and new technologies are (see Figure 7):

- Oxygen consumption in gasification minimized and the capital-intensive oxygen production (based on cryogenic air separation) replaced with OTM technology
- A separate shift conversion unit eliminated: H<sub>2</sub>/CO molar ratio can be adjusted already in the reforming step; VESTA methanation unit does not require strict control of H<sub>2</sub>/CO ratio and has an integrated sweet shift unit
- Capital-intensive wet acid gas removal process (e.g. Rectisol®) replaced with sorbent-based sulphur removal concept using activated carbon and ZnO

- VESTA methanation technology adopted: simplified approach with no need for gas recycling and CO<sub>2</sub> can be separated downstream methanation

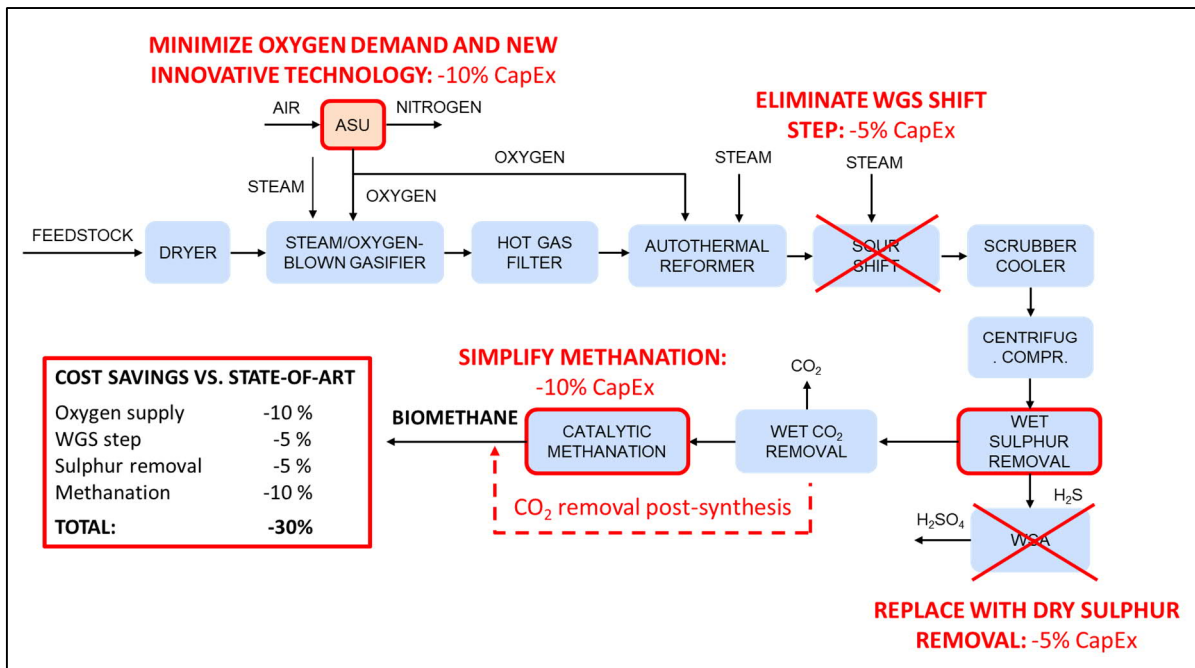


Figure 7. A simplified block diagram of a state-of-the-art biomass-to-SNG plant design, where design changes that lead to cost reductions in the FlexSNG concept have been highlighted.

The FlexSNG process configuration with all main unit operations is shown in Figure 8 and further described in the following sections.

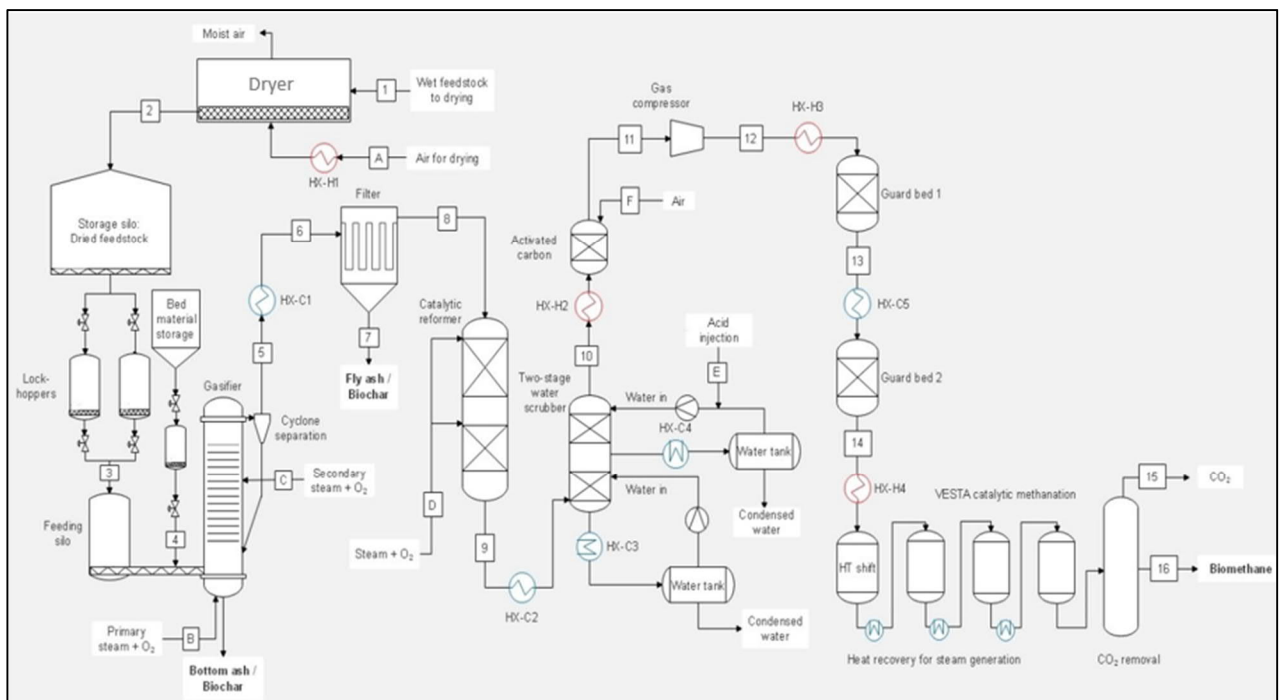


Figure 8. FlexSNG concept configuration for flexible production of SNG and biochar.

## 4.1 Steam/oxygen-blown gasification

Biomass conversion to bio-syngas starts with pre-processing of the feedstock e.g. by crushing and drying. After proper pre-treatment, the dried biomass is converted to raw syngas in a fluidised-bed gasifier that uses a mixture of oxygen and steam as fluidising agents and sand (possibly mixed with catalytically active dolomite) as bed material.

The FlexSNG concept was originally centered around a novel Bubbling Circulating Fluidised-Bed (BCFB) gasification technology that was developed and patented by VTT in the early 2000's. The BCFB gasifier was specifically designed for lower grade waste feedstocks and tested back then in fuel gas applications with waste fuels (air-blown mode). In this project, the target was to adapt the BCFB gasification technology for co-production of biochar and synthesis-quality gas, using steam and oxygen as fluidising gases.

The BCFB gasifier is essentially a combination of a bubbling fluidised-bed (BFB) bottom and a circulating fluidised-bed (CFB) top thus coupling the benefits of both reactor technologies. In co-production mode, the bottom section acts as the carbonization zone and the produced biochar is primarily recovered from the bottom of the gasifier. The gasifier bed is operated in the temperature range of 700-800 °C using a mixture of steam and oxygen as fluidising gases. The low gasification temperature inevitably leads to increased formation of tars, which may cause tar deposition or condensation in downstream units. Therefore, the upper part of the reactor is operated in circulating fluidised-bed mode with the purpose of partially decomposing tars prior to subsequent clean-up steps. This is achieved by introducing a catalytically active bed material (e.g. dolomite) in the top section and elevating the temperature to 800-900 °C through secondary steam and oxygen injection. Once switched to produce only biomethane, the BCFB gasifier is operated with lower biomass/waste throughput, more oxygen is supplied to the lower bed section and less secondary oxygen/steam is fed into the upper part of the reactor. In this mode, the temperature distribution becomes more uniform (ca. 900 °C) resulting in similar performance to a conventional CFB gasifier, which allows maximising the fuel conversion into syngas.

The BCFB gasifier design was adopted for the FlexSNG concept since the primary target was to recover the biochar product through the bottom of the gasifier (bottom ash). The "bottom char" was expected to be of superior quality and better suited for end use applications, like soil amendment, in comparison to the more fine char particulates that were entrained from the reactor and captured as fly ash in the filter unit. This assumption was mostly attributed to the PAH (polyaromatic hydrocarbon) content that was expected to be significantly higher in filter dust-derived char than in bottom ash-derived char.

VTT's preliminary gasification experiments with a modified BCFB gasifier design have shown that good-quality "bottom char" could be produced successfully from bark



pellets provided that the gasification temperature was maintained close to 700 °C and no external bed material was supplied to the reactor, i.e. the produced biochar acted as the sole bed material. Further characterisation of the biochar samples derived from bottom ash and filter dust revealed that the two biochar products were of very similar quality and satisfactory for the end use applications considered in the project. Even the PAH content of filter dust char was within the tolerable limits for soil amendment use. Since the relevant quality parameters of filter dust-derived char were not found to significantly differ from those of bottom char, it was concluded that the traditional CFB gasifier design could potentially be adopted for the FlexSNG concept instead of the BCFB gasifier.

Further gasification experiments have now been conducted at VTT with a CFB gasifier design using straw pellets and clean wood pellets as feedstock. In these tests, the target was to focus on optimizing the quality of filter dust char rather than pursuing to collect char from the gasifier bottom. In case the biochar quality is again acceptable, the BCFB gasifier will be replaced with a simple CFB gasifier in the FlexSNG concept, which further simplifies the transition between co-production and maximized operation modes. The final decision is expected to be made within the next two months once the biochar analyses are completed.

## 4.2 Gas cleaning prior to methanation

The raw gas formed in gasification comprises mainly of CO, H<sub>2</sub>, CO<sub>2</sub>, CH<sub>4</sub>, H<sub>2</sub>O and light hydrocarbons but also impurities originating from the feedstock. Typical impurities formed in biomass gasification include tars, sulphur (H<sub>2</sub>S, COS) and nitrogen compounds (NH<sub>3</sub>, HCN), solid particulates as well as alkali and heavy metals. These contaminants cause fouling of downstream equipment but also catalyst deactivation and therefore need to be separated from the gas stream prior to its application in synthesis processes.

### 4.2.1 Filtration

Upon exiting the gasifier, the coarser fraction of entrained char and bed material are separated from the raw gas in a cyclone and returned to the bottom of the gasifier through a return leg, while the finer solids along with alkali and heavy metals and most of chlorine are removed by filtration. The gas is first cooled down to 350-550 °C to condense the alkali and heavy metal species from the gas so that they can be subsequently captured on the filter along with other particulates. The filter elements are periodically regenerated by applying a reverse nitrogen pulse that detaches the accumulated fly ash. The detached fly ash is collected from the bottom of the filter vessel. Filter elements applied in biomass gasification conditions are typically either ceramic or metallic filter candles.

#### 4.2.2 Catalytic reforming

Filtration is followed by catalytic reforming of tars and light hydrocarbons where these undesired species are converted to  $H_2$  and CO in the presence of nickel or precious metal catalysts. In this project, the end product is biomethane and thus, the target is to achieve full conversion of tars, benzene and other hydrocarbons, while minimising reforming of methane. The two-stage reformer is operated autothermally using a mixture of oxygen and steam that is supplied on top of both catalyst beds. The oxidant feed to the reformer is adjusted to maintain the reformer outlet temperature at around 850-900 °C. A separate water-gas shift reaction step is usually required post-reforming to adjust the syngas molar  $H_2/CO$  ratio suitable for synthesis. In the FlexSNG concept, however, the VESTA methanation does not require strict control of  $H_2/CO$  molar ratio (due to the integrated sweet shift unit), and a dedicated water-gas shift unit can be omitted.

#### 4.2.3 Final gas cleaning

After reforming, the syngas still contains minor contaminants that need to be removed to meet the gas purity requirements of the subsequent methanation process. The main purpose of the final gas cleaning steps is to remove sulphur compounds ( $H_2S$ , COS), trace halides, nitrogen species ( $NH_3$ , HCN) as well as residual tars, benzene and syngas moisture prior to feeding the gas to methanation. Purification to sub-ppm or even ppb-level is generally required for these minor impurities to prevent catalyst poisoning.

The state-of-the-art solution for removal of sulphur compounds and  $CO_2$  from syngas streams is based on wet scrubbing either via chemical (amines) or physical absorption (Rectisol™, Selexol™) followed by guard beds. [2] Such wet scrubbing systems have been applied in coal gasification applications for treating sulphur-rich gas streams. Despite being effective in capturing impurities, the wet scrubbing processes are also complex and capital-intensive, which makes them suitable only for large-scale application. [3]

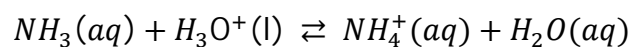
The final gas clean-up concept employed in FlexSNG is based on a simplified, low CAPEX approach where conventional wet scrubbing technologies are replaced with sorbent-based removal of sulphur.  $CO_2$  removal is omitted from this scheme as it is captured downstream the VESTA methanation unit.

The final gas cleaning process comprises the following operations:

- Removal of syngas moisture, chlorine, and ammonia in a scrubber cooler unit
- Two-stage dry sulphur removal using activated carbon and ZnO sorbents
- Gas compression to synthesis pressure
- Guard beds as the final polishing step

Two-stage water scrubber:

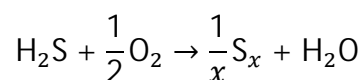
After exiting the reformer, syngas is first cooled down to around 150-160 °C in a heat exchanger and further passed to a scrubber cooler unit. The wet gas is cooled down to room temperature (exit temperature 25 - 30 °C) in the scrubber to condense the syngas moisture, and NH<sub>3</sub> is simultaneously removed by dissolving it in acidic water. The scrubber/condenser design is a countercurrent-flow packed tower where the scrubbing liquid is sprayed on top of the column, while the gas flows upwards. Ammonia capture in the second stage of the scrubber is regulated by controlling the pH of the scrubbing liquid (acid injection). In an acidic environment, ammonia reacts as follows:



Bulk sulphur removal using activated carbon:

The scrubbing step is followed by removal of the major sulphur contaminant H<sub>2</sub>S. Desulphurisation is performed in two consecutive stages: the bulk of H<sub>2</sub>S is removed using activated carbon, while the final polishing stage involves a ZnO-based sorbent. In this first step, the bulk of H<sub>2</sub>S along with residual tars and benzene are adsorbed in a reactor that is filled with activated carbons (AC). The reactor is operated at room temperature.

The first AC bed consists of carbons that are intended for residual tar and benzene adsorption. Heavy molecules have a higher affinity for physical adsorption than small molecules and, with the right carbon selection, they are relatively easy to remove. In the second activated carbon bed, a bulk microporous activated carbon is used for H<sub>2</sub>S removal. Experimental results show that oxidative removal of H<sub>2</sub>S achieves better performance due to the following reaction:



Thus, a small amount of air is supplied to the AC bed to improve H<sub>2</sub>S uptake. A certain amount of moisture in the gas has also shown to be necessary to facilitate oxidation at sufficient rate [4].

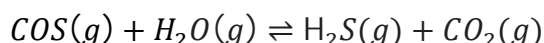
Guard beds:

The final gas cleaning process involves two guard beds: the first (warm guard bed) operates at 200 °C to facilitate catalytic reactions and the latter (cold guard bed) is maintained at room temperature and acts as the final polishing step.

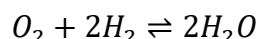
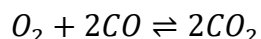
The warm guard bed typically involves at least two separate beds. The first contains a ZnO-based sorbent (with Al<sub>2</sub>O<sub>3</sub> support) that serves as the final H<sub>2</sub>S removal step and allows reducing the H<sub>2</sub>S concentration in the gas to sub-ppm level. ZnO is an efficient

adsorbent for H<sub>2</sub>S capture but requires activation (heat) and the disposal of the sulfide zinc poses a challenge. Therefore, in the final gas cleaning concept of this project, ZnO is employed only for trace H<sub>2</sub>S removal.

Owing to the Al<sub>2</sub>O<sub>3</sub> support, the ZnO adsorbent not only removes H<sub>2</sub>S but can also be used to convert carbonyl sulfide (COS) and hydrogen cyanide (HCN) into hydrogen sulfide (H<sub>2</sub>S) and ammonia (NH<sub>3</sub>), respectively, via hydrolysis reaction. Complete removal of COS is not necessarily achieved in the bulk sulphur removal stage (activated carbon bed), and thus COS needs to be converted to H<sub>2</sub>S before being separated. COS hydrolysis to H<sub>2</sub>S proceeds on metal oxide catalysts according to the following reaction:



The second bed involves a deoxygenation catalyst (either a precious metal catalyst, such as Pt, or a cheaper Cu-based catalyst) that is required to remove the oxygen that was injected to the gas in the first sulphur removal stage (AC reactor). The reactions over the deoxygenation catalyst are essentially combustion reactions and can be summarised as follows:



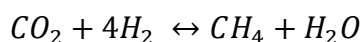
The cold guard bed acts as the final step and polishes the gas from any remaining impurities with acid/basic affinity, namely NH<sub>3</sub>, H<sub>2</sub>S, and HCl. High-performance activated carbons are used for this purpose. If HCN is hydrolysed in the warm guard bed, it will be captured in the form of NH<sub>3</sub> in the cold guard bed. Otherwise, the cold guard bed acts as a precautionary step to prevent accidental or one-off high impurity concentrations from entering the downstream methanation unit and poisoning the catalyst.

### 4.3 VESTA catalytic methanation

The methanation process occurs with the conversion of the carbon oxides, mainly carbon monoxide, and hydrogen into methane, in line with the following equilibrium reaction:



Carbon dioxide can also be converted to methane according to:



High methane yields are thermodynamically favoured by low temperatures and high pressures. Both these methanation reactions are strongly exothermic, hence the methanation processes are characterised by a large amount of heat released, and so the main issues to be faced during the design of a methanation process is the control

of the reactors' temperature by means of an efficient heat transfer system and the optimal recovery of the reaction heat. [5]

In conventional SNG processes, heat management is typically conducted through recycling of reaction gases, which requires investing in recycle compressors. In contrast to its competitors, WOOD's VESTA methanation technology is a once-through process that does not require gas recycling, and CO<sub>2</sub> removal is performed downstream the methanation unit. CO<sub>2</sub> and water act as temperature dampers and thus eliminate the need for recycling compressors. Another key feature of the VESTA methanation technology is its superior flexibility in terms of syngas composition. While state-of-the-art SNG processes require strict control of H<sub>2</sub>/CO ratio, VESTA can handle syngas of a variety of compositions derived from different sources, such as coal, biomass, petroleum coke and solid waste. Figure 9 presents a comparison between available SNG technologies and the VESTA technology.

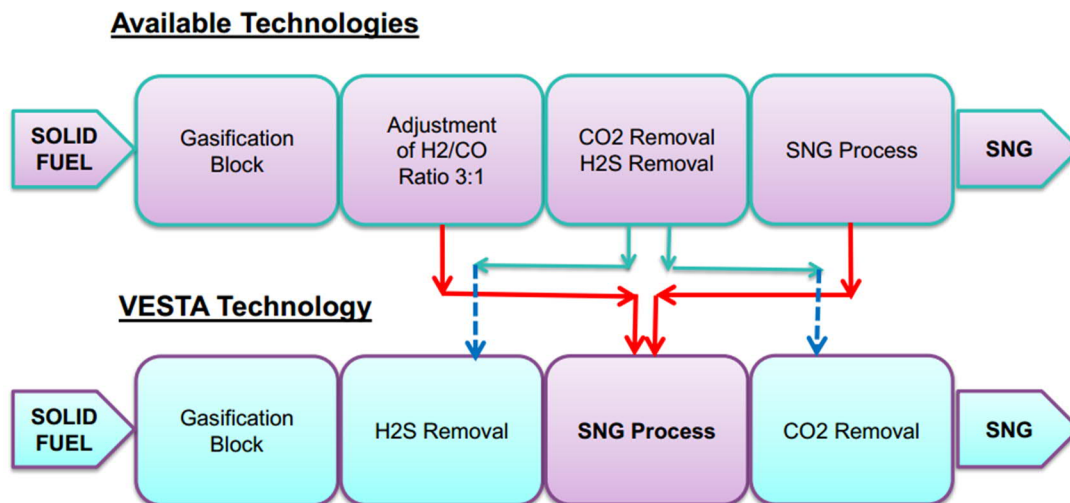


Figure 9. Comparison between available technologies and VESTA technology [6].

Moreover, VESTA methanation has an integrated sweet shift conversion unit, which makes the process insensitive to variations in syngas composition and can therefore easily tolerate process fluctuations in transition conditions without operator intervention. The coupling of the gasification process with VESTA methanation enables cost effective biomethane production already in medium-scale (50-150 MW<sub>th</sub>), while state-of-the-art SNG technologies would require over 200 MW plant size, which is challenging from the biomass logistics point of view. Figure 10 presents a rough configuration of the once-through VESTA methanation process.

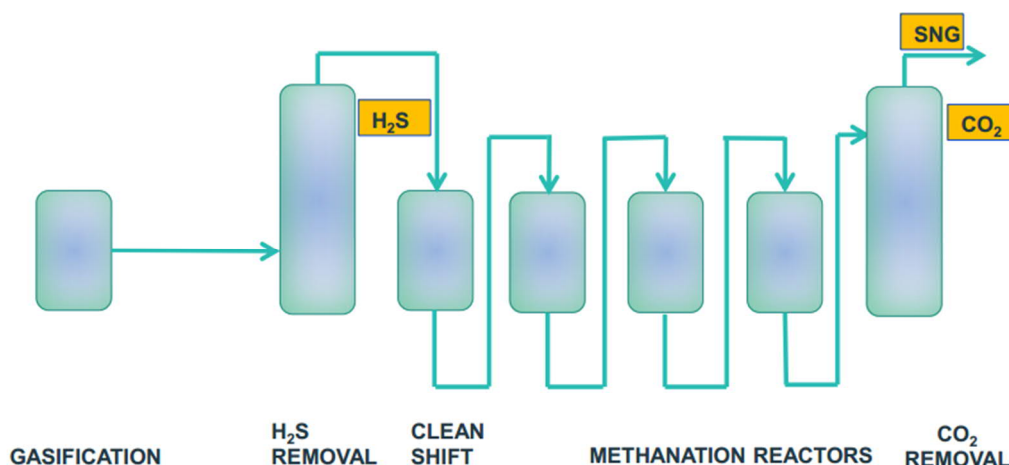


Figure 10. VESTA technology configuration as a once-through operation [6].

In Task 7.4, WOOD as the technology provider of the VESTA methanation technology will perform a conceptual process design, supported by process simulations, for the final gas clean-up and the catalytic methanation section that is able to convert the reactant flow of bio-syngas (from the upstream process) into biomethane (bio-SNG) that meets the requirements of pipeline quality. The work of WOOD will also be based on the results from technical development in WP3-5. The sensitivity of the VESTA process towards variations in syngas composition will be exploited to maximize the flexibility and availability of the plant during the two operational modes. The most attractive configuration for the methanation section will be identified taking into consideration several factors, including but not limited to: heat exchange, gas diffusion, catalyst type, process temperature and pressure. The final design by WOOD will also take into account the integration of different unit operations and will produce a cost estimate for the back-end of the plant.

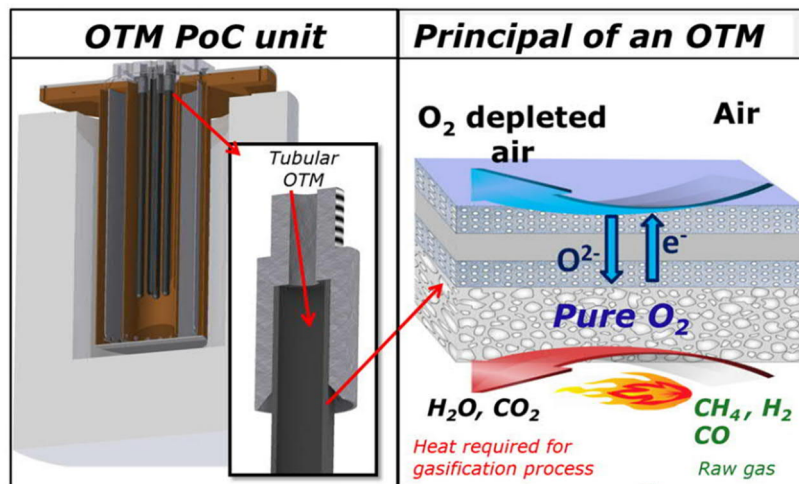
#### 4.4 Oxygen Transport Membranes (OTMs) for cost-effective oxygen production for the gasification process

Another key development topic of the FlexSNG project is the oxygen transport membrane (OTM) technology. Oxygen transport membranes are used in the FlexSNG process to supply oxygen to gasification and reforming. The OTM technology developed by DTU enables the production of high purity oxygen (> 99.5%) from air at low cost utilizing the heat available in the gasification process. This technology will be examined in detail by DTU in WP3. The overall aim of this work package is to demonstrate that the novel oxygen transport membrane (OTM) technology can produce high purity oxygen with 50 % reduced energy consumption compared to state-of-the-art oxygen production methods. The specific objectives are:

- Optimize oxygen transport membranes in terms of geometry, material, robustness and performance for operation in biomass gasifiers.

- Build a proof-of-concept oxygen membrane module and demonstrate on-site operation with a biomass gasifier (TRL 5).
- Provide a cost assessment and sensitivity analysis of a commercial-size, fully integrated oxygen membrane module optimized for biomass gasifiers with a size of 100 MW.

The key feature of an oxygen transport membrane is a gas-tight layer of a ceramic material, which can selectively conduct oxide ions ( $O^{2-}$ ) at temperatures above 700 °C. The difference in oxygen concentration between the two sides of the membrane provides the driving force for the process. Since high temperature heat sources are available in the gasification process and the required oxygen gradient can be achieved by flowing e.g. raw synthesis gas on one side of the membrane (direct integration), oxygen can be separated from air at a very low energy penalty. This makes it possible to realise oxygen-blown gasification processes also on a smaller scale than is economically feasible with conventional oxygen plants. Both direct integration of the membrane with the gasification process and stand-alone production of oxygen with OTMs will be considered in the project. The operation principle of OTMs supplying oxygen/heat for reforming (direct integration) is presented in *Figure 11*.



*Figure 11. Operation principle of OTMs in supplying oxygen/heat for reforming [7].*

The advantages of OTMs over conventional oxygen production methods like PSA (pressure swing absorption) and cryogenic air distillation are:

- OTMs deliver oxygen at a purity close to a 100 % (as only oxygen ions can pass through the membrane),
- OTM modules can easily be scaled to process needs, and
- they can be integrated into gasification processes.

During the first six months of the project, the work at DTU has focused on developing the first generation of OTM tubes and designing the core of the OTM module that will

later be transferred to VTT and operated in direct integration with the pilot gasification plant in validation test campaigns of Task 5.2. Already now, the OTM tubes have been tested under relevant conditions at DTU's lab and the first results look promising. In these experiments, gas compositions produced in the fluidised-bed gasifier were "mimed", which allows estimating the performance of the OTMs tubes in the planned field tests at VTT.

Figure 12 shows the first version of the core unit of the OTM reactor consisting of ten tubes that has already been made. As a next step, the auxiliary components of the OTM module (heating elements, heat exchangers, gas analysis, etc.) will be designed.

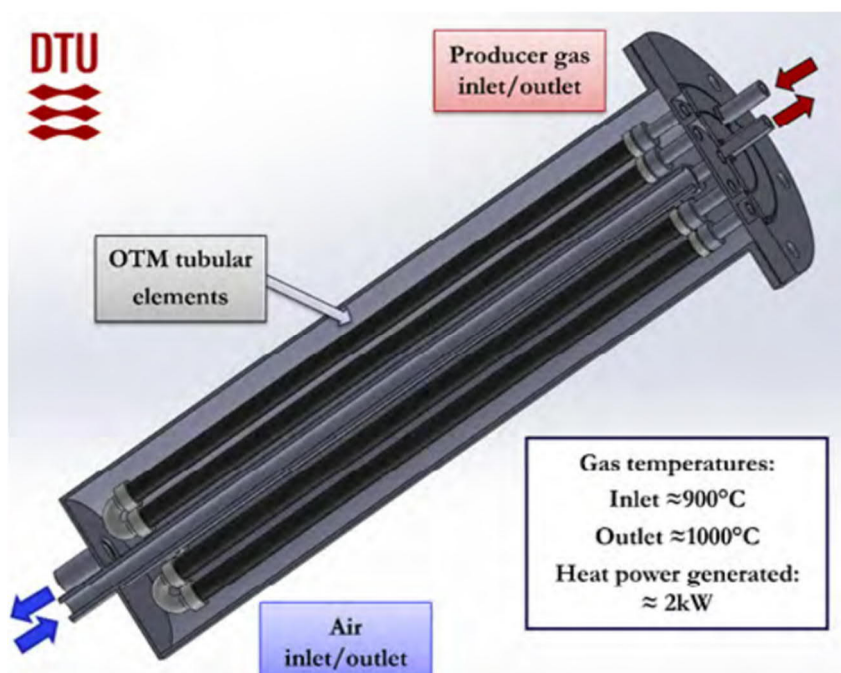


Figure 12. Core unit of the OTM module [7].



## 5 Conclusions

The aim of D7.2 was to define the overall process configuration of the FlexSNG concept and set an initial design and operational framework for each component of the proposed value chain. The final configuration has been determined as shown in Figure 8 and it involves the following steps:

- Feedstock pre-treatment that includes crushing/pelletising/drying etc. depending on the assortment (this will be refined in WP2)
- A Bubbling Circulating Fluidised-Bed (BCFB) or a Circulating Fluidised-Bed (CFB) gasifier (the final decision on the gasifier design will be made within the next two months)
- Hot gas filter for removal of particulates, alkali and heavy metals and most of chlorine
- Catalytic reforming of tars, benzene and light hydrocarbons, while minimising methane conversion
- Gas cooling in a heat exchanger post-reforming
- Two-stage water scrubber for removal of syngas moisture, ammonia and traces of HCl
- Bulk sulphur removal using activated carbon
- Gas compression to synthesis pressure
- Guard beds for final removal of minor contaminants, such as HCN, COS, H<sub>2</sub>S etc.
- VESTA catalytic methanation unit and CO<sub>2</sub> removal post-synthesis

The FlexSNG process configurations described in this deliverable will be used as a basis for process simulations that will be reported in D7.3 (“Preliminary performance estimates for the FlexSNG concepts” in M30) and they also lay a foundation for the upcoming case study assessments of WP8.

## 6 References

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