Final technical report for GaSTech project

1. Identification of the project and report

Project title	GaSTech
Project ID	271511
Coordinator	Shahriar Amini
Project website	https://www.sintef.no/projectweb/gastech/
Reporting period	August 2017 – December 2020

Participants

Organisation
[Coordinator] - SINTEF
SINTEF
NTNU
UPM
UBB
ETH
ESAM
HAYAT

2. Short description of activities and final results

The Laboratory of Energy Science and Engineering at ETH Zurich synthesized and investigated > 100 new oxygen carrier formulations for the different gas switching processes; these were characterized with regard to their activity, selectivity towards the desired products (e.g. CO2, synthesis gas or H2), compositional long-term stability and high-temperature durability. The most promising material formulations were reproduced by Euro Support Advanced Materials B.V. using cheap metal oxide or metal carbonate-based precursors; these were first ball-milled to a fine powder. Subsequently, spherical oxygen carrier particles (> 100 µm) were produced from the powdery materials via the spray drying process using industrially sized equipment, followed by high-temperature treatment to ensure a high mechanical stability of the particles. The oxygen carrier particles were then shipped to the project partner NTNU for the experimental demonstration of the different gas switching processes (between 10 and 50 kg for the processes GSWS, GSR/GSPOx and GSC).

Oxygen carriers developed by ETH and manufactured by Euro Support Advanced Materials were thoroughly tested by SINTEF and NTNU in a larger reactor infrastructure (5 cm ID) at relevant temperature and pressure conditions depending on the targeted process (GSWS, GSR/GSPOx and GSC). The performance under real fluidization of the oxygen carrier was evaluated for the different processes, where challenges were identified (e.g., carbon deposition and agglomeration), and solutions were proposed and implemented. Several samples of CaMn-based oxygen carrier were screened based on their mechanical stability and reactivity under the GSC conditions, before been upscaled by EuroSupport for testing in the larger reactor cluster that was developed in the project for

the scale up of the Gas Switching technology to a pre-pilot scale. Tests from this cluster have revealed the need for further refinement of the reactor design to minimize the elutriation of particles that proved to be the key challenge to solve for automated operation of the cluster.

The techno-economic part of project, UPM and SINTEF developed five base load power production schemes from solids fuels integrating Gas Switching Combustion (GSC) and Gas Switching Oxygen Production (GSOP) clusters with an additional two reference benchmark plants (with and without CCS). The configuration with GSC and natural gas added firing showed most attractive prospects, surpassing 50% efficiency with around 80% CO2 avoidance, leading to a cost of electricity of 70.9 €/MWh, and a CO2 avoidance cost of 24.3 €/ton. Additionally, three advanced power plants utilizing solid fuels as feedstock were designed employing different gasification technologies and integrating GSC with membrane reactors. These plants achieve flexible electricity and H2 production to balance variable renewable energy (VRE), with attainable electrical and H2 efficiencies above 50% and 67% respectively. Two reference advanced benchmark base-load power plants were considered as well in the evaluation. The flexibility benefits lead to negligible CO2 avoidance costs and an improved annual investment return by around 6%-points.
A key result was the design of flexible power-H2 plants integrating Gas Switching Reforming (GSR) in a natural gas combined cycle (NGCC), leading to similar electricity and CO2 avoidance costs as the post-combustion CO2 capture NGCC for base-load power production. When the GSR-CC plant is designed for mid-load operation, with alternating H2/power production to balance VRE, it attains 5%-point higher annualized investment return.
Finally, gas switching technology was investigated for standalone H2 production plants with inherent CO2 capture. In case of GSR, equivalent H2 efficiencies were slightly above the steam methane reforming (SMR) benchmark plant without CO2 capture, resulting in a CO2 avoidance cost of only 18 €/ton. The novel La-Fe based oxygen carrier developed by Work Package 2 for partial oxidation (GSPOX) of methane was evaluated and showed a similar performance to GSR for H2 production, avoiding the safety-related risks of Nickel. The GSPOX scheme was more suitable for partial integration in a power cycle, potentially avoiding electricity imports and diversifying plant revenue.

In the economic assessment part of the project, UBB investigated two Gas Switching Technologies: Gas Switching Reforming (GSR) and Gas Switching Combustion (GSC). The economic assessments for GSR/GSC plant were done base on mass and energy balance received from project's partners: NTNU, SINTEF and UPM.
Two primary GSR-based plants were designed and thoroughly assessed: for power production and hydrogen production. The GSR power plant was compared to two benchmarks: an NGCC power plant with no CO2 capture and the same NGCC plant with post-combustion MEA CO2 capture. A standard baseload economic assessment at a capacity factor of 85% revealed that the two CO2 capture plants show similar results (around 74 €/MWh), with the LCOE in the case of the GSR plant being slightly higher. However, GSR achieved an identical COCA (60.86 €/tone) to the MEA plant because of its higher CO2 avoidance rate. However, a more realistic mid-load scenario at a capacity factor of 45% reversed this outcome. When assuming an average electricity price of €60/MWh and a €1.35/kg hydrogen price, the GSR plant outperformed the MEA benchmark, showing an annualized investment return that is about 5 %-points higher. This advantage increased with higher CO2 prices due to the very high CO2 avoidance of the GSR plant.
In case of GSC plants, the study compared the economic performance of five different IGCC power plant configurations: a benchmark IGCC plant without CCS, conventional pre-combustion CCS, gas switching combustion (GSC), GSC with added firing with natural gas (GSC-AF) and a gas switching oxygen production pre-combustion (OPPC) configuration. The GSC plant returned a LCOE that is 11.5% lower than the conventional pre-combustion benchmark (94.23 €/MWh vs 83.4 €/MWh) while maintaining a CO2 capture rate of over 94%. Despite the higher cost of natural gas relative to coal, the large efficiency gain brought by added firing reduced the LCOE by another 15% to 70.93 €/MWh, reducing the cost of CO2 avoidance as low as 24.26 €/ton when compared to a supercritical pulverised coal power plant. The large efficiency benefit of replacing the ASU with GSOP reactors in the OPPC configuration was partially counteracted by an increase in gasifier cost, resulting in a similar LCOE to GSC, but a 4.1 €/ton higher cost of CO2 avoidance due to a lower CO2 capture rate. These results show that the GSC-AF configuration holds the most promise. Added natural gas firing

also makes the GSC-AF case less capital intensive (31% lower specific capital cost than GSC), limiting the cost increase related to lower capacity factors and higher discount rates.

The integration of the novel gas switching concepts developed in the project to the existing gasification plant in HAYAT Kimya and thus the production of valuable chemicals (methanol, formaldehyde, etc.) was the commercial scenario proposed by HAYAT Kimya. This business model was evaluated for both GSC and GSR processes considering both atmospheric and pressurized versions of GSC. Since the additional H2 production makes the whole process very expensive, integration of atmospheric GSC seemed to be unfeasable. Compared to the current process, the production capacities of electricity and heat energy are higher in case of pressurized GSC integration. In this respect, it provides a benefit compared to the current process and becomes economically competitive. Integrated process including GSDR was not found feasible as it requires high investment cost. Actually, need for installation of gas purification systems which are not currently available in HAYAT Kimya doubles the investment cost. This makes the evaluation more specific which means that it may be more sensible to assess economic feasability without regarding such cost increasing secondary factors.

The key results from all workpackages in the project are reported in details as follows:

▪ Materials selection and manufacturing (WP1)

Work package 1 dealt with the selection, testing and manufacturing of suitable oxygen carrier materials for the four gas switching processes combustion (GSC), water splitting (GSWS), reforming (GSR) and oxygen production (GSOP). The initial plan was to select the materials based on > 2000 published works in the chemical looping area, such that length material development works would be avoided. Promising material formulations were supposed to be reproduced/synthesized at the Laboratory of Energy Science and Engineering (LESE) at ETH Zürich and investigated/tested under relevant reaction conditions (defined by WP2 in which the actual gas switching reactor setup is investigated at larger scale). The best material compositions were produced by Euro Support Advanced Materials B.V. (ESAM) via a commercialized spray-drying process.

Shortly after the beginning of the project it became apparent that the selection of oxygen carriers solely based on results/compositions that have been declared as “promising” in the literature cannot be realized. The majority of published works have employed small-scale testing equipment using powdery oxygen carriers, thus significantly simplifying the process conditions that are encountered in a scaled process of industrial significance. In such processes, which were modelled through WP 3 and 4, and investigated experimentally through WP 2, the following deviations from the idealized laboratory-scale works exist: (i) Oxygen carriers cannot be operated in powdery form but need to exist in particle form of diameter > 150 µm. (ii) The mechanical stability of the oxygen carrier particles needs to be guaranteed over thousands of redox cycles. The physical integrity of the particles needs to be maintained despite the temperature variations and phase transitions during the redox reactions, and the collisions with other particles and the reactor walls. A high initial strength is required, which is typically related to the compression strength of individual oxygen carrier particles. Dust and fines formed through abrasion or particle breakage would be entrained from the reactor and would have to be replaced, adding to the operational costs of the process. (iii) A high mechanical stability of the oxygen carrier particles requires high calcination temperatures, typically > 1200 °C. However, mixed metal oxides will form at such high temperatures (yet, such high temperatures have hardly been employed in the literature), so that the conventional concept of active metal oxide and inert support is not applicable when producing long-lasting oxygen carrier particles; most strategies in the chemical looping literature aiming for a high long-term redox stability of oxygen carriers have relied on an inert support material (e.g. Al_2O_3

or ZrO_2) that stabilizes the redox-active metal oxide (e.g. Fe_2O_3 or CuO). (iv) In small-scale testing equipment, parameters that are relevant at the process level can often not be investigated (e.g. gas conversion), because reactive gases are diluted or reaction temperatures and pressures deviate from those in large reactors. It is important to understand that a fast transition of the oxygen carrier between its reduced and oxidized state, which is easily observed in small-scale studies (of the order of mg rather than kg), does not necessarily imply that the oxygen carrier is sufficiently reactive to convert the reducing or oxidizing gases completely.

The material development work within WP 1 was therefore more extensive than initially planned, and in total more than 100 original material compositions were developed. The different oxygen carriers were investigated and characterized in detail to assess their potential for the actual gas switching processes. For that, a set of state-of-the-art techniques was utilized at the LESE, including X-ray diffraction (XRD), Raman spectroscopy, scanning electron and transmission electron microscopy (SEM/TEM), N_2 sorption, inductively coupled plasma spectroscopy (ICP), compression strength measurements, and laboratory-scale reactors (thermogravimetry, fixed and fluidized bed reactors). The goal was to understand why some oxygen carriers perform well and others do not, such that the optimization of the materials is conducted rationally rather than following a trial-and-error approach. The development of the oxygen carriers was performed in close collaboration with WP 2, as not every aspect that is relevant at the process level could be emulated and investigated in WP 1 (e.g. the mixing of gas and solids in a large reaction vessel).

Materials were initially synthesized from nitrates to investigate the effect of the elemental composition on the oxygen carrier's performance in the absence of contaminants; later, particles of the most promising compositions were manufactured by ESAM using cheaper precursors of lower purity based on metal oxides or carbonates. Figure 1 illustrates the general methodology employed by ESAM to manufacture the spray-dried oxygen carrier particles, i.e. the deliverables of WP 1.

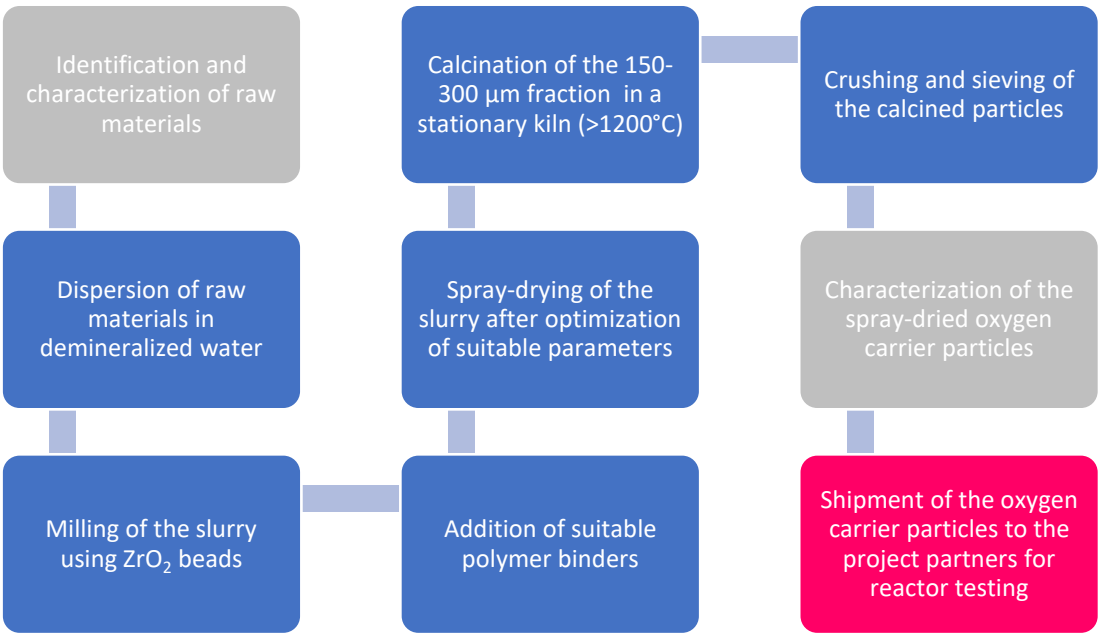


Figure 1: Overview of the general methodology employed by ESAM for the production of spray-dried oxygen carrier particles.

Table 1: Summary of the spray-dried oxygen carrier particles produced in WP 1, which were shipped to the project partners in WP 2. Note that no suitable materials were found for the GSOP process, and

so the focus was shifted towards the most promising process GSPOx for which additional material was produced for testing in the gas switching cluster (see WP 2).

Milestone	Gas switching process	Oxygen carrier composition	Amount delivered
1	GSWS	$Mg(Fe_{0.9}Al_{0.1})_2O_4$ with 5 wt.% CuO	2*10 kg
3	GSR / GSPOx	$La_{0.85}Sr_{0.15}Fe_{0.95}Al_{0.05}O_3$ and $La_{0.8}Sr_{0.2}Fe_{0.95}Al_{0.05}O_3$	15 kg and 50 kg
6	GSOP	Ca_2AlMnO_5	0.5 kg
7	GSC	$CaMn_{0.775}Ti_{0.125}Mg_{0.1}O_3$	50 kg

Spray-dried oxygen carrier particles were classified as successful if they (i) had the same elemental composition as the materials produced at the LESE from nitrate precursors, (ii) showed the same reactivity, product gas selectivity and compositional long-term stability, and (iii) had a high compression strength (> 30 MPa).

Table 1 summarizes the successfully produced oxygen carrier particles that were shipped to the project partners in WP 2 for experimental investigations in the actual gas switching reactor. The GSR process requires a catalytically-active component in the oxygen carrier that can activate CH_4. Nickel-based materials needed to be avoided as they would have required additional safety measures at ESAM. Precious metals, e.g. Pt or Rh, were avoided owing to their high costs. There has been not evidence in the literature that any other materials could activate CH_4, and so the GSR process was replaced by the GSPOx process (gas switching partial oxidation), where CH_4 would not be activated catalytically, but instead reacted via a thermodynamic, partial oxidation route. For the envisaged GSOP process, no suitable oxygen carrier formulations were found that could fulfill the strict thermodynamic requirements identified through WP 3 and 4 for the process to outperform benchmark processes. The oxygen carrier Ca_2AlMnO_5 listed in Table 1 was identified as a promising candidate in previous works, but it was found in this project that this material cannot be reoxidized using air at temperatures > 625 °C, i.e. much lower than required in the GSOP process.

The best-performing oxygen carriers in WP 1 were those produced for the GSC and GSPOx processes with a high resistance towards sintering and an excellent long-term stability; more than 50 kg of both oxygen carriers were thus produced for experiments using the gas switching cluster developed in WP 2, which is more than initially planned in the project. Oxygen carriers produced at high calcination temperatures, such as those manufactured for the GSC, GSWS and GSPOx processes, consisted of a single metal oxide phase composed of several elements. The advantage of such materials is that they can be recovered and recycled completely without requiring any additional purification steps. Dust or fines could readily be used as precursors in the milling process (Figure 1) because their elemental composition is the same as in the fresh oxygen carrier.

▪ Reactor testing (WP2)

WP2 was responsible for experimental demonstration of the selected GST processes using the material developed by WP1. Four chemical looping applications (Figure 2)- combustion, reforming, water splitting, and partial oxidation) were investigated:

a. **Combustion:** oxycombustion of gaseous fuel using the lattice oxygen of metal oxide (oxygen carrier) to produce a pure stream of CO_2 ready for storage/further utilization. The reduced oxygen carrier is regenerated by a highly oxidation reaction with oxygen in air (inherent separation of N_2 from the CO_2 produced during oxidation). The hot stream of N_2 gas can drive a gas turbine for power generation.
b. **Dry reforming:** CO_2 reforming of methane to produce syngas (H_2 and CO) with integrated carbon capture. The oxygen carrier should not only act as an oxygen reservoir but also as a catalyst for the reforming reaction. The dry reforming reaction is highly endothermic, so the required heat is generated through the oxidation reaction.
c. **Water splitting:** Partial oxidation of an oxygen carrier with steam is used to produce pure H_2. The oxygen carrier is first reduced by carbon-rich fuel gases in an N_2-free environment thus ensuring inherent CO_2 capture. After the partial oxidation of the reduced oxygen carrier with steam, the lattice oxygen is fully restored by complete oxidation with air that also generates heat for the endothermic reduction reaction.
d. **Partial oxidation:** Heterogenous partial oxidation of methane using the lattice oxygen of a metal oxide to produce syngas (H_2 and CO) of H_2/CO ratio ~2 for Gas-to-Liquid applications. Similar to the other processes heat is supplied through the oxidation reaction of the oxygen carrier with the oxygen from air.

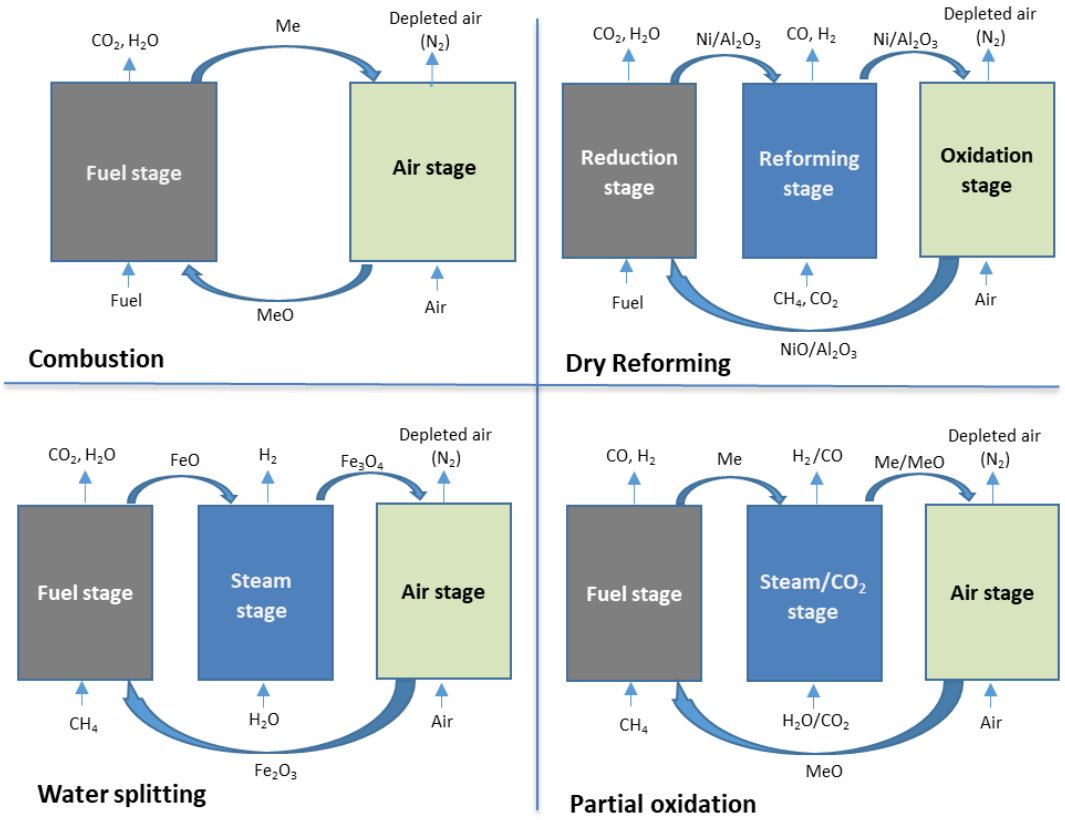


Figure 2: The four chemical looping processes under investigation using gas switching technology.

Methodology

The experiments were completed using an existing pressurized 5 cm ID fluidized bed reactor by Norwegian University of Science and Technology (NTNU) and SINTEF Industry (Figure 3). The aim was to achieve autothermal operation for each GST concept at pressurized conditions. A proper gas feed system consisting of gas mass flow controllers, stop and multiway valves (controlled through a LabVIEW program) were in place. Temperature and pressure sensors in the reactor setup were used

for monitoring process analysis purposes while the gas composition at the reactor outlet was analyzed using an ETG Syngas analyzer.

Following the successful demonstration in the standalone setup, a 50KW$_{th}$ pre-pilot cluster (Figure 4) of three dynamically identical reactors (10cm ID each) was developed and commissioned to operate the GST reactor in a continuous mode. The working principle is to alternate different redox stages among the three reactors to achieve pseudo-continuous operation in each one, but the entire cluster can deliver continuous streams of each of the gaseous products (Figure 4a). The setup can withstand up to 1100°C and 20bar and a lance was designed to feed gas towards the bottom of the bed to achieve fountain-like gas distribution for good circulation of gases across the bed. The first-of-its-kind unit was used to demonstrate gas switching combustion using a CaMn-based as would be explained in the next page.

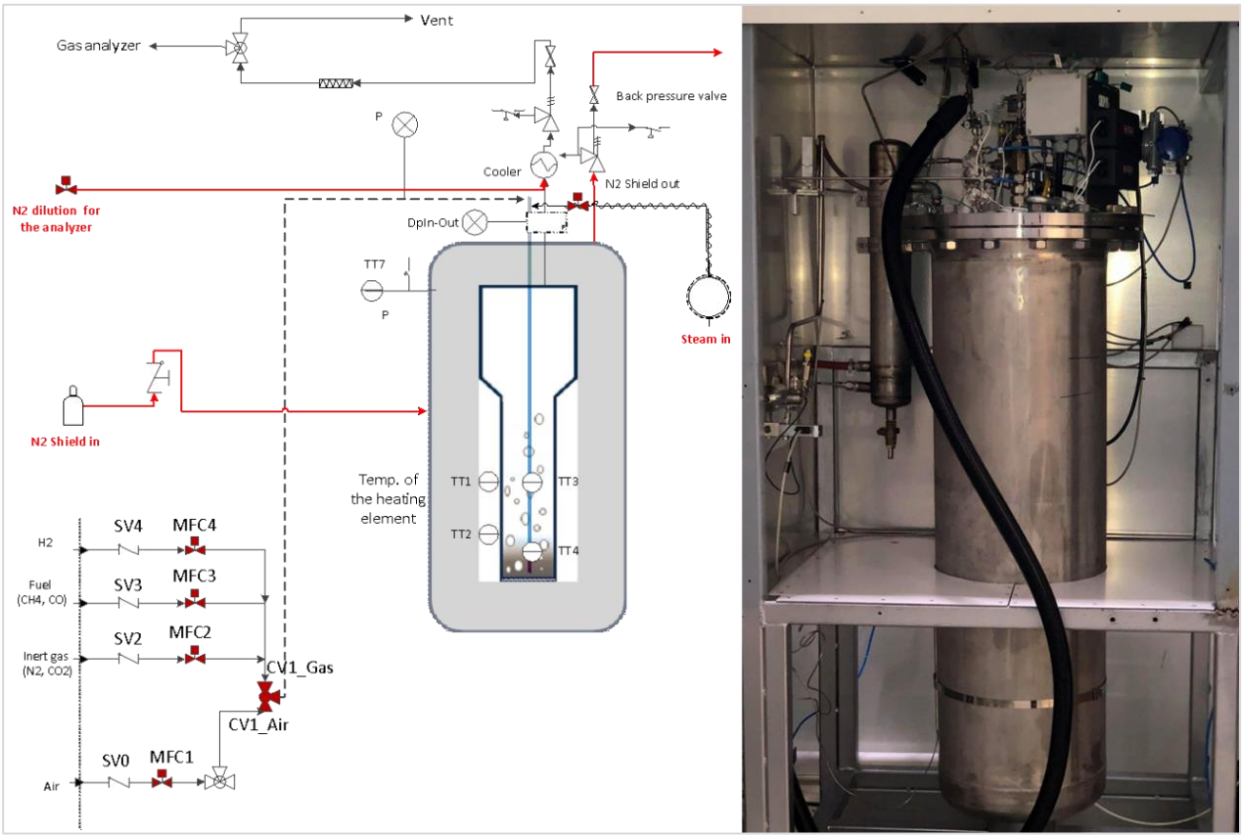


Figure 3: Setup of the standalone pressurized fluidized bed reactor used for experimental demonstration. SV04 *represents stop valves and MFC1-4 represents mass flow controllers for air, the inert gas (N_2 and CO_2), the fuel (CH_4, CO), and H_2 respectively. TT1 and TT2 represent the temperature transmitter (thermocouple) that measures the temperature of the heating element on the reactor external circumference, while TT3 and TT4 represent temperature transmitters (thermocouple) that measure the bed temperature inside the reactor. P is pressure sensors while TT7 is the temperature transmitter (thermocouple) that measures the temperature inside the reactor shell.*

Figure 4: The experimental setup of the GST three-reactor cluster designed to achieve continuous operation. (a)the working principle where each circle represents one reactor in a different redox stage; (b) the symmetrical arrangement of the three dynamically identical reactor cluster (c)the experimental setup under construction; (d) the fully commissioned setup.

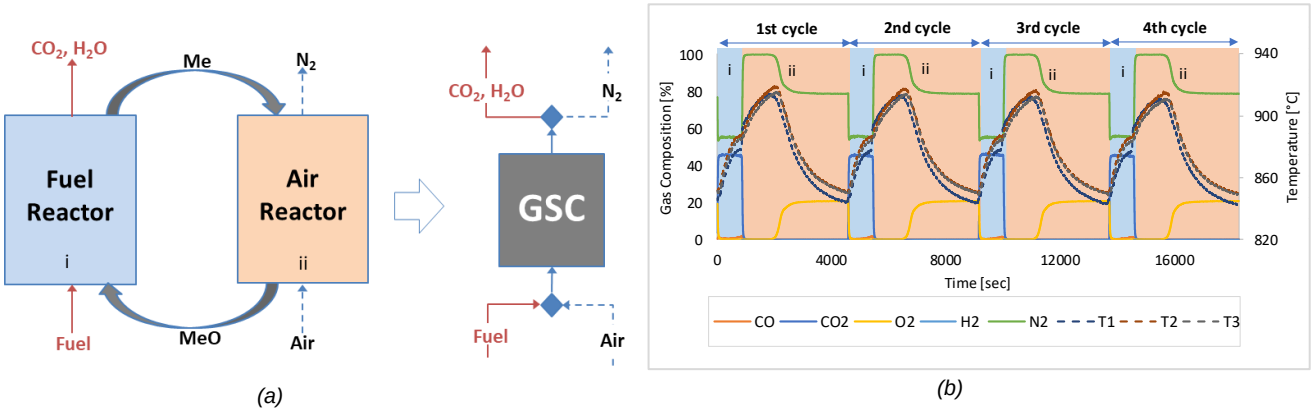


Figure 5: (a)Gas switching combustion process design, (b) The autothermal transient gas composition and temperature profile of Reactor 1 at 850°C and 1bar. The reduction/fuel stage is indicated as i (blue) while the oxidation stage is indicated as ii (pitch). T1, T2, and T3 are temperature measurements at the bottom, centre, and top of the bed inside the reactor. For each cycle, the flowrate at the fuel stage is as follows: CO (20nl/min) and N_2 (15nl/min) for 15 min at the reduction/fuel stage while 30nl/min of air was fed in the oxidation stage for 75min.

Key Results

a. *Gas Switching Combustion (GSC)*

The gas switching combustion was demonstrated in the reactor cluster (Figure 4) as a two-stage process (Figure 5a) using an optimized $CaMn_{O3-\delta}$-based oxygen carrier developed in WP1. Autothermal operation (without external heat supply) was achieved in each reactor using CO as fuel under atmospheric conditions. The gas composition and temperature profiles were repeatable over several cycles (Figure 5b). Complete conversion of CO was achieved with about 99.99% CO_2 purity and 98.9% CO_2 capture efficiency. No CO_2/CO was observed in the oxidation stage (Figure 5 b), indicating no carbon deposition. However, particle elutriation was a major problem that hampered the automated

pressurized cluster operation.

b. Gas Switching Dry Reforming (GSDR)

Gas switching dry reforming was demonstrated using Ni-based carrier in a three-stages process (Figure 6a). Autothermal and pressurized (Figure 6b) operation over a wide operating and feed conditions. The ability to control the syngas quality (H_2:CO ratio) was demonstrated by adjusting CO_2:CH_4 ratio and addition of steam. The H_2/CO molar ratio between 0.25 – 2 was achieved with up to 90% sygnas purity suitiable for different GTL (gas-to-liquid) processes. Integrating GSDR to GTL processes can achieve improved process efficiency, reduced GHG emission and increased profitability. The process can be improved by optimizing CO_2:CH_4 ratio, steam addition, high pressure and elevated temperature.

c. Gas Switching Water Splitting (GSWS)

The experimental demonstration of Gas Switching Water Splitting (GSWS) was completed in a three-stages process (Figure 7a) using two iron-based oxygen carriers. The first GSWS demonstration with 35 wt.% Fe_2O_3/Al_2O_3 (Figure 7b) showed good reactor performance with no agglomeration but H_2 purity was compromised due to gas mixing that takes when switching between the process stages. It was proposed to increase the active content of the oxygen carrier to achieve longer the stages and reduce the extent of mixing on H_2 purity. This led to the development of Cu-doped Mg$(Fe_{0.9}Al_{0.1})_2O_4$ spinel OC with 74 wt.% active content that was used for the second GSWS demonstration. Although the second oxygen carrier is very reactive, it exhibited a high degree of carbon deposition and agglomeration resulting in poor performance.

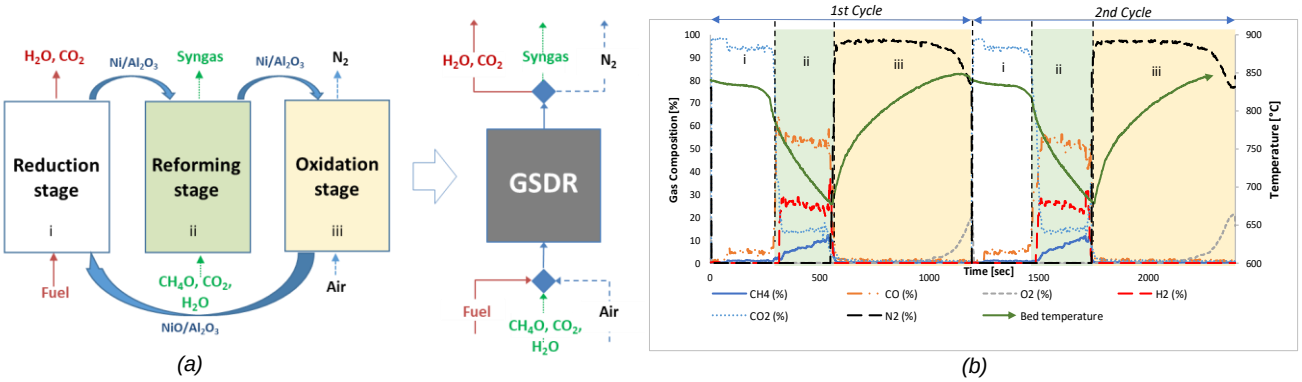
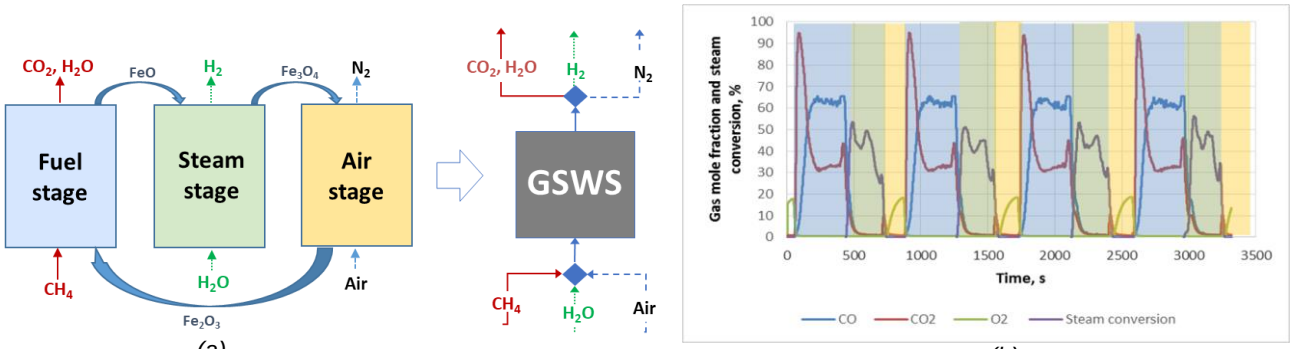
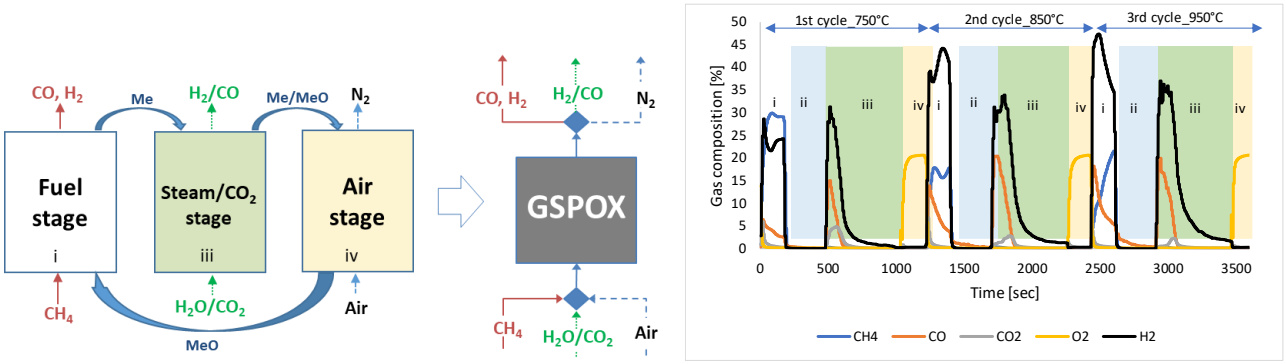


Figure 6: (a)The three-stage Gas switching dry reforming process design, (b) Two autothermal GSDR cycles showing transient gas composition and temperature profile. The reduction starts at a temperature of 850°C (target temperature). 1bar operating pressure, CO_2/CH_4 molar ratio of 2 and gas flowrate as follows: CO-12.8nl/min, CH_4- 3.2nl/min, CO_2-6.4nl/min, Air- 10nl/min. i, ii and iii represent the reduction, reforming and oxidation stages respectively.



(a) (b)

Figure 7: (a) Three-stage Gas Switching Water-splitting process design (b)The transient gas composition of 4 cycles of GSWS using CO as fuel at 900°C and 1bar. Fuel stage in blue; Steam stage in green; Air stage in yellow. Flowrate: 5 Nl/min CO for 6min (80% degree of OC reduction), 1.9 Nl/min steam for 5min (CO : steam molar ratio feeds=2.5), 10Nl/min Air for 3min.



(a) (b)

Figure 8: (a)Three-stage GSPOX process design. (b) Three cycles showing the transient gas composition under Gas Switching Partial Oxidation (GSPOX) at CH_4 molar fraction of 50 % diluted in N_2, 1 bar, and temperature from 750 to 950 °C. i: fuel stage (Gas input: CH_4 4.1 nl/min, N_2 4.1 nl/min for 2.93 min); ii. N_2 purge (Gas input: N_2 10 nl/min for 5 min); iii: steam stage (Gas input: H_2O 2 nl/min for 10 min); iv: Air stage (Gas input: air 10 nl/min for 3 min).

d. Gas Switching Partial Oxidation (GSPOX)

A Lanthanum-based oxygen carrier was tested under the Gas Switching Partial Oxidation conditions for combined syngas and H_2 production in a three-stages process (Figure 8a). Over 70% CH_4 conversion to syngas (at the fuel stage) and about 30% H_2O conversion to H_2 (at the steam stage) was achieved at at 950˚C and atmospheric conditions. Despite the high reactivity and stability of this oxygen carrier, substantial carbon deposition was observed at high CH_4 concentration with a resultant increase in the syngas (H_2/CO) ratio beyond 2 (Figure 8b). The deposited carbon was gasified completely gasified in the steam stage making carbon deposition not an issue if syngas production is targeted. However, carbon deposition can be problem if pure H_2 production is targeted in the steam stage due to the contamination by carbon gasification imposing additional purification measures. The extent of carbon deposition was reduced by co-feeding an oxidizing gas (H_2O or CO_2) with CH_4 in the fuel stage.

▪ Techno-Economic Assessment (WP3 & WP4)

Introduction

a. Scope

WP 3 has developed several process configurations by integrating gas switching (GS) reactor clusters in power and H_2 production plants for inherent CO_2 capture, starting from solid (coal) and gaseous (natural gas) fuels. The GS technologies that received primary focus were reforming and combustion, although some preliminary concepts assess the potential of oxygen production, using and assumed reactor performance from literature. Since the development of this oxygen carrier was not pursued by WP 1 & 2, further evaluations were not carried out. The power plant boundary assumptions and feedstock characteristics are taken from [1]. WP 4 has used the data provided by WP 3 to elaborate a consistent economic assessment of the process concept. The results of these WP's are shown jointly.

b. Key performance Indicators

The process configurations are evaluated based on three main pillars: energy (Table 2), environmental (Table 3) and economic (Table 4) perspective:

Table 2: Energy performance indicators.

Name	Electrical Efficiency	Equivalent H_2 Efficiency
Definition	$\eta_{el} = \frac{\dot{W}_{net}}{\dot{m}_f LHV_f}$	$\eta_{H_2,eq} = \frac{\dot{m}_{H_2} LHV_{H_2}}{\dot{m}_{NG} LHV_{NG} - \frac{\dot{W}_{net}}{\eta_{el,ref}} - \frac{\dot{Q}_{th}}{\eta_{th,ref}}}$
Units	%	%

Where $\dot{W}_{net}$ indicates net electric output, $\dot{m}$ is the flowrate, LHV is the lower heating value and ref refers to a reference benchmarking plant.

Table 3: Environmental performance indicators.

Name	CO_2 Avoidance/Equivalent Carbon Capture Ratio	Specific primary energy consumption for CO_2 avoided (SPECCA)
Definition	For Power: $CA = \frac{E_{CO_2,ref} - E_{CO_2,CCS}}{E_{CO_2 ref}}$ For H_2: $CCR_{eq} = \frac{\dot{m}_{CO_2,capt.}}{E_{NG}\dot{m}_{NG}LHV_{NG} - E_{th}\dot{Q}_{th} - E_{el}\dot{W}_{net}}$	$SPECCA = \frac{\frac{1}{\eta_{CCS}} - \frac{1}{\eta_{Ref}}}{E_{CO_2,Ref} - E_{CO_2,CCS}}$
Units	%	MJ/kg

Where CA is the CO_2 avoidance, E is the CO_2 intensity of a given plant (electricity, steam) or feedstock (natural gas), CCS refers to the plant with carbon capture and storage. $\dot{Q}_{th}$ indicates the steam enthalpy

difference from export conditions to saturated liquid. CCR_{eq}stands for equivalent carbon capture ratio, applied to H_2 plants only.

Table 4: Economic performance indicators.

Name	Levelized Cost of Electricity	Levelized Cost of Hydrogen	Cost of CO_2 Avoided
Definition	$NPV = \sum_{t=0}^{n} \frac{ACF_t}{(1+i)^t}$ For Power: $ACF_t = \phi \cdot LCOE \cdot W_e^y - C_{CAPEX} - C_{FOM} - C_{VOM}$ For H_2: $ACF_t = \phi \cdot LCOH \cdot m_{H_2}^y - C_{CAPEX} - C_{FOM} - C_{VOM}$		For Power: $COCA = \frac{LCOE_{CCS} - LCOE_{ref}}{E_{CO_2,ref} - E_{CO_2,CCS}}$ For H_2: $COCA = \frac{LCOH_{CCS} - LCOH_{ref}}{E_{CO_2,ref} - E_{CO_2,CCS}}$
Units	€/MWh	€/kg	€/ton

Where NPV stands for net present value of the project, ACF_t is the annual cash flow rate, C_{CAPEX} C_{FOM} C_{VOM} is the cost of capital, fixed operation and maintenance and variable operation, respectively. ϕ indicates the plant capacity factor, i is the discount rate and t is the operating year. Performance of flexible power-H_2 plants is described in more in the next section. Further details of the performance indicators can be found in deliverables 3.4, 3.6 and 4.1.

Methodology

a. Process Synthesis

The configurations were developed in commercial process flowsheet simulators: Aspen Plus, Thermoflex and Unisim Design were employed by the WP members. The modelling and equipment assumptions for the performance of the plant components was taken from the European Best Practice Guidelines for Assessment of CO_2 Capture Technologies [1]. Additional modelling assumptions are extensively provided in the appendixes of deliverable 3.4. The reactor cluster behaviour was modelled in equation oriented solvers such as Matlab and Scilab, the latter using an in-house thermodynamic database: Patitug. The dynamic cluster was represented assuming a Continuous Stirred Tank Reactor (CSTR) behaviour and full fuel conversion. The reactor solves the dynamic molar and energy balances obtaining the instantaneous reactor profile and outlets in flow, composition and temperature. The instantaneous outlets of each reactor step were determined with a post-processing code, considering the nº of reactors in the cluster, which was specified to minimize fluctuations with respect to the averaged values of flow and temperature. Further details on the kinetics, sizing, cluster configuration and heat management strategies can be found in deliverables 3.1 and 3.6.

An iterative procedure, introducing the averaged outputs in the stationary process simulation and obtaining new input values for the dynamic model was established until convergence is reached. An integrated model between Scilab and Unisim using a CAPE-OPEN unit operation allowed to reduce interfaces for information exchange. Such integrated scheme was also employed for the simulation of the gasification plants with membrane H_2 reactors, which required a dedicated model in Scilab.

b. Economic Assessment

The economic assessment methodology applied in the evaluation of the plants comprises three major components: capital cost estimation, fixed and variable operating cost estimation, and a discounted cash flow analysis for quantifying the levelized cost of electricity and the CO_2 avoidance cost. For

evaluating the value of flexible power and hydrogen production, the cash flow analysis is used to calculate the expected investment returns under given assumptions of electricity and hydrogen prices. The capital cost estimation methodology is divided in reactor cost, heat exchangers cost and major plant units cost (WGS unit, Air separation unit, Gasifiers, Gas Turbine, Steam Turbine, etc). The assumptions for the fixed and variable operating and maintenance costs include main cost elements such as fuel, oxigen carrier, catalysts, CO_2 transport and storage etc. A discounted cash flow analysis was performed to determine the main economic performance indicators of the GSR/GSC plant and to compare it with other technologies. The levelized cost of electricity (LCOE) is calculated using the cash flow analysis. All costs and additional revenue are considered and the LCOE is calculated for a net present value of zero at the end of the economic lifetime, given a specified discount rate. Additional economic assumptions are extensively provided in the appendixes of deliverable 4.1.
The flexible power and hydrogen production from solid and gaseous fuels is evaluated by comparing mid-load power plants responsible for balancing variable renewables at a capacity factor of 45%. Given that the electricity sales price will be considerably higher during times of low wind and sun when such mid-load plants are producing power, an electricity sales price premium of 10-40 €/MWh over the average grid electricity price of 60 €/MWh is explored. In addition to this higher sales price, the flexible plants also sell hydrogen to the market at a conservatively low price of €1.35/kg relative to alternatives [2] to maximize the utilization of plant capital. This flexibility also maximizes the utilization of downstream CO_2 T&S infrastructure, reducing the cost of storing CO_2 relative to the inflexible benchmark cases where this infrastructure is only utilized intermittently.

Process Configurations

a. Power Plants from Solid Fuels

A preliminary collection of plants employing solid fuels as feedstock for base-load electricity production, integrating a gas switching combustion cluster or alternatively oxygen production, with gasification as an intermediate step was developed. The plants integrating GS technology also benefit from high temperature syngas clean-up (HGCU) [3]. The main features and nomenclature are shown in *Table 5*, further description can be found in deliverables 3.4 and 3.6.

Table 5: Power plants from solid fuels.

Type	*Name*	*Description*
Benchmark	IGCC	Unabated Integrated Gasification Combined Cycle, using Shell gasification, advanced GT assumptions for syngas fuels, and diluting with N_2 from ASU for NOx control.
	IGCC-PCC	Pre-combustion CO_2 capture plant, equivalent to IGCC, but adding a water gas shift and Selexol units for CO_2 capture to generate a H_2 rich fuel for combustion free of carbonaceous emissions.
GSC	GSC	A GSC cluster is integrated after syngas clean-up, using N_2 recycle to maintain high oxidation outlet temperatures. Firing temperatures are limited by GSC, and require ad-hoc GT. Shel gasification
	GSC-AF	An extra firing chamber using natural gas is added, increasing firing temperature in the GT thereby boosting efficiency, at the cost of a lower capture rate. O_2 slip heat management strategy is used for the GSC. Shell gasification
	GSC-HAT	Integrated solution of a GSC cluster and a humid air turbine cycle. Decoupled operation of the reduction and oxidation sections of the plant, allowing the GSC cluster to operate as an energy storage device, providing flexible power output.
GSOP	OPPC	The oxygen production pre-combustion plant (OPPC), integrates a Winkler gasifier with a GSOP cluster, to deliver an oxidant stream. Part of the syngas is used in the GSOP, preheating an air stream, and part is decarbonized with a pre-combustion unit to generate H_2 and reach high firing temperatures.
	GSOP-GSC	Based in the COMPOSITE process previously published [4], but integrating fluidized bed GSOP-GSC clusters with Winkler gasification, and an ad-hoc GT.

b. Flexible power-H_2 plant from solid fuels

The core principle of this concept is the integration of the GSC cluster with a membrane assisted water gas shift reactor (MA-WGS) for the production of a pure H_2 fuel, to raise the temperature for GSC outlet to the GT reference combustor outlet temperature when electricity prices are high. In market conditions with low electricity prices, the MA-WGS reactor is operated to maximize H_2 product, while the GSC cluster is adjusted to maintain a constant CO_2 stream for transport and storage. Thus, the gasification island operates at a nominal point in each mode. This concept is represented in Figure 9:

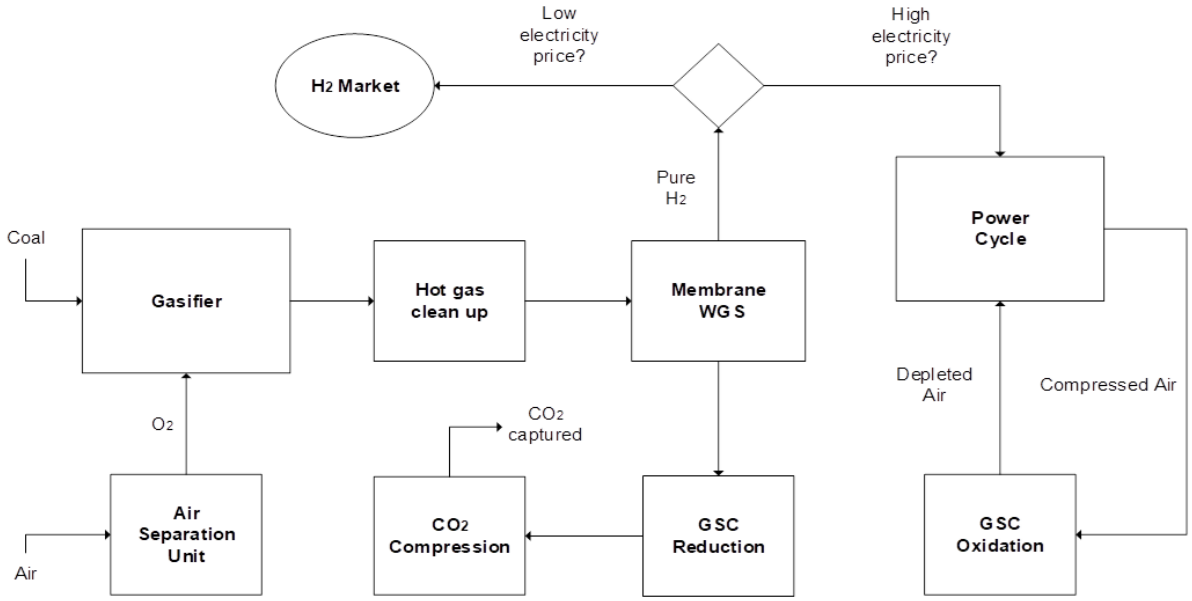


Figure 9: Flexible IGCC GSC-MAWGS concept.

This plant models incorporate advanced H-class GT's and HGCU technology and are summarized in Table 6. Further information can be found in deliverable 3.6.

Table 6 Flexible Power-H_2 plants from solid fuels

Type	*Name*	*Description*
Benchmark	IGCC	Advanced IGCC plant with H-class turbine and HGCU. N_2 and steam dilution to mitigate NOx emissions.
	IGCC-PCC	Advanced pre-combustion CO_2 capture plant, with H-class GT and HGCU, simplifying the Selexol unit.
GSC-MAWGS	GSC-Shell	Standard configuration with Shell gasifier and reduction gases recuperator.
	GSC-HTW	Includes a pre-gasification unit and a Winkler gasifier and syngas recuperator. High efficiency but high process complexity.
	GSC-GE	Pressurized GE gasifier with water quench allows to operate the MA-WGS with N_2/steam sweep in power/H_2 modes, reducing pressurization requirements and decoupling with steam cycle. Good trade-off between efficiency and cost.

c. Flexible power-H_2 plants from gaseous fuels

A key configuration using natural gas as feedstock developed during the project consists of the integration of a GSR (reforming) island, which produces a H_2 fuel from a pressure swing adsorption (PSA) unit, and a combined cycle. A N_2 stream outlet from the GSR oxidation step is used to dilute the H_2 fuel, minimizing NOx emissions. The GSR island can achieve complete independent operation

allowing to flexibly produce electricity or H_2 depending on market conditions. The concept is represented in Figure 10, and further details can be found in deliverables 3.2 and 3.5.

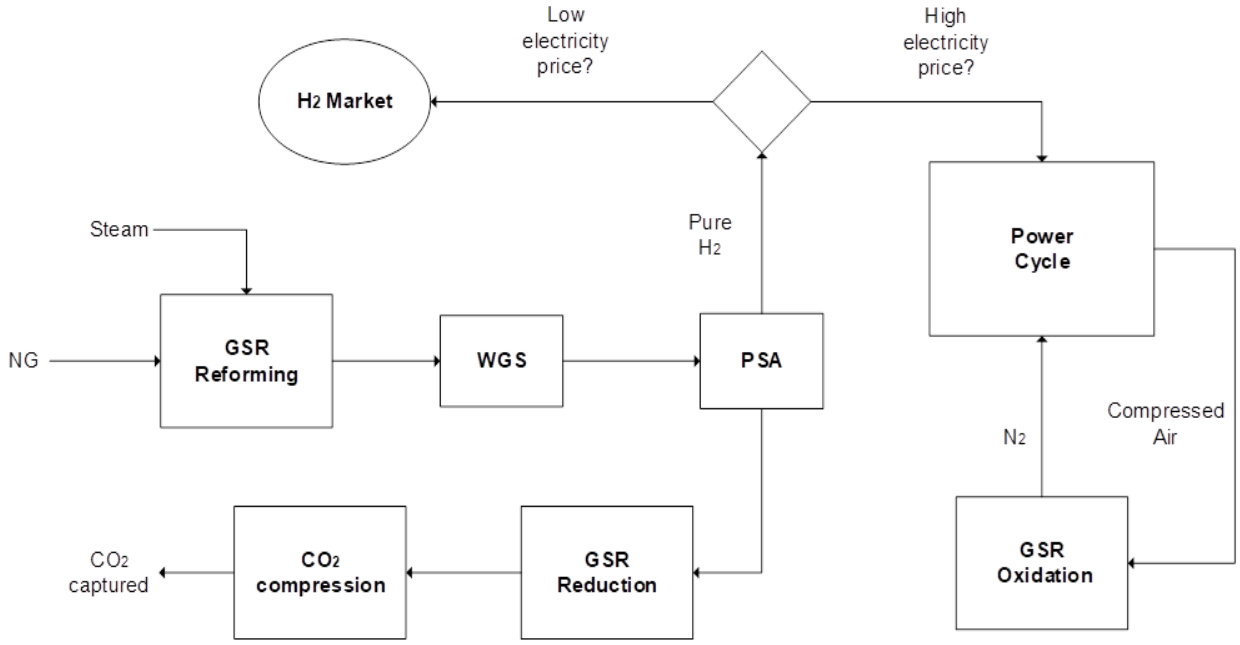


Figure 10: GSR-CC flexible Power-H_2 concept.

This flexible GSR-CC was consistently benchmarked with a natural gas combined cycle with and without post-combustion CO_2 capture in terms of efficiency, emissions, and economic perspective from [1].

d. H_2 plants

A set of plant models for H_2 production (with a natural gas input of 130 MW) were designed. Such plant integrates GSR clusters similarly to the GSR-CC, although the oxidation section can be integrated to generate more steam for the reforming step, enhancing H_2 efficiency. Alternatively, the Lanthanum-based oxygen carrier was modelled in a gas switching partial oxidation (GSPOX) cluster and compared to the GSR plant. By employing a different reactor operation strategy, the GSPOX can be more effectively integrated with a small power cycle, in order to produce a substantial power output to diversify plant revenue. The novel H_2 plants are benchmarked against traditional unabated steam methane reforming (SMR) process, and an SMR process with MDEA CO_2 capture. Modelling and economic assumptions for these plants were taken from [5].

Key Results

a. Power plants from solid fuels results

The technoeconomic performance parameters for the solid fuelled power plant concepts discussed previously is shown in Table 7:

Table 7: Results for power plants from solid fuels.

Plant	*Energy*	*Environmental*		*Economic*	
	η_{el} (%)	CA (%)	$SPECCA$ (MJ/kg)	$LCOE$ (€/MWh)	$COCA$ (€/ton)*
IGCC	47.6	0.0	-	60.2	-
IGCC - PCC	37.8	88.1	3.08	94.2	57
GSC	43.4	91.4	1.12	83.4	38.7
GSC - AF	49.5	80.7	-0.48	70.9	24.3
GSC-HAT	41.6	99.1	1.52	-	-
OPPC	46.3	83.0	0.36	83.0	42.8
GSOP-GSC	46.3	84.0	0.36	-	-

*Advanced supercritical coal boiler is used as reference plant

b. Flexible power-H_2 plants from solid fuels results

Table 8 shows the results for these plant concepts with the economic metrics for base-load power production:

Table 8: Results for power-H_2 plants from solid fuels for base-load power production.

Plant	*Energy*		*Environmental*		*Economic*	
	η_{el} (%)	$\eta_{H_2.eq}$(%)	CA (%)	$SPECCA$ (MJ/kg)	$LCOE$ (€/MW)	$COCA$ (€/ton)*
IGCC	51.6	-	0.0	-	54.3	-
IGCC - PCC	41.9	-	89.5	2.70	80.9	44.3
GSC - Shell	47.2	60.7	94.3	1.03	77.6	36.9
GSC - HTW	50.3	66.2	98.0	0.28	70.7	24.9
GSC - GE	47.1	63.5	98.3	1.02	76.2	30.3

*IGCC is used as reference plant

The economic performance of the plants accounting for the flexibility feature of H_2 co-production is presented in Figure 11: The value of flexibility was evaluated by comparing mid-load power plants responsible for balancing variable renewable at a capacity factor of 45%. According to Figure 11**Feil! Fant ikke referansekilden.**, given the very high CO_2 avoidance of the GSC-HTW and GSC-GE plants, the investment returns from these plants are almost unaffected by the CO_2 tax. The unabated IGCC plant becomes less attractive than all the GSC-MAWGS plants at a 30 €/ton CO_2 tax and yields

negative returns at all electricity price premiums when the tax exceeds 50 €/ton.

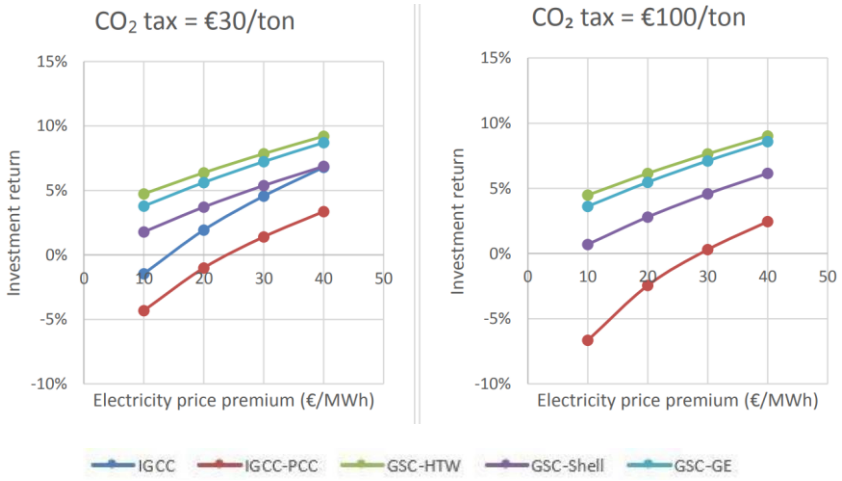


Figure 11: Investment return as a function of electricity price premium and CO_2 tax.

c. Flexible power-H_2 plants from gaseous fuel results

Table 9 shows the results for these concepts with the economic metrics for base-load power production.

Table 9: Results for the Power-H_2 plants from gaseous fuels for base load power production.

Plant	*Energy*		*Environmental*		*Economic*	
	η_{el} (%)	$\eta_{H_2.eq}$ (%)	CA (%)	$SPECCA$ (MJ/kg)	$LCOE$ (€/MW)	$COCA$ (€/ton)
NGCC*	58.3	-	0.0	-	53.4	
NGCC – MEA*	49.9	-	89.7	3.30	73.2	60.9
GSR-CC	51.1	80.5	98.1	-	75.0	60.9

*from EBTF report.

The economic performance of the plants accounting for the flexibility feature of H_2 co-production is presented in Figure 12. The discounted cash flow analysis indicates that a larger price premium causes substantial increases in the expected investment returns from all cases. When the CO_2 tax is only €30/ton, the unabated NGCC plant still offers the best investment return, but it drops strongly when the CO_2 tax increases to €100/ton, showing the risk posed by future CO_2 tax increases. Moreover, the results reveal that the GSR plant outperforms the MEA plant in that scenario, counter to the economic outlook from the baseload economic assessment: the advantage of GSR-CC plant over the NGCC - MEA plant increases with increasing CO_2 price.

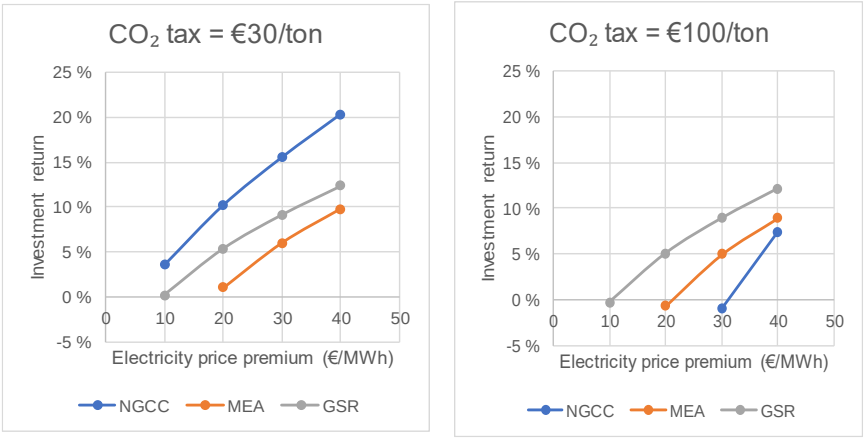


Figure 12: Investment return as a function of electricity price premium and CO_2 tax.

d. H_2 plants results

Table 10 shows the technoeconomic results for the H_2 plants developed.

Table 10: Results for the H_2 plants.

Plant	*Energy*	*Environmental*		*Economic*	
	$\eta_{H_2.eq}$ (%)	CCR_{eq} (%)	$SPECCA$ (MJ/g)	$LCOH$ (€/kg)	$COCA$ (€/ton)
SMR	79.3	0.0	-	1.71	-
SMR MDEA	72.5	85.1	2.28	-	-
GSR H_2	80.4	89.0	-0.26	1.85	18.0
GSPOX H_2*	82.5	90.8	-0.51	-	-
GSPOX H_2-Power*	79.4	140.4	0.15	-	-

*Advanced H-class combined cycle is used as reference electricity plant

Conclusions

Multiple concepts integrating a GSC cluster in a gasification unit were designed for base-load electricity production from solid fuels. Maximizing firing temperatures beyond the reactor limits proved essential to achieve low energy penalties. The configuration with GSC cluster and natural gas extra firing showed the most promising technoeconomic results. Flexible power-H_2 plants integrating gasification, GSC cluster and membrane H_2 reactors incorporating advanced H-class GT technology allowed to surpass 50% efficiency with CO_2 capture from solid fuels. Such concepts are designed to operate flexibly to balance variable renewables, showing attractive investment returns for fluctuating electricity demand.

For thermal power plants using gaseous fuels, the GSR-CC configuration achieves similar baseload performance to the MEA post-combustion CO_2 capture NGCC plant. When incorporating the flexible H_2-power feature in the economic assessment, the GSR-CC investment returns greatly improve. The GSR-H_2 configuration clearly outperforms the unabated SMR reference plant in terms of equivalent efficiency, whilst attaining a high CO_2 avoidance. The GSR-H_2 concept is reliant on electricity imports. The GSPOX cluster incorporating the La-based oxygen carrier developed by WP 1 & 2 presents comparable results to Nickel for H_2 production, but allows to tune the plant design to effectively integrate a power cycle, producing a net electricity output to diversify plant revenues.

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[1] Rahul Anantharaman, Olav Bolland, Nick Booth, Eva Van Dorst, Eva Sanchez Fernandez, Flavio Franco, Ennio Macchi, Giampaolo Manzolini, Djordje Nikolic, Allen PfefferCesar Deliverable D2.4.3. “European Best Practice Guidelines For Assessment Of CO_2 Capture Technologies”. 2018.
[2] Nikolaidis P, Poullikkas A. A comparative overview of hydrogen production processes. Renew Sustain Energy Rev 2017;67:597–611. https://doi.org/10.1016/j.rser.2016.09.044.
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▪ Business case evaluation (WP5)

In this project based on renewable resources of biomass, a special version of GSC called pressurized GSC and GSDR processes have been used for HAYAT Kimya to valorize hot water and steam and to sell the electricity to the grid at a relatively high price (13 euro-cents per KWh).

General Analysis of the Business Case:

In order to analyze the feasibility of pressurized GSC and GSDR processes, investigation of any aspect of biomass collection is essential. There are 3 main functions necessary for the conversion of biomass into the renewable energy: i) setting up the equipment, ii) collecting biomass into a container truck and transporting to the site, iii) valorizing waste energy at HAYAT Kimya production campus and selling electricity to the grid. Each function has been examined from a financial point of view, and the required cost and efficiency data have been obtained from internal studies done at HAYAT Kimya before.

Site Preparation & Set-up:

HAYAT Yenikoy campus has all the infrastructure needed for this project from public electricity grid connection to the piping to steam and hot water system. The rest of the process has been only to allocate some space for storing biomass big bags. For a stock of one-week operation, 330 big bags would be needed to be stored at any time considering one big bag weighs 1200 kg. In this case an empty space of 60 mt is only required (4 stores and each shelf space can take 4 big bags back and forth) to construct the storage shelves, which is widely available in the vicinity. The process and gasifier would require almost 30*60 mt area because most of the process setup will be big in height, not the other way around. The site has other possibilities like providing any size of crane at any time as well as plenty of electricians, mechanics, iron worker, welder, and any other sort of technicians. Therefore, many of the costs related to the process construction would be eliminated. The only issue would be to get the process equipment on site as quickly as possible. This would also be very easy because HAYAT runs a private port along with a bonded warehouse in walking distance to the potential construction site. As a result, unloading the equipment from vessel, customs clearance and inland transportation could be done rather quickly.

Loading & Transportation of Biomass:

Transportation of wood biomass would be performed by trucks. When the truck to carry wood biomass gets on KEAS site, it gets filled with biomass big bags in 20 minutes and preferably by a forklift operator only as this will help eliminate waiting times. This cost is negligible and included in the total cost of the

biomass charged by KEAS at 42.12 Euros per ton. The capacity of the biomass truck is around 21 tons, and it takes 45 minutes (50 km) to transport the waste powder to the HAYAT Kimya site (Figure 13). Assuming that the truck carrying the biomass will have the same transportation cost as any other case in Istanbul province, one load would cost 77.61 Euros. Therefore, it would cost 3,695 Euros per ton to load and transport the trucks. In this case, the total delivered cost of biomass is 45.82 Euros.

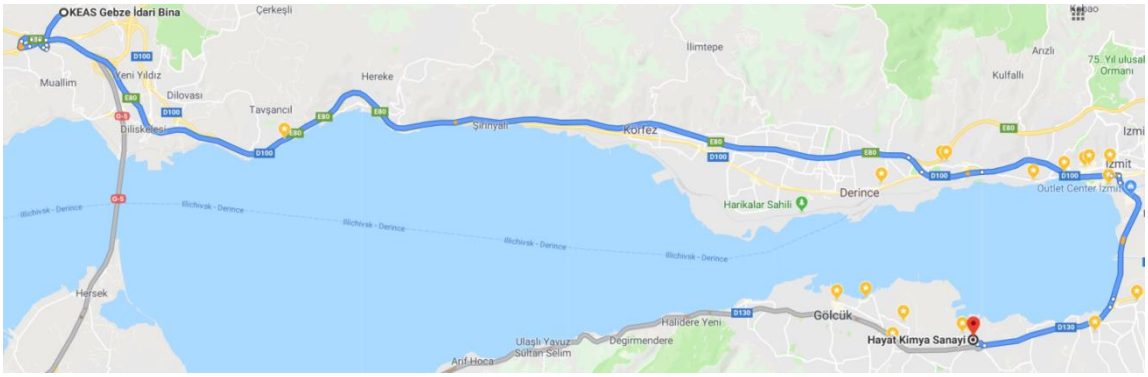

Figure 13: Transportation route of the wood biomass from KEAS to HAYAT Kimya.

The biomass that originates from HAYAT tissue plant is however quite different. HAYAT currently pays the incinerator company 142 Euros per ton to pick up and eliminate this waste. The plant would require 1,700 tons of biomass per month, and the secondary biomass resource could be as high as 98 tons per month, which means HAYAT would get 1,602 tons of wood biomass from KEAS. Accordingly, the overall cost of biomass would only be 34.99 Euros.

Waste Energy Valorization & Electricity Sales to the Grid:

The energy generated by the process could be utilized in three ways; i) steam, ii) hot water, and iii) electricity. The following figures in Table 11 could be taken into consideration for the financial evaluation.

Table 11: Figures for financial evaluation.

Description	Unit	Price (Euro)
Electrical Power	KWh	0.13
Thermal Power	MWh	25.09
Hot Water	ton	16.32

Marketing:

In order to properly market the outcome effectively, the product, place, price and promotion must be optimized. These are critical to conduct a proper and effective marketing strategy. Starting with product, HAYAT Kimya will maintain the integrity of their process through ISO 50001 certification, if it is pursued. Energy efficient strategies help organizations save money as well as conserve resources and tackle climate change. ISO 50001 supports organizations in all sectors to use energy more efficiently, through the development of an energy management system. If ISO 50001 is not an option, then the high internal energy management standards of HAYAT will be maintained through their best management practices.

Place is how the product is going to be utilized, or the logistics of the operation. The biomass could be either coming from a very nearby location or being generated at the very same site. Transportation could be done by trucks travelling on mostly highway roads. The HAYAT production campus has the entire infrastructure required; the waste energy out of the process itself could be consumed at the same location at the same time, simultaneously. The system is already connected to the grid to ensure that the electrical power could be sold to the system. The site is also licensed to be auto-energy

generator and seller, which is a must according to the legislation enforced by Turkish energy regulatory authority (EPDK).

Thermal energy (steam and hot water) price could be set by the overall energy cost of HAYAT Yenikoy production campus, which is very competitive in Turkey. Therefore, this could not be very attractive for this business case although selling most of the outcome (50% of hot water at least and 100% of the steam) generates a big advantage. Most new players in renewable energy market do not have this opportunity. The electricity price, however, will be fixed by a contract with the distribution companies. The electrical energy could be sold to the grid but a relatively high price (13 euro-cents per KWh) could be under the guarantee of Turkish government for a ten year period. Then the price would be defined by free market although HAYAT could consume all the electricity produced by this plant. Their total consumption today is more than 80 MWh, so 3 MW should be something very easy to integrate.

The promotion part could be less likely to be taken into consideration in this particular business case. The reason is very simple; HAYAT would be either a self-consumer or selling to the public at a contracted price. Therefore, there would be no promotion required which in turn could reduce some of the non-technical costs associated with the commercial phase of this project.

Revenues:

The simulated pressurized GSC plant consumes 1,700 tons and for this, it generates 6.5 MW thermal power and about 2.2 MW of electricity. About 3 MW of heat should be recoverable as hot water. 3 MW of thermal power can heat about 43 tons of water per hour from 20°C to 80°C (or alternatively, 129 tons of water per hour from 73°C to 93°C). If an overall efficiency of 35% of the plant is assumed it would generate a projected revenue of 182.611 Euros per month.

Payback Time:

Capital must be regained with the profits made with this investment to be considered a success. With the competitive edge in the renewable energy industry, profit margins are not so high. The operational costs would be around 4,772 Euros per month while biomass would take around 59,483 Euros per month. Therefore, considering the fact that the plant would create a cash flow of 118,356 Euros per month, the payback time for a roughly estimated Capex of 5.5m Euros would be around 46 months which could be considered convenient. If HAYAT Yenikoy production campus could consume all of the hot water at 43 tons per hour rate, this could be as low as 27 months.

GSDR Considerations:

HAYAT has a biomass gasification system based on fixbed gasifier technology. Syngas produced in this system is not pressurized and not clean enough to produce methanol. Therefore, purification system is needed for natural gas (NG). GSDR methanol system mentioned here is designed for NG for which the prices are too high in Turkey. Turkey has not got its own source for NG in the country. Costs of additional units required for GSDR-GTL integration (methanol case) are shown in Table 12. To conclude, purification system investment CAPEX is too high for a feasible solution for the existing biomass gasification plant in HAYAT.

Table 12: Costs of additional units required for GSDR-GTL integration (methanol case).

Description	Capacity	Price (M€)
GSDR reactor	KWh	12
PSA		4.7
Syngas cooling		5
NG purification		36
Methanol plant	30 ton h^{-1}	35
TOTAL		**92.7**

Present an overview of financial results as well, per partner and per work package.

3. Project impact

- **Materials selection and manufacturing (WP1)**

The work carried out in WP 1 demonstrated that there exist discrepancies between laboratory-scale investigations of oxygen carriers and practically relevant process requirements; these have been addressed in the project and suggestions been given on what oxygen carrier properties are relevant for scale-up. The gas switching technology is based on the chemical looping principle, which is still a relatively young reaction concept that is yet to be applied at the industrial scale. WP 1 has shown that the production of oxygen carrier particles is not an obstacle to the scale-up and commercialization of chemical looping-based technologies. Spray-drying is a proven technique that is suitable to produce stable and long-lasting materials. The limitations of oxygen carrier particles for industrial use do not lie in the production process or the costs, which are largely determined by the costs of the raw materials, but in the inherent physical and chemical properties of the redox-active metal oxide species in the oxygen carrier – most importantly the sintering and melting temperatures of the phases that form during the redox reactions. To the best of our knowledge, ESAM is the only company in Europe (and one of only two institutions next to VITO, Belgium) that has successfully produced oxygen carrier particles in quantities close to the ton scale for chemical looping applications.

- **Reactor testing (WP2)**

WP2 contributed to diversifying the low CO_2 footprint pathways of syngas and hydrogen production from methane reforming and optimizing their performance by minimizing the extent of carbon deposition while increasing the value of CO_2 into usable products. An important feature that has been demosntrated through this work is the tunability of the produced syngas compsition thus facilitating its efficient integration to a variaty of downstream GTL applications. A 50 kWth pre-pilot cluster of three reactors able to operate at realistic temperature and pressure (1100 °C and 20 bar) was developed and commissioned which can be used for further maturation and scale of the different GST processes. The outcome from this work package has been presented in eight international conferences and six international journal articles.

- **Techno-economic Assessment (WP3 & 4)**

WP 3&4 showed that several process concepts for fossil fuel based thermal power and H_2 generation with inherent CO_2 capture are attractive from a technoeconomic perspective. Process concepts were developed which reached very high CO_2 avoidance indexes and low emissions of other pollutants such as particulate matter, NOx and SOx. The GSR-H_2 concepts show great potential and can trigger industrial interest after appropriate dissemination of the results obtained.

- **Business case evaluations (WP5)**

HAYAT Kimya played an important role in the transition of the project to the next commercial demonstration phase by conducting technical and economic feasibility studies of the project outputs for obtaining methanol from CO_2 and H_2 on an industrial scale, especially in the last phase of R&D activities. Besides, HAYAT Kimya ensured that the first steps are taken to ensure the spread of economic CO_2 Capture and Storage (CCS) processes in Europe on an industrial scale.

4. Collaboration and coordination within the Consortium

- *All consortium*: biweekly meetings, regular phone calls, exchange of materials, consortium meetings, different countries / transnational collaboration, traffic light reports, annual reports for each country

- WP 1 and 2 worked closely together throughout the project. Materials produced in WP 1 were investigated in the gas switching reactor in WP 2; these materials were then characterized at the LESE again to better understand the performance observed. The GaSTech project was outlined to minimize the risk that deliverables could not be delivered in time. Thus, all work packages worked on the different aspects of the gas switching processes simultaneously and it was not intended that the materials developed in WP 1 and tested in WP 2 would function as input for the WP 3 (process modelling) and WP 4 (techno-economic assessment). Instead, WP 3 provided a property space based on their modelling and simulation results which the oxygen carriers would have to possess for the gas switching processes to outperform benchmark processes. Only towards the end of the project was a process developed and assessed based on the thermodynamic properties of an oxygen carrier developed in WP 1.

- WP 3 & 4: The collaboration between WP 3 & 4 was very close and effective. Proof of that is the substantial nº of publications carried out. From a management perspective, a due to the close interrelation between economic assessment and process simulation, it is recommended that in future projects the technical evaluation and design of process concepts is merged with the economic assessment in a single work package. The coordination from SINTEF was agile and effective, allowing the different partners to develop and put forth their own ideas, while providing guidance to each project member to achieve effective results. The international collaboration is a very enriching professional experience, allowing to synergistically merge the expertise from different organizations into a single outcome. Clearly, the results achieved in GaSTech would not have been possible without the diversity of “know how” across the project members.

- WP5: HAYAT Kimya collaborated with Kastamonu Entegre (KEAS), a HAYAT Holding company, throughout the project. The main biomass resource, i.e. the wood biomass, can come from KEAS, whose site is about 60 km far from the production site of HAYAT Kimya. KEAS already runs an organic rankine cycle (ORC) plant at 10 MW peak power.

5. Dissemination activities (including list of publications where applicable)

- **WP1 (Materials selection and manufacturing)**

1. F. Donat, Y. Xu, C.R. Müller, Combined Partial Oxidation of Methane to Synthesis Gas and Production of Hydrogen or Carbon Monoxide in a Fluidized Bed using Lattice Oxygen, Energy Technol. 8 (2020) 1900655. doi:10.1002/ente.201900655.
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3. F. Donat, C.R. Müller, CO2-free conversion of CH4 to syngas using chemical looping, Appl. Catal. B Environ. 278 (2020) 119328. doi:https://doi.org/10.1016/j.apcatb.2020.119328.

- **WP2 (Experimental demonstration)**

List of publications

1. Ugwu, A., F. Donat, A. Zaabout, C. Müller, K. Albertsen, S. Cloete, G. van Diest and S. Amini, *Hydrogen Production by Water Splitting using Gas Switching Technology*. Powder Technology, 2020. 370: p. 48 - 63
2. Ugwu, A., M. Osman, S. Cloete, A. Zaabout and S. Amini, *Novel Clean Energy Conversion Technologies with Integrated CO_2 capture.* in 2020 Spring Meeting & 16th Global Congress on Process Safety. 2020. AIChE.
3. Ugwu, A., A. Zaabout, and S. Amini, *An advancement in CO_2 utilization through novel gas switching dry reforming.* International Journal of Greenhouse Gas Control, 2019. 90: p. 102791.
4. Ugwu, A. Zaabout, JR. Tolchard, PI. Dahl and S. Amini, *Gas Switching reforming for syngas production with iron-based oxygen carrier-the performance under pressurized conditions.* International Journal of Hydrogen Energy, 2020. 45(2): p. 1267-1282.
5. Zaabout, A., PI. Dahl, A. Ugwu, JR. Tolchard, S. Cloete and S. Amini, *Gas Switching Reforming (GSR) for syngas production with integrated CO_2 capture using iron-based oxygen carriers*. International Journal of Greenhouse Gas Control, 2019. 81: p. 170-180.
6. Ugwu, A., A. Zaabout, SM. Nazir and S. Amini, Gas-to-liquid process for CO_2 utilization through gas switching dry reforming. *Energy and fuel*, 2020. To be submitted.
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Conference contribution

1. Ugwu, A., A. Zaabout, F. Donat, C. Müller, K. Albertsen, G. van Diest, S. Amini, *The demonstration of pressurized Gas Switching Partial Oxidation (GSPOX) of methane using Lanthanum based oxygen carrier.* 2019, Trondheim CCS Conference (TCCS 10) Trondheim.
2. Zaabout, A., A. Ugwu, F. Donat, C. Müller, K. Albertsen, G. van Diest and S. Amini, *Pressurized Gas Switching Combustion in a pre-pilot scale reactor cluster.* 2019, Fluidization XVI Conference Guilin, China.
3. Ugwu, A., F. Donat, A. Zaabout, C. Müller, K. Albertsen, S. Cloete, G. van Diest and S. Amini, *Gas Switching Water Splitting (GSWS) for efficient hydrogen production.* 2019, Fluidization XVI Conference Guilin, China.
4. Ugwu, A., M. Osman, S. Cloete, A. Zaabout and S. Amini, *Gas Switching Reforming for syngas production with iron-based oxygen carrier- The performance under pressurized conditions.* 2019, PARTEC International Congress on Particle Technology, Germany.
5. Ugwu, A. Zaabout, JR. Tolchard, PI. Dahl and S. Amini, *Pressurized Gas Switching Reforming (GSR) for syngas production with iron-based oxygen carrier*. 2018, GHGT 14 International Conference Melbourne, Australia.
6. Ugwu, A., A. Zaabout, and S. Amini, *An advancement in CO2 utilization through novel Gas Switching Dry Reforming*. 2018, 5th International Conference on Chemical Looping Park City Utah, USA
7. Ugwu, A., A. Zaabout and S. Amini, *Demonstration of Gas Switching Technology for Accelerated Scale-up of Pressurized Chemical Looping Applications (GaSTech)*. 2018, 2018 Energy Conference organized by The Research Council of Norway, Oslo.
8. Ugwu, A., A. Zaabout, F. Donat, C. Müller, K. Albertsen, and S. Amini, *Gas Switching Water Splitting (GSWS) for high-efficiency Hydrogen Production*. 2018, 25th International Conference on Chemical Reaction Engineering, Florence, Italy.
9. Ugwu, A., A. Zaabout and S. Amini, *Gas Switching Water Splitting for Efficient Carbon-Free Hydrogen Production from Natural Gas: Heat Management*. 2018, International Hydrogen and Fuel Cell Conference Trondheim, Norway.

- **WP 3 & 4 (Techno-Economic assessment)**

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2. Szima, S., S. M. Nazir, S. Cloete, S. Amini, S. Fogarasi, A.-M. Cormos and C.-C. Cormos (2019). "Gas switching reforming for flexible power and hydrogen production to balance variable renewables." *Renewable and Sustainable Energy Reviews* 110: 207-219. https://doi.org/10.1016/j.rser.2019.03.061
3. Nazir, S. M., J. H. Cloete, S. Cloete and S. Amini (2019). "Efficient hydrogen production with CO_2 capture using gas switching reforming." *Energy* 185: 372-385. https://doi.org/10.1016/j.energy.2019.07.072
4. Nazir, S. M., J. H. Cloete, S. Cloete and S. Amini (2020). "Pathways to low-cost clean hydrogen production with gas switching reforming." *International Journal of Hydrogen Energy*. https://doi.org/10.1016/j.ijhydene.2020.01.234
5. Cloete, S. Khan, M.N, Nazir, S.M, Amini, S. "Cost effective clean ammonia production using membrane assisted autothermal reforming" *Chemical Engineering Journal* Volume 404. https://doi.org/10.1016/j.cej.2020.126550
6. C. Arnaiz del Pozo, S. Cloete, J.H. Cloete, Á Jiménez Álvaro and S. Amini, "The potential of chemical looping combustion using the gas switching concept to eliminate the energy penalty of CO_2 capture" *International Journal of Greenhouse Gas Control.* 2019, vol. 83, pp. 265-281. https://doi.org/10.1016/j.ijggc.2019.01.018.
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8. C. Arnaiz del Pozo, A. Jiménez Álvaro, J.H Cloete, S. Cloete and S. Amini, "Exergy Analysis of Gas Switching Chemical Looping IGCC Plants" *Energies.* 2020, vol. 13, no. 3, pp. 544. https://doi.org/10.3390/en13030544
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13. C. Arnaiz del Pozo, S. Cloete, A. Jiménez Álvaro, F. Donat, S. Amini. "The potential of La-Fe based oxygen carriers to improve the efficiency of clean hydrogen production through gas switching partial oxidation". *International Journal of Hydrogen Energy. To be submitted.*

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3. C. Arnaiz del Pozo, A. Jiménez Álvaro, J. Rodríguez Martín, S. Sánchez Orgaz, I. López Paniagua. C. González Fernández. R. Nieto Carlier. Exergy Calculation Modelling Tool for Mixtures in Power Generation: Application to WGS and ASU units of an IGCC Power Plant with Pre-combustion CO_2 Capture. *XI Congreso Nacional y II Internacional de Ingeniería Termodinámica*. 2019. Nº ISBN: 978-84-09-11635-5.

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5. C. Arnaiz del Pozo, A. Jiménez Álvaro, J.H. Cloete, S. Cloete, S. Amini. Integration of Gas Switching Chemical Looping Technology in IGCC plants for Inherent CO_2 Capture. 14th *Conference on Sustainable Development of Energy Water and Environment Systems –SDEWES*. 2019. Nº ISBN: 1847-7186.
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