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WP N°	Del. N°	Title	Contributors	Lead beneficiary	Nature	Dissemination level	Delivery date from Annex I	Actual delivery date dd/mm/yyyy
3	3.5	Performance assessment of GSR/GSWS process	Shareq Mohd Nazir (NTNU), Schalk Cloete (SINTEF)	NTNU	R	PU	31/08/2020	31/10/2019

Summary

In the GaSTech project, NTNU has investigated two promising process configurations based on the GSR technology: A flexible combined cycle power and hydrogen production plant (GSR-CC) and a dedicated hydrogen production plant (GSR-H_2). Both plants have been designed for optimum performance via combined reactor and process simulations and published in a high-ranking journal. The optimized GSR-CC plant with more than 95% CO_2 capture incurs only a 7.2%-point efficiency penalty when compared to reference Natural Gas Combined Cycle (NGCC) power plant. This, in combination with its flexibility to produce either power or pure hydrogen, makes it a promising candidate for deployment in future energy systems with high shares of variable renewables. GSR-H2 has a specific primary energy consumption for CO_2 avoided (SPECCA) of only 0.07 MJ/kg-CO_2 when almost 90% CO_2 is avoided from the process when compared to reference steam methane reforming (SMR) plant. Without CO_2 capture, the GSR-H2 plant significantly outperforms the SMR plant. Thus, the GSR-H2 plant can first be deployed without CO_2 capture and later retrofitted for CO_2 capture when market conditions are right.

Performance assessment

Two primary GSR-based plants were designed and thoroughly assessed: the GSR-CC plant for power production and the GSR-H2 plant for hydrogen production. The GSWS process was not considered due after experiments showed that it is not a promising concept for scale-up.

Gas Switching Reforming Combined Cycle Power Plant (GSR-CC)

The schematic of the improved GSR-CC configuration is shown in Figure 1 and the main results for process performance are shown in Table 1. The results are compared against the NGCC plant without CO_2 capture.

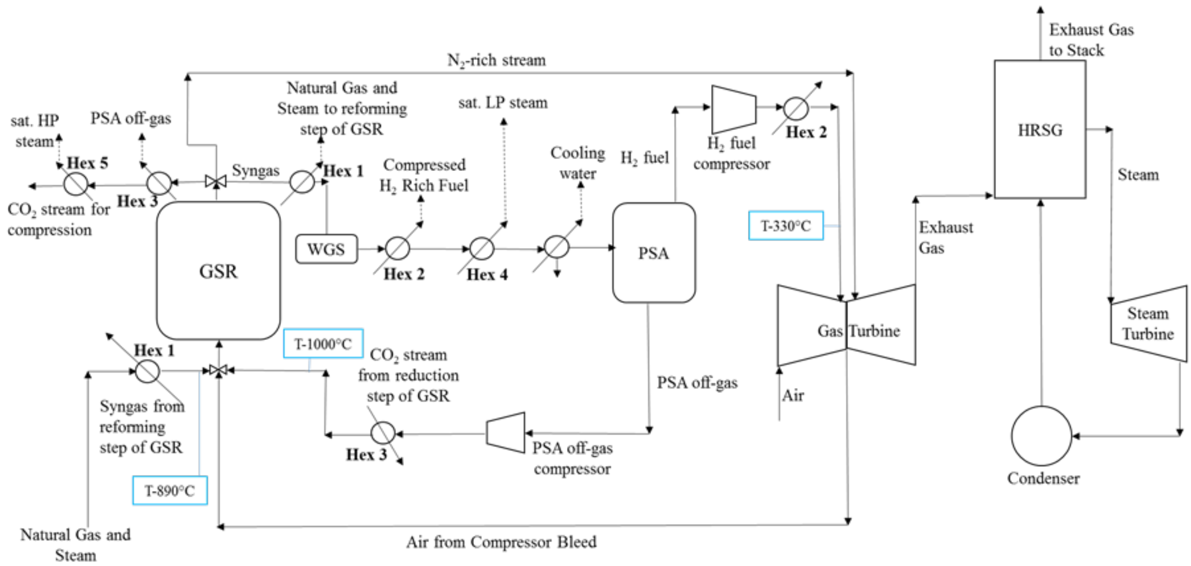

Figure 1: Schematic of improved GSR-CC plant [1]

GSR-CC shows an efficiency penalty of only 7.2 %-point when compared to reference NGCC plant with more than 95% CO_2 avoided. This outperforms post-combustion CO_2 capture systems with 7.6-8.4 %-point energy penalty and 88% CO_2 avoidance [2, 3].

Almost the entirety of the GSR-CC energy penalty is related to the conversion of NG to H_2, particularly the need to raise steam for the NG reforming reaction. Since the produced H_2 is combusted in a combined cycle, the condensation enthalpy of the resulting steam cannot be recovered, implying that all energy used to raise steam for reforming is lost for the purpose of producing useful work. In the GSR-CC plant, 298 TPH of steam needs to be raised, requiring 187 MW of heat – about 10% of LHV fuel input. If the power cycle efficiency is assumed to be 58%, this translates to a 5.8 %-points loss in net electric efficiency. Other losses include 1 %-point from CO_2 compression and 2.3 %-points from the PSA off-gas compressor, although the electrical energy input to the latter is directly integrated into the process by heating the PSA off-gas stream, meaning that the actual energy penalty is also around 1 %-point. On the positive side, the latent heat recovery from 85 TPH of steam in the CO_2 stream and 65 TPH of steam in the syngas stream via the two-phase flow heat exchangers improves the overall electrical efficiency.

Table 1: Performance assessment of GSR-CC plant [1]

Cases	Units	Ref. case (NGCC without capture)	GSR-CC
Gas Turbine	% - LHV	37.7	34.6
Steam Turbine	% - LHV	21.9	21.1
N_2-rich Stream Turbine	% - LHV	-	-
Diluent N_2 Stream Compressor	% - LHV	-	-
H_2 fuel Compressor	% - LHV	-	- 0.3
Air Compressor	% - LHV	-	-
PSA off-gas compressor	% - LHV	-	- 2.3
CO_2 Compressors and Pump	% - LHV	-	- 1.0
Auxiliaries	% - LHV	- 1.3	- 1.0
Net LHV Input to process	MW	1513	1851
Net Electrical Efficiency	% - LHV	58.3	51.1
CO_2 Avoidance	%	-	98.1
CO_2 Capture	%	-	98.7

Given that the primary added value of the GSR-CC process is in the conversion of NG to H_2 with integrated CO_2 capture and not in the conversion of the resulting H_2 to electricity, the flexibility of the process to produce either product is very important. As a power plant, it would be more efficient to use gas switching combustion (GSC) [4] to convert NG to high grade heat for power production with integrated CO_2 capture without any of the losses related to H_2 production. However, GSC also faces efficiency challenges from the maximum temperature limitation of the reactors and downstream valves, and will require additional fuel combustion after the reactors to reach the operating temperatures achievable by modern gas turbines.

Despite the efficiency penalty of H_2 production, the ability of GSR-CC to produce clean H_2 continuously and only convert this H_2 to electricity during times when the electricity price becomes high enough promises to be a major benefit in a future energy system with high shares of variable wind and solar power. In practice, the power cycle in the GSR-CC plant will operate flexibly in response to wholesale electricity price signals just like NGCC plants operate today. The primary difference is that the H_2-production train will keep on producing H_2 for export during times when the power cycle is shut down because wholesale electricity prices are too low for profitable operation.

The benefit of this flexibility was quantified techno-economically in collaboration with WP4, illustrating how it could improve the return on investment from a power plant by about 5 %-points relative to a conventional NGCC plant with post-combustion CO_2 capture [5].

Gas Switching Reforming Hydrogen Production (GSR-H2) process

The schematic of the base case GSR-H2 process is shown in Figure 2. In Table 2, the improved GSR-H2 process has additional thermal mass in the form of metal rods inside the GSR to reduce the temperature variation across the transient GSR cycle. This allowed for higher reforming temperatures, in turn allowing for high methane conversion with lower S/C ratios. The use of lower S/C ratios reduces the amount of heat required for steam production, allowing more of the heat from the reactors to be converted to valuable electricity in a gas turbine instead. As a result, Table 2 shows that the added thermal mass almost eliminated the energy penalty of the process with an insignificant SPECCA of 0.07 MJ/kg-CO_2.

The GSR-H2 process demands higher electricity imports when compared to the SMR plant, but is less dependent on steam exports. Therefore, GSR-H2 becomes less attractive when all power must be produced on site, but more attractive when steam exports are not possible. In general, it is less likely that electricity cannot be imported than that steam can be exported, mitigating this potential challenge of the GSR-H2 plant. A fully independent plant that expands all excess steam in a steam turbine and produces all power requirements onsite with a thermal efficiency of only 30% will increase the SPECCA of the GSR-H2 process to 1.15 MJ/kg-CO2 and reduce the CO_2 avoided by 6 %-points.

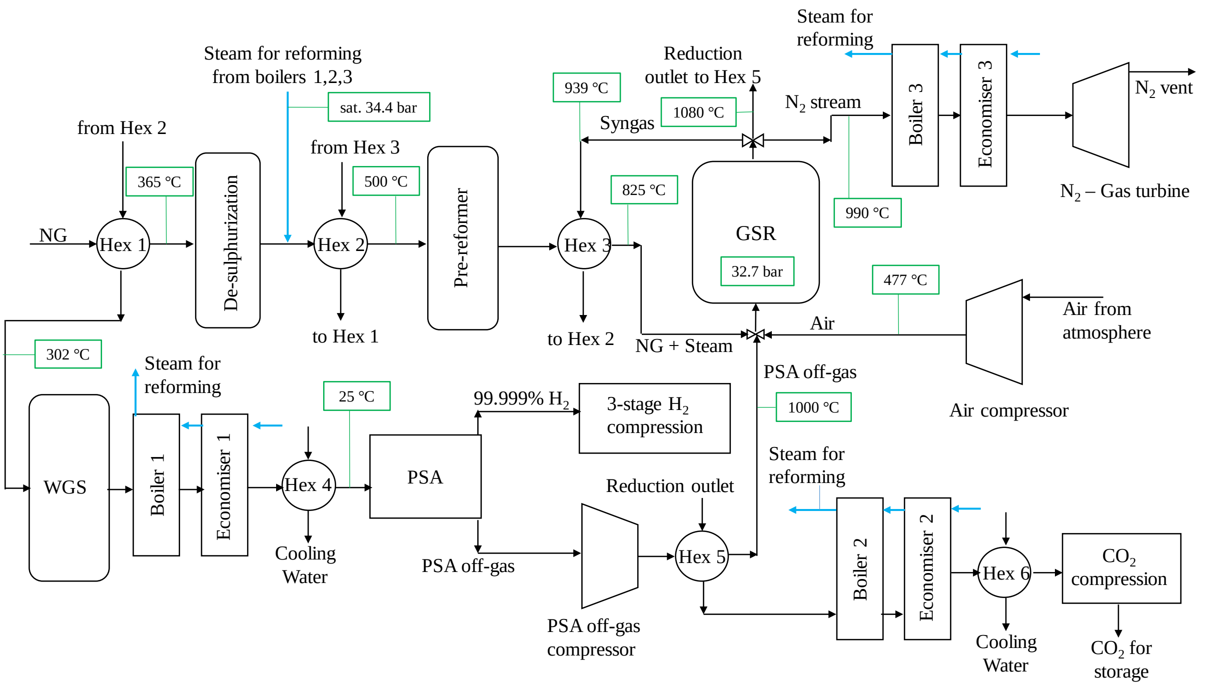

Figure 2: Base case GSR-H2 process [6]

When the CO_2 stream produced by the GSR-H2 plant is expanded and vented instead of compressed for transport and storage, the hydrogen production efficiency increases by about 3 %-points, outperforming the reference SMR plant. This presents an interesting commercialization strategy for the GSR-H2 plant: The plant can first be constructed without CO_2 capture, producing hydrogen at an efficiency significantly above that of state-of-the-art SMR plants. Later, when CO_2 prices rise and CO_2 transport and storage networks become available, this plant can be easily retrofitted to compress and store the concentrated CO_2 stream instead of expanding and venting it.

Table 2: Main results for SMR and GSR-H2 process performance [6]

Cases	Units	SMR	GSR-H2 Base case	GSR-H2 improved
$m_{eq,NG}$	TPH	9.83	11.40	10.76
Steam to Carbon ratio		2.70	2.66	1.80
H_2 produced	TPH	3.02	3.33	3.30
Hydrogen production efficiency	**%**	77.92	86.03	85.00
Equivalent H_2 production efficiency	**%**	79.28	75.45	79.01
Electricity Consumed				
Air compressor/blower	MW (MJ/kg-H_2)	0.33 (0.39)	6.78 (7.32)	6.98 (7.63)
H_2 compressors	MW (MJ/kg-H_2)	2.58 (3.08)	2.90 (3.13)	2.86 (3.13)
Pumps	MW (MJ/kg-H_2)	0.13 (0.15)	0.06 (0.07)	0.04 (0.05)
Off-gas compressor	MW (MJ/kg-H_2)		4.41 (4.76)	4.56 (4.98)
CO_2 compression	MW (MJ/kg-H_2)		0.87 (0.94)	0.81 (0.88)
Electricity Produced				
Steam Turbine	MW (MJ/kg-H_2)	2.61 (3.11)	-	-
N_2-gas turbine	MW (MJ/kg-H_2)		4.46 (4.82)	8.52 (9.31)
Net Electric Power	MW (MJ/kg-H_2)	-0.43 (-0.51)	-10.56 (-11.40)	-6.73 (-7.36)
Steam Exported (6 bar)	TPH	4.52	0.00	2.70
Q_{th}	MJ/hr	9592	0	5702
Specific CO_2 emissions	g-CO_2/MJ	72.90	2.12	2.00
Equivalent CO_2 specific emissions	g-CO_2/MJ	71.64	11.40	7.07
SPECCA	MJ/kg-CO_2		1.06	0.07
CO_2 capture ratio	**%**		96.21	96.57
CO_2 avoidance	**%**		84.35	89.75

The operating pressure is a key optimization parameter for the GSR-H2 plant. At low operating pressures, the CO_2 separation performance of the GSR reactors is high, allowing the use of shorter cycles, which result in higher reforming temperatures and the use of lower S/C ratios. At high operating pressures, on the other hand, the PSA unit becomes more efficient, allowing for less steam to be introduced to produce hydrogen in the GSR and WGS units. These two competing effects create an optimum pressure ratio as illustrated in Figure 3.

The inclusion of additional thermal mass in the reactor shifts the optimum to higher pressure ratios because the larger temperature variation across the GSR cycle at higher operating pressures is reduced by the inclusion of thermal mass.

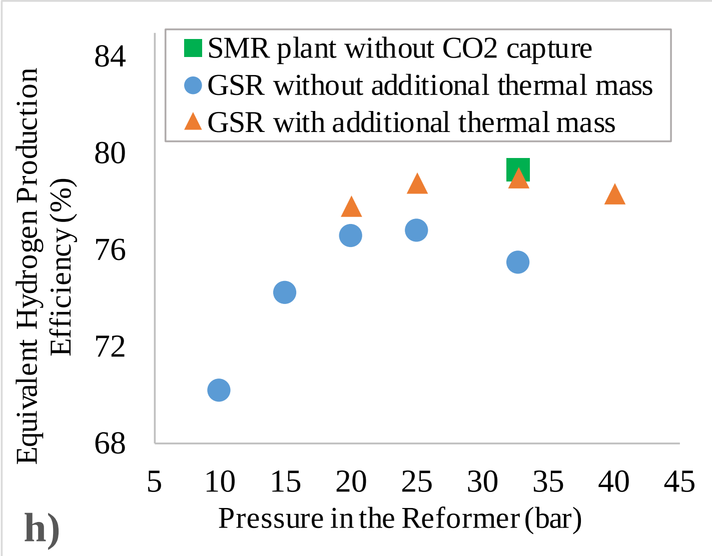

Figure 3: Equivalent hydrogen production efficiency of SMR and GSR-H2 process with and without added thermal mass over a range of operating pressures.

Conclusion

The main conclusion from this work is that the GSR concept can be deployed in two promising configurations for power and hydrogen production. The GSR-CC plant can be very attractive in a future scenario of high wind and solar market share due to its ability to flexibly produce power or clean hydrogen. In this way, the GSR-CC plant can provide flexibility to the power system without reducing the utilization factor of capital-intensive CO_2 capture, transport and storage equipment, while also providing clean hydrogen for decarbonizing sectors of the economy other than power. A dedicated GSR-H2 plant can be optimized for high efficiency to match a benchmark SMR plant. When no CO_2 is captured from the GSR-H2 plant, its efficiency becomes significantly higher than the state-of-the-art SMR benchmark. This suggests that the GSR-H2 plant can first be constructed without CO_2 capture and then easily retrofitted for CO_2 capture when market conditions are right.

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