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Novel hybrid electricity storage system producing synthetic natural gas by integrating biomass gasification with pressurized solid oxide cells

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Abstract:

A future fossil-free energy system based on intermittent renewable energy sources will require efficient and flexible large-scale electricity storage systems, as well as alternative solutions for the heating and transport sector. Electricity storage systems using reversible solid oxide cells (SOCs) have shown to be promising solutions for large-scale electricity storage, in terms of cost and efficiency. The combination of pressurized SOCs and catalytic reactors is a particularly interesting option, enabling the production of synthetic natural gas (SNG) during electrolysis mode and allowing the use of the existing natural gas infrastructures for SNG storage. In fuel cell operating mode, the natural gas is reconverted to electricity and the produced CO_2 is stored in an underground cavern for later use in electrolysis mode. Previous analysis indicate this solution can achieve roundtrip efficiencies of up to 80%. In this work, a hybrid electricity storage system using pressurized solid oxide cells and a biomass gasifier is analyzed by thermodynamic modelling. By using the syngas produced by a gasifier in both fuel cell mode and electrolysis mode, the system has the ability to produce extra SNG, which is not reused in fuel cell mode, and can be used instead for transportation or industrial processes. This also means that the operational time in electrolysis mode will be greater than the operational time in fuel cell mode, and by adjusting the size of the gasifier, the system can match the need of the electricity grid – e.g. 80% of the time in electrolysis mode and 20% of the time in fuel cell mode. Finally, it is expected that the system will operate non-stop, as it can choose to operate in part-load based on only converting the syngas to either SNG or power. Compared with the pure electricity storage system, the system design is simplified, as a pre-reformer is not needed in fuel cell mode as syngas is mixed with the SNG input. The SOC operating conditions are also improved. The results show that the overall syngas to SNG upgrading efficiency of the hybrid system is 87-88 % for different input syngas mass flows, which is higher than for syngas upgrading by hydrogen addition and methanation to SNG, which has a maximum upgrading efficiency of 78 %.

Keywords:

Biomass gasification, Energy storage system, Polygeneration, Solid-oxide electrolysis, Synthetic natural gas.

1. Introduction

Several countries aim to reduce the global greenhouse gas emissions, e.g. Denmark aims to be independent from fossil fuels by 2050. The utilization of intermittent renewable energy sources like wind and solar will increase to reach these goals. In order to balance mismatches between power supply and demand, electricity storage systems are required. The future storage need in Europe has been estimated to be 10-20 % of the annual load [1]. There are different technologies for electricity storage (ES). As of today, pumped hydroelectric storage is the only ES system fulfilling the required properties of high capacities, high efficiency and relatively low capital cost per unit of energy [2]. In recent years, a number of papers has been published emphasising the usability of reversible solid cell (ReSOC) systems for ES. It was shown that methane production within a solid oxide electrolysis cell is possible and beneficial for the efficiency of the solid oxide cell stack [3]. Experiments on the reversible operation of pressurized SOCs were conducted in [4]. An ES system based on ReSOCs, using two caverns, one to store a CO_2-H_2O-rich "exhaust gas" and on for a CH_4-H_2-CO-rich "fuel gas" was proposed in [5]. An economic analysis of the system was conducted, showing that the storage costs can be estimated to 3 ¢/(kW h), which is comparable to pumped hydroelectric storage. A new design of a large scale ES system, using pressurized ReSOCs and catalytic reactors was presented in [6]. In electrolysis mode, catalytic reactors are used after the SOEC to produce gas-grid-quality synthetic natural gas (SNG). This leads to the possibility of storing electricity in the existing gas grid. In fuel cell mode, gas is taken from the natural gas grid and oxidized in the solid oxide fuel cell (SOFC) to generate electricity. Thereby, CO_2-rich gas is produced, which is stored in a storage tank or a cavern and later used again in electrolysis mode. The round-trip efficiency is up to 80 % and is thus comparable to pumped hydroelectric storage. However, not only the electricity sector, but also the heat and transport sector will have to change in order to become fossil free. Hence, additional flexible and adaptive systems, providing heat, biofuels etc. are required to achieve an effective energy system [7]. In [8], an alternative polygeneration plant was proposed. The plant uses ambient pressure ReSOCs and biomass gasification to produce electrofuel, heat and power. When the electricity demand is low, bio-SNG is produced by generating syngas in a biomass gasifier and hydrogen in the SOEC, which react in a methane reactor, producing gas-grid quality SNG. When electricity demand is high, syngas from the biomass gasifier is used in the SOFC and an additional gas turbine or gas engine to generate electricity. Thus, the bio-SNG produced in SOEC mode is not used in SOFC mode, but can be used for transportation or industrial processes. This decouples the operating modes from each other, allowing a continuous operation of the system, depending on the demand of the electricity grid. In this paper, the design proposals of [6] and [8] have been combined. A hybrid ES system, using pressurized reversible solid oxide cells and biomass gasification was designed and evaluated by thermodynamic modelling. This system allows for storing electrical energy in the natural gas grid, by producing SNG during electrolysis mode and the reversed operation in fuel cell mode. By using the syngas produced by the gasifier in both operating modes, the system has the ability to produce additional SNG, which is not reused in fuel cell mode, but can be used in other sectors.

2. Methods

The system was modelled in the modelling tool "Dynamic Network Analysis" (DNA). DNA is a component based simulation tool for zero-dimensional thermodynamic modelling [9]. The work presented in this paper is obtained using a previous developed DNA-based ES system model [6]. The ES system model is divided into two separate models, one for the fuel cell operation mode and one for the electrolysis operating mode. The two models are connected to each other by ensuring the inlet gas composition of one mode corresponds to the outlet composition of the other mode. In the next sections, it is shown how the gasifier is connected to the system.

2.1. The system

2.1.1. Fuel cell operating mode

In fuel cell operating mode, the system converts a mixture of natural gas (NG) and syngas from a biomass gasifier to a CO_2-rich gas while generating electricity. The CO_2 rich gas is stored and used in electrolysis mode. A simplified flow sheet of the hybrid ES system in fuel cell mode is provided in Figure 1.

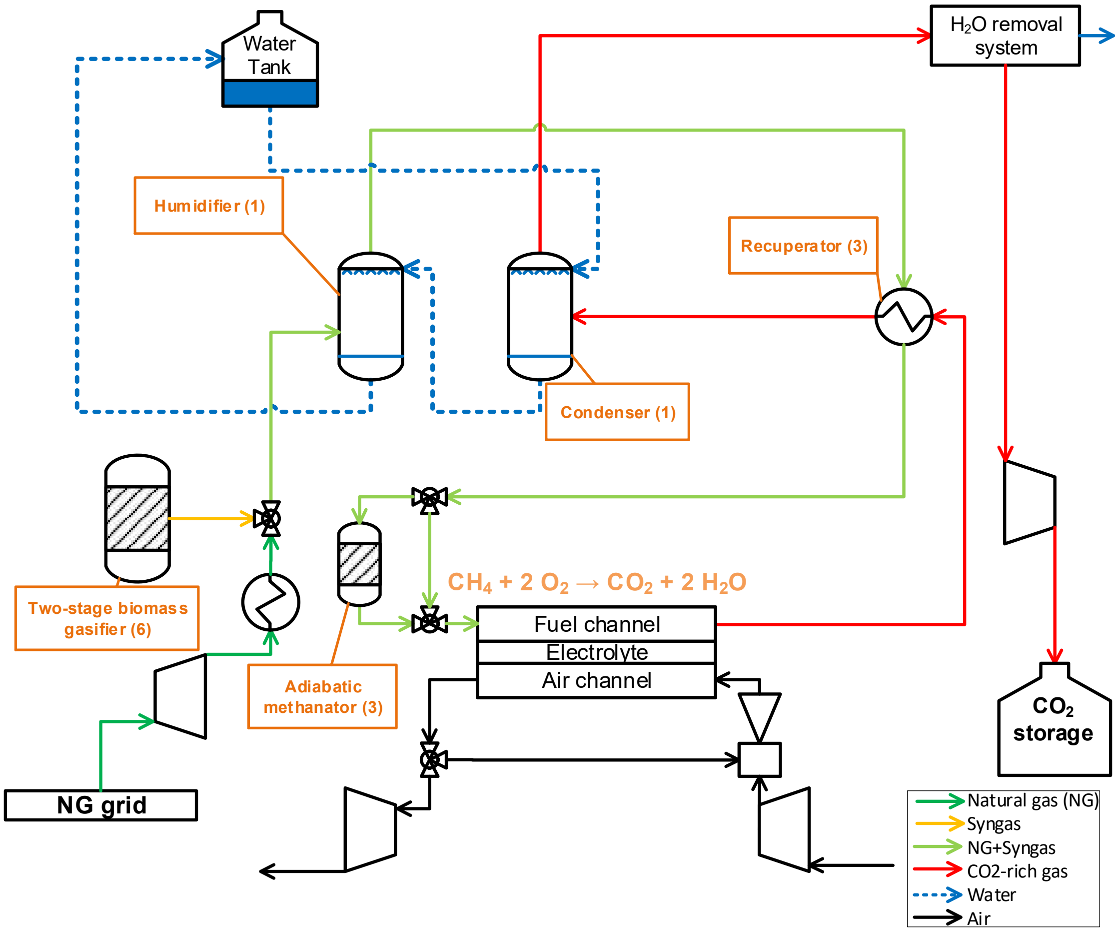

Figure 1. Simplified flowsheet of the hybrid ES system in fuel cell mode.

Starting at the bottom left of the flowsheet, NG is taken from the grid and expanded to the required pressure. NG is then mixed with the syngas coming from a two-stage biomass gasifier. The gas mixture goes to the humidifier, where the steam content is increased to the amount required by the SOFC. The humid gas mixture is preheated in a recuperator, using the hot gas coming from the SOFC. In contrast to the system presented in [6], there is no pre-reforming within the recuperator, because the syngas has a high H_2 and CO content. In most cases, the preheated gas goes directly to the SOFC, but at high syngas to NG ratios, the gas goes to an adiabatic methanator for further gas preheating, and to equilibrate the gas before the SOFC. The gas mixture is oxidized in the SOFC, while generating electricity. Compressed air is used as an oxidant. A part of the exhaust air is recycled, using an ejector. The wet CO_2-rich gas, exiting the SOFC, is then cooled in the recuperator. Subsequently most of the water vapour is condensed within the condenser unit. The condensate is reused in the humidifier. Finally, the remaining water vapour is removed through e.g. adsorption, before the CO_2- rich gas is compressed for storage in tanks or a cavern.

2.1.2. Electrolysis operating mode

In the electrolysis operating mode, electricity is used to convert the CO_2-rich gas and syngas from the biomass gasifier to synthetic natural gas (SNG), which is injected to the natural gas grid. In this mode, the SOC works as an SOEC. A simplified flow sheet of the hybrid ES system in electrolysis mode is provided in Figure 2. In [10], a more detailed description of the system, including a model for a two-stage gasifier, can be found.

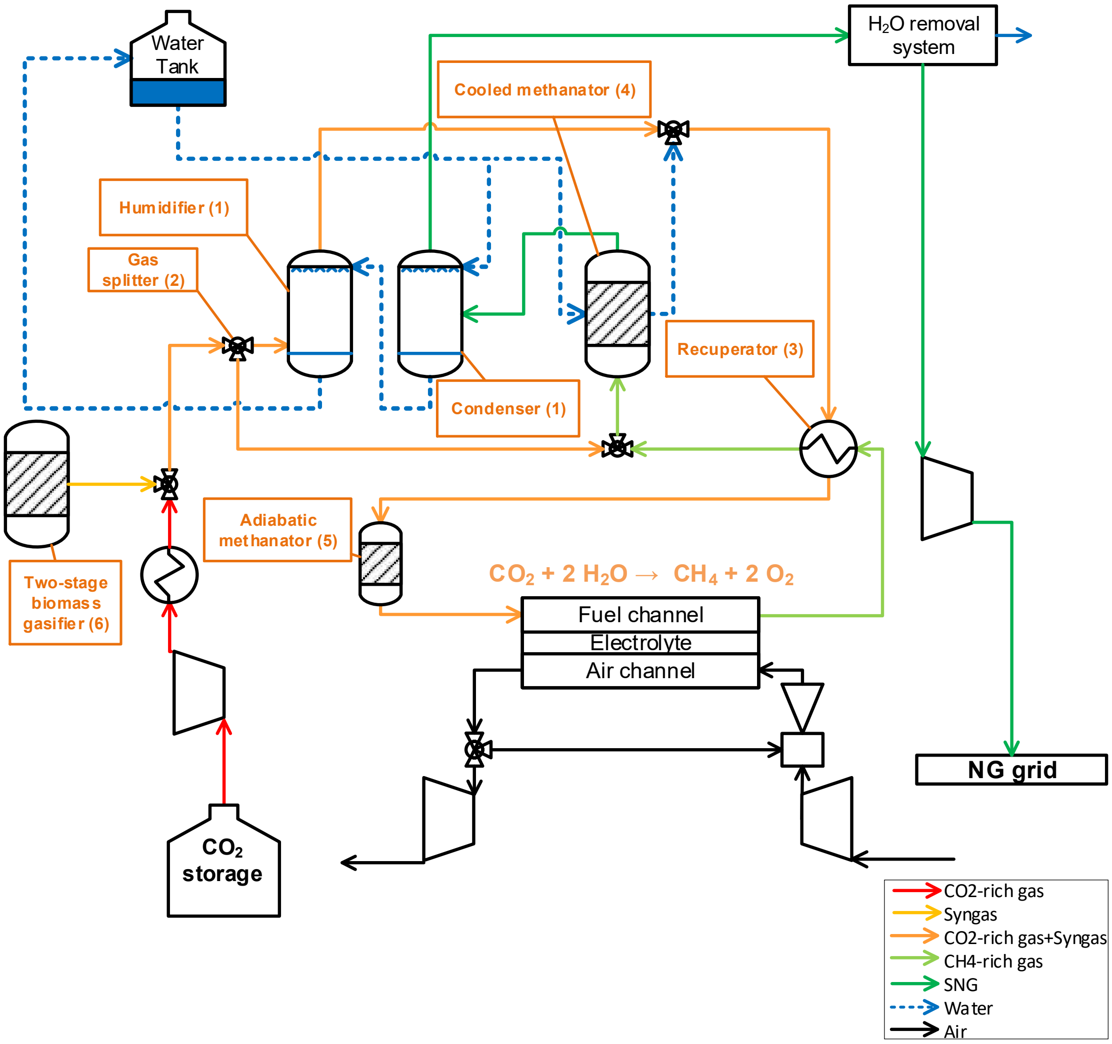

Figure 2. Simplified flowsheet of the hybrid ES system in electrolysis mode.

Starting in the lower left corner of the figure, first the CO_2-rich gas is expanded, before it is mixed with the syngas from the two-stage biomass gasifier. The gas mixture is then split into two parts. One part goes to the humidifier for increasing the steam content. The steam content is further increased with steam coming from the cooled methanator. The humid gas mixture is then preheated in the recuperator and the temperature is further increased in the adiabatic methanator, while increasing the methane content. The methane content is further increased in the SOEC, where air is used as a sweep gas to enhance the performance of the cells. The methane-rich gas is then cooled in the recuperator, and mixed with the gas coming from the upstream gas splitter. This insures the necessary amounts of CO_2, CO and H_2 for the methanation reactions in the cooled methanator, where the final methane content is achieved. The water vapour in the gas is then removed in the condenser and H_2O-removal system, before the SNG is compressed and injected to the NG grid.

2.2. Input parameters

To be consistent, most of the input parameters, or process design parameters, for the system were taken from the work presented on the pure electricity storage system [6]. The process design parameters used are listed in Table 1.

Table 1. Process design parameters used for both fuel cell and electrolysis operating mode

Active Area [m^2]	20000	$p_{SNG\text{-}injected}$[bar]	80
ASR [Ω cm^2]	0.20	$p_{discharge,\ air\text{-}turbine}$[bar]	1.1
T_{SOC} [°C]	700	Δp_{BOP} [mbar]	0
$T_{max,\ inlet,\ air}$ [°C]	650	$\Delta p_{SOC,\ fuel/air\ channel}$ [mba	30
$\Delta T_{outlets,\ Re\text{-}SOC}$ [°C]	0	$\eta_{EJECTOR}$	0.20
$\Delta T_{min,\ gas\text{-}gas}$ [°C]	30	$\eta_{compressor,\ is}$	0.88
$\Delta T_{min,\ gas\text{-}liq}$ [°C]	10	$\eta_{compressor,\ mech}$	0.98
$\Delta T_{min,\ humidifier}$ [°C]	5	$\eta_{turbine,\ is}$	0.90
$\Delta T_{min,\ condenser}$ [°C]	5	$T_{SNG\text{-}injected}$[°C]	30
p [bar]	20	$x_{H_2O,SNG\text{-}injected}$[ppm]	39
$p_{storage\text{-}exhausts}$[bar]	140	H/C ratio in SOC	6.05

A maximum temperature for the inlet air $T_{max,\ inlet,\ air}$ is set to avoid very high recycle flows via the air ejector. When the inlet fuel temperature is lower than this value, the air temperature is set equal to the inlet fuel temperature.For explanations to the other design parameters of Table 1, please see [6]. Table 2 shows the process design parameters that are only used in one of the operating modes. The H/C ratio is set equal for both operating mode, ensuring that carbon formation is avoided in both operating modes. Another important parameter is the oxygen content of the depleted air at the outlet of the air channel. This should not be below 5%, in order to avoid problems with oxygen electrode stability.

Table 2. Process design parameters used either in electrolysis mode or fuel cell mode.

Variable	Fuel cell operating mode	Electrolysis operating mode
Utilization Factor (UF)	0.73	-
i_{SOC} [A/cm^2]	0.50	-0.50
$x_{H_2O} + x_{CO_2}$ outlet	-	0.10
$T_{methanation,\ out}$ [°C]		280
$x_{O_2,min,out,air\ channel}$	0,05	-

Note: "-" means that the parameter is not an input but an output from the model.

The influence of the addition of syngas from a two-stage gasifier is investigated by varying the size of the gasifier, while the size of the SOC is kept constant. To simplify the model, the gasifier is not included as a component. Instead, the gas composition is fixed as shown in Table 3, while changing the syngas mass flow.

Table 3. Dry syngas composition from an air-blown two-stage gasifier working with a feed of wet wood chips (42.5% water) at atmospheric pressure [11]. *Note: nitrogen content is subtracted, as an oxygen-blown gasifier is assumed for the hybrid ES system.*

x_{H2} [%]	x_{CO} [%]	x_{CO2} [%]	x_{CH4} [%]
48.3	32.8	17.7	1.2

The syngas mass flow was kept constant for both operating modes, as it is desirable from both an economic as well as an operational point of view, to have the gasifier working non-stop at full load. The size of the gasifier was varied in order to achieve different operation conditions for the system. These operation conditions are:

- Inlet temperatures to the SOFC (fuel cell mode) of 600 °C, 630 °C, 650 °C, 670 °C and 700 °C

- Each mode working only with syngas as an input

2.3. Output parameters

In order to evaluate the hybrid ES system, different parameters were examined. Firstly, the capacity factor of the system was calculated for each operating mode. The capacity factor describes, how much time of a period, e.g. a year, the system works in one of the two operating modes. The capacity factor of the electrolysis operating mode τ_{EOM} and the fuel cell operating mode τ_{FCOM} can be calculated according to (1) and (2). The equations are derived from a mass balance of the storage tank or cavern of the CO_2-rich gas. Hence, the capacity factors are only dependent on the inlet mass flow rate of CO_2-rich gas in electrolysis mode $\dot{m}_{\mathrm{CO2,EOM}}$ and the outlet mass flow rate in fuel cell mode $\dot{m}_{\mathrm{CO2,FCOM}}$.

$$\tau_{\mathrm{EOM}} = \frac{\dot{m}_{\mathrm{CO2,FCOM}}}{\dot{m}_{\mathrm{CO2,EOM}} + \dot{m}_{\mathrm{CO2,FCOM}}} = \frac{t_{EOM}}{t_{EOM} + t_{FCOM}} \quad (1)$$

$$\tau_{\mathrm{FCOM}} = \frac{t_{FCOM}}{t_{EOM} + t_{FCOM}} = 1 - \tau_{\mathrm{EOM}} \quad (2)$$

The energetic evaluation is based on averaged energy flows, as the operating times in each operating mode are not equal. The chemical energy of the material streams is calculated according to (3), while the electrical energy is calculated with (4), where the subscript i denotes the different material streams, as SNG, syngas or CO_2-rich gas and OM denotes the different operating modes (FCOM or EOM).

$$\bar{\dot{E}}_{i,\mathrm{OM}} = \dot{m}_{i,\mathrm{OM}} \cdot LHV_i \cdot \tau_{\mathrm{OM}} \quad [\mathrm{kWh/h}] \quad (3)$$

$$\bar{\dot{W}}_{\mathrm{OM,net}} = \dot{W}_{\mathrm{OM,net}} \cdot \tau_{\mathrm{OM}} \quad [\mathrm{kWh/h}] \quad (4)$$

In order to evaluate the hybrid ES system, it was divided into three subsystems. This is illustrated graphically in the results section. This was done by accounting the chemical energy of the outlet gas of each operating mode, e.g. SNG in electrolysis mode and CO_2-rich gas in fuel cell mode, to the different inlet gases in each operating mode. More specifically, this was done proportional to the carbon ratios $\gamma_{i,OM}$, which describes the amount of carbon with the inlet gas i over the total amount of carbon entering the system in each operating mode.

$$\gamma_{\mathrm{i,OM}} = \frac{\dot{C}_{\mathrm{i,OM}}}{\dot{C}_{\mathrm{tot,OM}}} \quad (5)$$

Furthermore, the net electricity input or output of each operating mode were accounted to the different gas inputs.

$$\bar{\dot{W}}_{net,FCOM} = \bar{\dot{W}}_{\mathrm{NG,FCOM}} + \bar{\dot{W}}_{Syn,FCOM} \quad (6)$$

$$\bar{\dot{W}}_{net,EOM} = \bar{\dot{W}}_{CO2,stor,EOM} + \bar{\dot{W}}_{CO2,add,EOM} + \bar{\dot{W}}_{Syn,EOM} \quad (7)$$

It was then assumed that the conversion efficiency of NG from the gas grid to electricity and CO_2-rich gas in fuel cell mode (FCOM) is equal to the conversion efficiency of the system without addition of syngas from [6]:

$$\eta_{\mathrm{NG,FCOM}} = \frac{\bar{\bar{W}}_{\mathrm{NG,FCOM}}}{\bar{\bar{\dot{E}}}_{\mathrm{NG,FCOM}} - \gamma_{\mathrm{NG}} \cdot \bar{\bar{\dot{E}}}_{\mathrm{CO2,FCOM}}} = 89\ \% \tag{8}$$

In the same way, the conversion efficiency of CO_2-rich gas to SNG in electrolysis mode (EOM) is equal to the one of the system without addition of syngas:

$$\eta_{\mathrm{CO2,EOM}} = \frac{\bar{\bar{\dot{E}}}_{SNG,stor,EOM} - \gamma_{\mathrm{NG}} \cdot \bar{\bar{\dot{E}}}_{\mathrm{CO2,FCOM}}}{\bar{\bar{W}}_{CO2,stor,EOM}} = \frac{\bar{\bar{\dot{E}}}_{SNG,add,EOM} - \gamma_{\mathrm{syn}} \cdot \bar{\bar{\dot{E}}}_{\mathrm{CO2,FCOM}}}{\bar{\bar{W}}_{CO2,add,EOM}} = 89\% \tag{9}$$

The equation shows that the conversion efficiency is 89% no matter if the CO_2 originates from NG or syngas oxidation in fuel cell mode. This allows for dividing the chemical energy of the SNG, produced in EOM from CO_2-rich gas $E_{SNG,CO2,EOM}$ into two parts, one for the purpose of electricity storage $E_{SNG,stor,EOM}$, and one for additional SNG production $E_{SNG,add,EOM}$ as shown in (10). Thereby, all the SNG produced for electricity storage purposes is reused in FCOM, which is described by (11).

$$\bar{\bar{\dot{E}}}_{SNG,CO2,EOM} = \gamma_{\mathrm{CO2,EOM}} \cdot \bar{\bar{\dot{E}}}_{\mathrm{SNG,EOM}} = \bar{\bar{\dot{E}}}_{SNG,stor,EOM} + \bar{\bar{\dot{E}}}_{SNG,add,EOM} \tag{10}$$

$$\bar{\bar{\dot{E}}}_{SNG,stor,EOM} = \bar{\bar{\dot{E}}}_{\mathrm{NG,FCOM}} \tag{11}$$

With this, the efficiency of the different subsystems can be evaluated. The roundtrip efficiency η_{RT} of the energy storage subsystems is calculated with (12). From (8) and (9) it can be shown, that the roundtrip efficiency is

$$\eta_{\mathrm{RT}} = \frac{\bar{\bar{W}}_{NG,FCOM}}{\bar{\bar{W}}_{CO2,stor,EOM}} = 79\ \% \tag{12}$$

For the evaluation of upgrading systems, input-output efficiencies were used. The upgrading efficiency of the syngas upgrading subsystem was calculated with (13). The upgrading efficiency of the electricity production and syngas upgrading subsystem was calculated with (14). Note that the net electricity consumption is used in (14). The overall upgrading efficiency was calculated by combining the two.

$$\eta_{\mathrm{Up,EOM}} = \frac{\gamma_{\mathrm{Syn,EOM}} \cdot \bar{\bar{\dot{E}}}_{\mathrm{SNG,EOM}}}{\bar{\bar{W}}_{\mathrm{Syn,EOM}} + \bar{\bar{\dot{E}}}_{\mathrm{Syn,EOM}}} \tag{13}$$

$$\eta_{\mathrm{Up,FOM}} = \frac{\bar{\bar{\dot{E}}}_{SNG,add,EOM}}{\bar{\bar{W}}_{\mathrm{CO2,add,EOM}} - \bar{\bar{W}}_{\mathrm{Syn,FCOM}} + \bar{\bar{\dot{E}}}_{\mathrm{Syn,FCOM}}} \tag{14}$$

The syngas upgrading subsystems of the hybrid ES system were compared to a more common syngas upgrading system, using hydrogen produced in an SOEC and methanation reactors, presented in [12]. The upgrading efficiency of this system was calculated according to (15) to (17).

$$\eta_{\text{Up,H2}} = \frac{\gamma_{Syn,EOM} \cdot \dot{E}_{SNG,EOM}}{\dot{W}_{SOEC,H2} + \dot{E}_{Syn,EOM}} \tag{15}$$

$$\eta_{\text{SOEC,H2}} = \frac{\dot{E}_{H_2,\text{need}}}{\dot{W}_{\text{SOEC,H2}}} = \frac{\dot{n}_{H_2,\text{need}} \cdot \overline{LHV}_{H_2}}{\dot{W}_{\text{SOEC,H2}}} = 92\ \% \tag{16}$$

$$\dot{n}_{H_2,\text{need}} = 4 \cdot \dot{n}_{CO_2,\text{Syn,SOEC}} + 3 \cdot \dot{n}_{CO,\text{Syn,SOEC}} - \dot{n}_{H_2,\text{Syn,SOEC}} \tag{17}$$

3. Results

First, the influence of increasing the gasifier size (increasing syngas mass flow) on the fuel inlet temperature to the SOC in both operating modes is examined. The fuel inlet temperature is an important parameter, because high temperature gradients over the SOC induce thermo-mechanical stresses, which have a negative impact on the lifetime of the cells. Figure 3, left, shows the fuel inlet temperature for both operating modes. The data point with a syngas mass flow of zero corresponds to the pure ES system presented in [6], where a catalytic recuperator is used and an inlet temperature of 600 °C was achieved in fuel cell mode. The next data point at a mass flow of $\dot{m}_{Syn} = 2.15\ kg/s$ denotes the operation conditions where the same fuel inlet temperature is achieved with a conventional recuperator (no catalytic reactions). Further increase of the syngas mass flow leads to increasing fuel inlet temperatures in both operating modes. For all cases, the fuel inlet temperature in electrolysis mode is higher than in fuel cell mode.

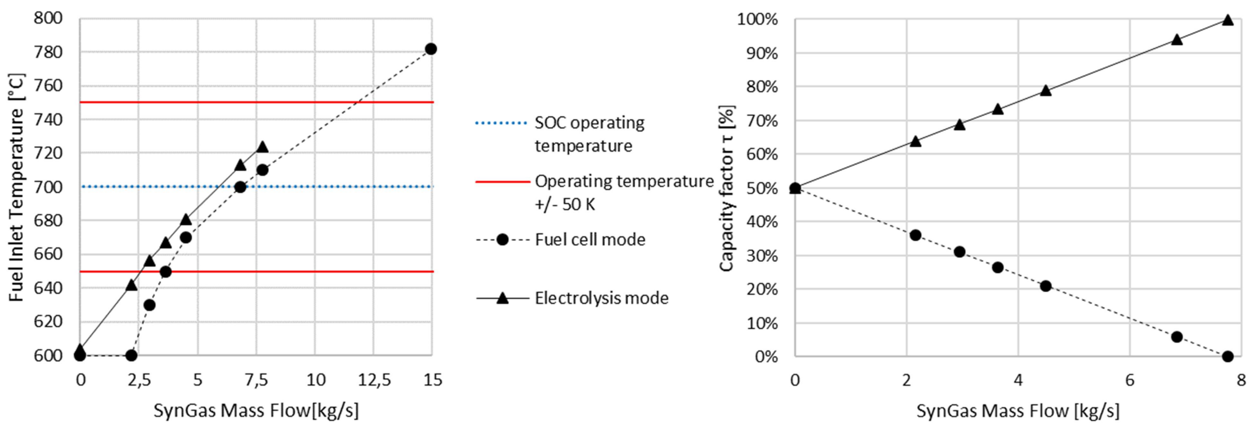

Figure 3. Left: The fuel inlet fuel temperature for different syngas mass flows for both operating modes. Right: Capacity factor for different syngas mass flows for both operating modes.

The maximum input of syngas is not the same for each operating mode. In electrolysis mode, syngas is the only carbon input to the system already at $\dot{m}_{Syn} = 7.8\ kg/s$, while for fuel cell mode, the value is 14.9 kg/s. A gasifier size corresponding to a syngas mass flow of 7.8 kg/s is therefore the maximum feasible size. The red lines denote inlet temperatures of +/- 50 K of the operating temperature of the SOC. This operating space would allow low thermo-mechanical stress on the SOC. It is achieved at a syngas mass flow higher than 3.6 kg/s. In Figure 3, right, the capacity factor of both operating modes is shown for different syngas mass flows. It shows that the capacity factor depends linearly on the syngas mass flow. Considering a syngas mass flow of 4.5 kg/s, the system would operate 20% of the time in fuel cell mode and 80% of the time in electrolysis mode. Having on-demand power production (fuel cell mode) for 20% of the time could fit well with the expected needs of a future electricity grid based on renewables such as wind and solar – also considering import and export between countries.

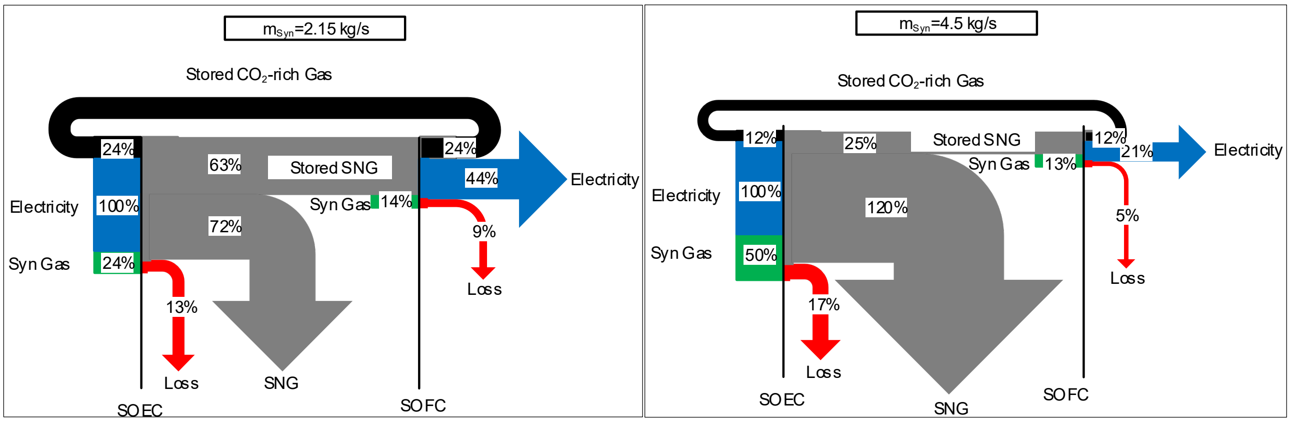

Figure 4. Electrical and chemical energy flows (LHV) and conversion losses for the hybrid ES system working with a syngas input of 2.15 kg/s (left) and 4.5 kg/s (right). Note: All flows are normalized to the net electricity input to the SOEC.

Figure 4 shows the averaged energy flows in and out of the system in both operating modes at a syngas mass flow of 4.5 kg/s, and compares it with a case where the syngas mass flow is smaller, to show how the energy flows depend on the syngas mass flow. Increasing the syngas mass flow leads to increasing net SNG production and less electricity storage.

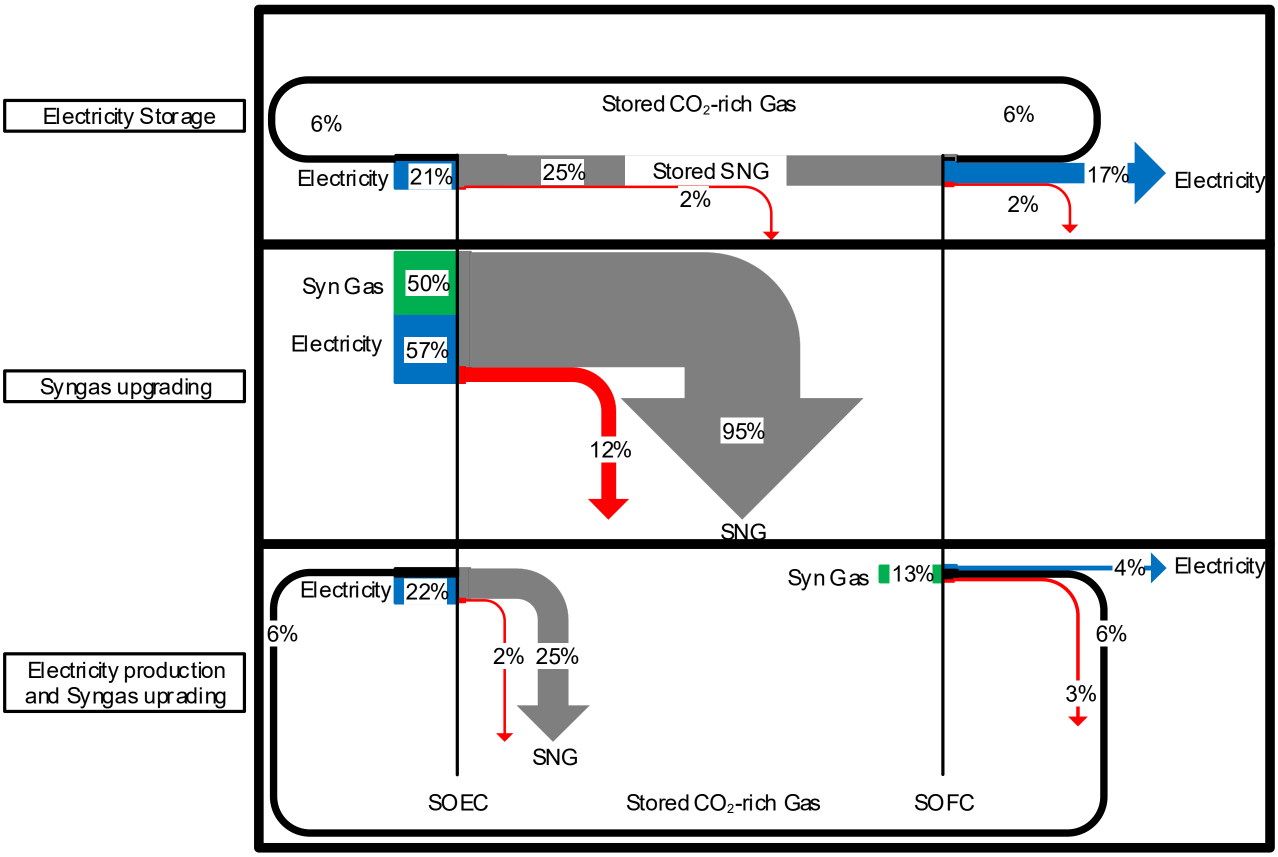

Figure 5. Detailed Sankey diagram showing all electrical and chemical energy flows (LHV) and conversion losses and the division into three subsystems for the hybrid ES system working with a syngas input of 4.5 kg/s. Note: All flows are normalized to the net electricity input to the SOEC as seen on Figure 4.

Using the methods described in section 2.3, the system was divided into three subsystems, which are depicted in Figure 5. In the electricity storage subsystem, electricity is converted to SNG, which is stored in the NG grid and later reconverted to electricity. In the syngas upgrading subsystem, syngas is directly upgraded to SNG in electrolysis mode. In the electricity production and syngas upgrading subsystem, the syngas input in fuel cell mode is first converted to electricity and CO_2-rich gas. This part of the CO_2-rich gas is then upgraded to SNG.

As the roundtrip efficiency for the electricity storage subsystem is assumed constant at 79 % for all syngas mass flows, the upgrading efficiencies of the two syngas upgrading subsystems and the entire hybrid ES system vary with increasing syngas mass flows. Figure 6, left shows how these three upgrading efficiencies depend on the syngas mass flow. Additionally, the upgrading efficiency of a syngas upgrading by hydrogen addition and methanation to SNG is depicted. It may be seen that the efficiency of the syngas upgrading subsystem has the highest efficiency, which is dropping from 90 % to 88 % with increasing syngas mass flows. The upgrading efficiency of the electricity production and syngas upgrading subsystem is nearly constant at around 82 %. The overall upgrading efficiency of the hybrid ES system increases with increasing syngas mass flows from 87 % to 88 %, reaching the efficiency of the syngas upgrading subsystem at $\dot{m}_{Syn} = 7.8\,kg/s$. This makes sense, as the system works only in electrolysis mode at this syngas mass flow.

The upgrading efficiency of the system, working by hydrogen addition and methanation is significantly lower with around 78 % for different syngas mass flows. The difference is also visible in Figure 6, right, where the normalized electricity consumption per produced unit of SNG is depicted. It can be seen that the hybrid ES system consumes 18-21 % less electricity to produce the same amount of SNG.

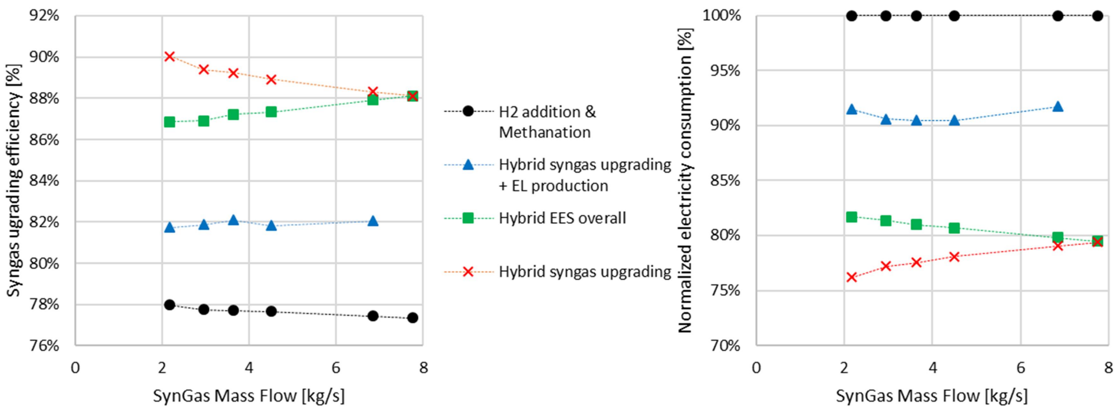

Figure 6. Left: Upgrading efficiency for the hybrid ES system and its SNG producing subsystems and the reference case. Right: the same data shown on the basis of a normalized electricity consumption.

4. Discussion

Within this work, the system was assumed to only work in two different operating modes. It could however also operate in part-load in both operating modes by only using syngas as input. In this way, part-load operation of the hybrid ES system is achieved, while having full-load operation of the gasifier. This increases the adaptability of the hybrid ES system to fluctuating electricity prices. In Figure 7, the idea of how to operate the system according to the electricity price is depicted. At very low electricity prices, the system operates in full-load electrolysis mode, using the maximum electricity input to upgrade syngas and CO_2-rich gas to SNG. In this operating mode, the system works as explained in section 2.1.2. At moderately low electricity prices, the system operates in part-load electrolysis mode, upgrading only syngas to SNG. At moderately high electricity prices, the system operates in part-load fuel cell mode, oxidizing only syngas. At high electricity prices, the system operates in full-load fuel cell mode oxidizing syngas and NG from the grid, as explained in section 2.1.1. At very high electricity prices, the electricity production could be boosted by integrating a gas turbine into the system. The CO_2-rich gas from the SOFC would be combusted together with additional NG and then expanded to atmospheric pressure. The exhaust gas of the system would then be released to the environment and not stored in the CO_2-rich gas storage.

Preliminary modelling shows that the electricity output could be doubled in the "boosted SOFC mode".

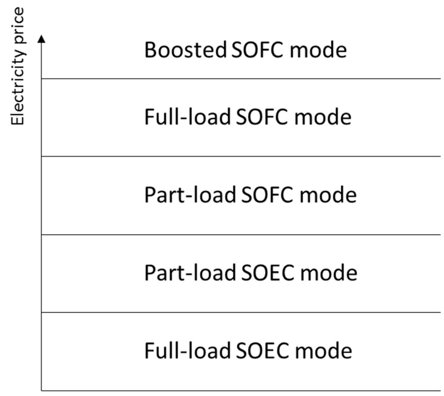

Figure 7. Operation of the hybrid ES system for different electricity prices

The economic feasibility of the system based on variable electricity prices should be assessed. This assessment should include all 5 operating modes listed in Figure 7. However, further modelling and evaluation of the part-load operating modes as well as the boosted SOFC mode should be done beforehand.

5. Conclusion

Within this work, a hybrid electricity storage system using pressurized solid oxide cells and biomass gasification was presented and analyzed by thermodynamic modelling. The addition of syngas from a biomass gasifier enables the production of surplus synthetic natural gas in addition to the electricity storage capability. The surplus SNG can be used in the transportation sector or for industrial purposes. Additionally, the introduction of the biomass gasifier means that the system will operate more in electrolysis mode than in fuel cell mode. Hence, by adjusting the size of the gasifier, the system can be adapted to the needs of the electrical grid and thereby increasing the revenue of the system. In comparison to the pure electricity storage system presented in [6], the introduction of a biomass gasifier eliminates the need for a catalytic recuperator in fuel cell mode. This reduces complexity and capital cost, and allows inlet temperatures to the SOC, which are closer to the operating temperature, reducing thermo-mechanical stresses and hence, leading to increased SOC lifetime. The evaluation of the hybrid electricity storage system showed that the overall syngas to SNG upgrading efficiency is 87-88 %, depending on the input syngas mass flow. The system was compared to a syngas upgrading system using hydrogen addition and methanation reactors, which achieves upgrading efficiencies of maximum 78 %.

Nomenclature

ASR	area specific resistance, Ω cm^2	$\dot{n}$	molar flow, mol/s
$\dot{C}$	carbon flow, mol/s	p	pressure, bar
$\dot{E}$	chemical energy flow, kW	T	temperature, °C
i	current density, A/cm^2	t	time, h
LHV	lower heating value, kJ/kg	$\dot{W}$	electrical power, kW
$\dot{m}$	mass flow rate, kg/s	x	molar fraction, %

Greek symbols

γ	carbon ratio, %	τ	capacity factor, h/h
η	energetic efficiency, %		

Subscripts and superscripts

add	additional SNG production	is	isentropic
CO_2	CO_2-rich gas	OM	operating mode
BOP	balance-of-plant	mech	mechanical
EOM	electrolysis operating mode	RT	roundtrip efficiency
FCOM	fuel cell operating mode	stor	electricity storage
H_2	hydrogen addition and methanation	Syn	Syngas
i	stream	tot	total
in	inlet	up	syngas to SNG upgrading

Abbreviations

ES	electricity storage	SOC	solid oxide cell
NG	natural gas	SOEC	solid oxide electrolysis cell
SNG	synthetic natural gas	SOFC	solid oxide fuel cell

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