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Impact of management strategy on green methane production from wind energy

Valeria Pignataro[1], *Angelica* Liponi[1], *Eleonora* Bargiacchi[2], and *Lorenzo* Ferrari[1*]

[1]University of Pisa, Dept. of Energy, Systems, Territory and Construction Engineering, Pisa, Italy
[2]Systems Analysis Unit, IMDEA Energy, 28935, Móstoles, Spain

Abstract. Mitigating the effects of global warming by reducing greenhouse gas emissions requires the adoption of sustainable practices and the promotion of renewable energies. However, in an energy scenario strongly dominated by intermittent energy sources, storage systems are becoming increasingly important. In this context, the conversion of renewable energy peaks into green hydrogen can be considered an interesting possibility. Furthermore, the use of power-to-gas systems solves, at least in a transition phase, the problems associated with the lack of infrastructure dedicated to hydrogen. In this study, a power-to-gas system producing synthetic methane from wind energy was modelled. Three management strategies were implemented and compared to assess the flexibility and versatility of the system. Results showed the importance of using an intermediate hydrogen storage tank to reduce the amount of surplus hydrogen. However, the choice of a management strategy depends on the purpose for which the power-to-methane system is designed.

1 Introduction

According to the Hydrogen Europe Roadmap, “hydrogen is the best (or only) choice for at-scale decarbonization of selected segments” [1]. This report describes an ambitious scenario for hydrogen deployment in the EU in which hydrogen could provide up to 24% of the total energy demand in the EU by 2050. In this context, the prospect of using hydrogen for the synthesis of hydrocarbons like methane in power-to-gas systems is becoming interesting. Numerous power-to-gas systems were commissioned around the world [2, 3], whose design, size, and management strategy depend on project objective and context. Gorre et al. [4, 5] analyze the impact that an intermediate hydrogen storage tank has on the performance of a power-to-gas system; also, they assert that production costs of methane are strongly influenced by the size of storage and methanation unit, but the sizing of subsystems also depends on the adopted operating strategy. Ipsakis et al. [6] develop three power management strategies for an integrated energy system producing hydrogen from renewable sources. According to this study, the choice of the optimal management strategy depends on the availability of energy from renewable energy sources (RES) and plant location. In a previous study [7], a power-to-gas system was modelled, and its dynamic behaviour was studied in

* Corresponding author: lorenzo.ferrari@unipi.it

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detail with a particular focus on the effect of the presence of a storage tank in the operational condition of the methanation unit. In this study, three management strategies (MSs) are proposed for the regulation of the operation of the methanation unit and hydrogen storage tank. The MSs are compared to identify the most influenced operational variables and to evaluate their impact on the operation of the power-to-gas system.

2 Power-to-methane system: description and modeling

The power-to-gas system is entirely modelled on Matlab. A wind farm with a nominal power of 12 MW supplies the electrolyzers of the system. The electrolysis system (ES) consists of four electrolyzers, with a nominal power of 3 MW each. The electric energy provided by the wind farm is used to start the water-splitting reaction, which produces gaseous hydrogen and oxygen.

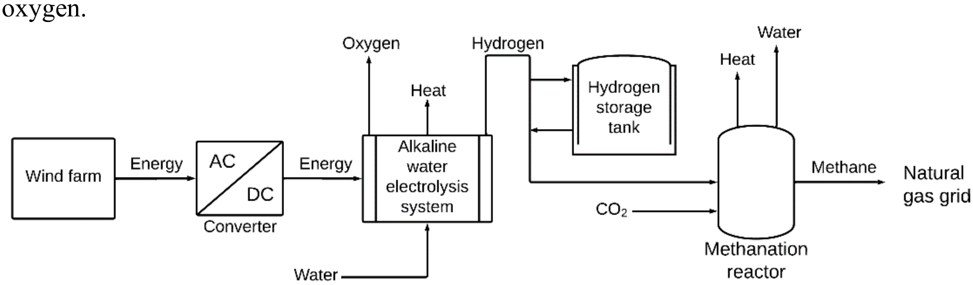

Figure 1. Power-to-methane system scheme

The produced hydrogen reacts with carbon dioxide in a catalytic methanation reactor to produce methane. Since the methanation unit's nominal feed flow rate is lower than the nominal hydrogen flow rate produced by the ES, in some hours there could be an excess of hydrogen that is stored in a hydrogen storage tank for later use. In Table 1, the operating parameters of the electrolyzer, the storage tank, and the methanation unit are given. The modeling of the main components of the system is given in the following subsections.

2.1 Alkaline electrolysers

The baseline model for the alkaline electrolyzer is a lumped parameter configuration, based on energy and mass balances with adjustable parameters [8]. A thermal model and an electrochemical model are implemented to calculate all the operating variables of the stack [7]. To mitigate the negative effect that coupling with renewable energy sources would have on the operation of the electrolyzers (e.g., frequent shutdowns and part-load operations), a management algorithm is developed, to guarantee that all the electrolyzers have comparable operating conditions while avoiding frequent shutdowns [7].

2.2 Storage tank and methanation unit

The hydrogen storage tank is considered an ideal component; in particular, it is modelled as a variable volume at constant pressure [7]. Its capacity corresponds to the amount of hydrogen that allows the methanation unit to operate continuously for two-and-a-half hours at nominal conditions. The model of the methanation unit is only based on stoichiometry [7]. The hydrogen nominal feed flow rate is 80% of the nominal hydrogen production of the ES. Some constraints are imposed on the operation of the methanation unit:

- Its permissible operative range is 40-100% of the nominal feed flow rate [4].
- Its maximum load change rate is of ±10%/min [4].

Table 1. Alkaline electrolyzer, hydrogen storage tank, and methanation unit operating parameters at nominal conditions [7].

Parameter	Unit	Value
Alkaline electrolyzer		
Stack temperature	°C	70
Stack power	MW	3
Electrolyzer efficiency	%	60
Stack pressure	bar	16
Hydrogen production	Nm^3/h	553
Specific energy consumption	kWh/Nm^3	4.45
Hydrogen storage tank		
Pressure	bar	16
Capacity	Nm^3	4,434
Methanation unit		
mol H_2: mol CO_2	-	4:1
Pressure	bar	16
Methanation efficiency at nominal conditions	%	80 [4]
Nominal hydrogen volume flow	Nm^3/h	1,770
Nominal carbon dioxide volume flow	Nm^3/h	442

3 Management strategies

Due to the variability of wind source, the hydrogen flow rate from the ES could strongly fluctuate throughout the year. In addition, the maximum hydrogen processing rate of the methanation unit is lower than the maximum production rate of the ES.

In this context, the constraints imposed on the operation of the methanation unit make it extremely difficult to ensure its continuous operations and conversion of all the produced hydrogen without any losses. Therefore, the two subsystems must be decoupled by using a hydrogen storage system. Also, an MS to regulate the hydrogen flow rate to the storage tank and the methanation unit must be implemented.

In the following sections, three MSs are proposed. The decision variables are the hydrogen flow rate provided by the ES, the state of charge (SOC) of the storage system, the state of the methanation unit at the previous timestep, and the constraints imposed on its operation. The SOC is defined as the ratio between hydrogen volume contained inside the tank at the previous timestep and its storage capacity.

$$\mathrm{SOC(t)} = \frac{V_{H_2,tank}(t-1)}{V_{H_2,tank,max}} \tag{1}$$

3.1 Management Strategy A (MSA)

MSA is the simplest of the three MSs. If the produced hydrogen is within the operating range of the methanation unit, the methanation setpoint is set equal to the incoming flow rate from the ES. If this setting does not respect the rump up or the rump down constraint, the storage tank can be used to allow continuous operations of the system; for example, if this setting does not respect the rump up constraint, the methanation setpoint is set to the value that respects the constraint and the storage tank stores excess of hydrogen. If the SOC of the storage tank is 100%, excess hydrogen from the ES is discharged. On the other hand, if the rump-down constraint is violated, the storage tank provides the necessary amount of hydrogen. If the storage tank is empty, the methanation unit shuts down, and the produced hydrogen from the ES is stored.

If the produced hydrogen is lower than the methanation unit minimum flow rate, the storage tank provides the necessary amount of hydrogen to allow continuous operations of the system. This is feasible only if the SOC of the storage tank is at least equal to an imposed minimum value (SOC_{min} = 50%) or if the methanation unit was in the "on state" at the previous timestep; otherwise, the methanation unit shuts down, and the produced hydrogen from the ES is stored. On the other hand, if the produced hydrogen is higher than the methanation unit maximum flow rate, the storage tank stores excess hydrogen. Note that the storage tank can store hydrogen until the SOC reaches 100%; then, surplus hydrogen is discarded.

3.2 Management Strategy B (MSB)

MSB is similar to MSA in its behaviour when constraints are violated. When the methanation unit operates within its load range, instead, there could be an increase or a reduction of hydrogen feed flow rate, according to the SOC of the storage tank.

If SOC > SOC_{target} (SOC_{target} = 50%), then the storage provides an additional amount of hydrogen to the methanation unit. If SOC < SOC_{target}, a part of the hydrogen produced by the ES is stored into the tank. The inlet flow rate to the methanation unit is set to:

$$\dot{m}_{met}(t) = \dot{m}_{ES}(t) + \dot{m}_{SOC}(t) \quad (2)$$

where $\dot{m}_{ES}(t)$ is the ES hydrogen production and $\dot{m}_{SOC}(t)$ depends on the SOC of the hydrogen storage tank at timestep "t-1", and it is defined as:

$$\dot{m}_{SOC}(t) = \left[\frac{(SOC(t-1) - SOC_{target})}{100}\right] \cdot \dot{m}_{ES}(t) \quad (3)$$

3.3 Management Strategy C (MSC)

MSC is similar to MSB in terms of control algorithm, but it differs in the amount of additional hydrogen provided by the storage tank during "in-range" operations of the methanation unit. While the additional term of Eq. (2) in MSB depends on the SOC of the hydrogen storage tank, in the current case it corresponds to the maximum amount of hydrogen that can be provided by the storage system.

$$\dot{m}_{met}(t) = \dot{m}_{ES}(t) + \dot{m}_{tank}(t) \quad (4)$$

When the support of the storage system is required to allow continuous operations of the system (e.g., violation of the minimum or the ramp-down constraints), the amount of hydrogen provided by the storage tank is limited to the strictly necessary value that allows continuous operations of the methanation unit.

4 Results

Annual results show that the utilization of a storage tank and the employment of an MS instead of directly converting all the hydrogen produced by the ES without any storage system in between significantly decreases the amount of surplus hydrogen. In addition, a reduction of the number of annual shutdowns, and an increase of the utilization factor of the methanation unit can be observed (see Table 2). Table 2 also reports the number of equivalent charge/discharge cycles (n_{eq}), computed as:

$$n_{eq} = \sum_{t=1}^{105119} \begin{cases} 0 & if\ \Delta SOC(t) \geq 0 \\ \frac{\Delta SOC(t)}{100} & if\ \Delta SOC(t) < 0 \end{cases} \quad (5)$$

with $\Delta SOC(t) = SOC(t+1) - SOC(t)$ and 105119 is the total number of timesteps.

As a comparison among the three management strategies, the methanation unit operation with MSA was comparable to its operation without any hydrogen storage system when constraints were respected (see Figure 2). However, using a hydrogen storage tank, surplus hydrogen can be stored and used by the methanation unit subsequently instead of being lost.

Table 2. Hydrogen storage tank and methanation unit annual performances with different management strategies.

Parameter	Unit	Value			
Management strategy	-	A	B	C	No st. tank
Methane production	Nm^3	1,541,314	1,542,389	1,553,318	1,253,340
Carbon dioxide consumption	Nm^3	2,138,123	2,139,613	2,154,774	1,738,643
Surplus hydrogen	Nm^3	159,250	154,947	110,329	1,324,880
Methanation unit utilization factor	%	40.1	40.1	40.4	32.6
Number of methanation unit shutdowns	-	352	301	964	1,006
Storage tank under the SOC target value	%	82.1	77.4	92.5	-
Eq. charge/discharge cycles (n_{eq})	-	135.6	172.4	238	-
Number of charge/discharge cycles	-	1,085	1,188	1,557	-

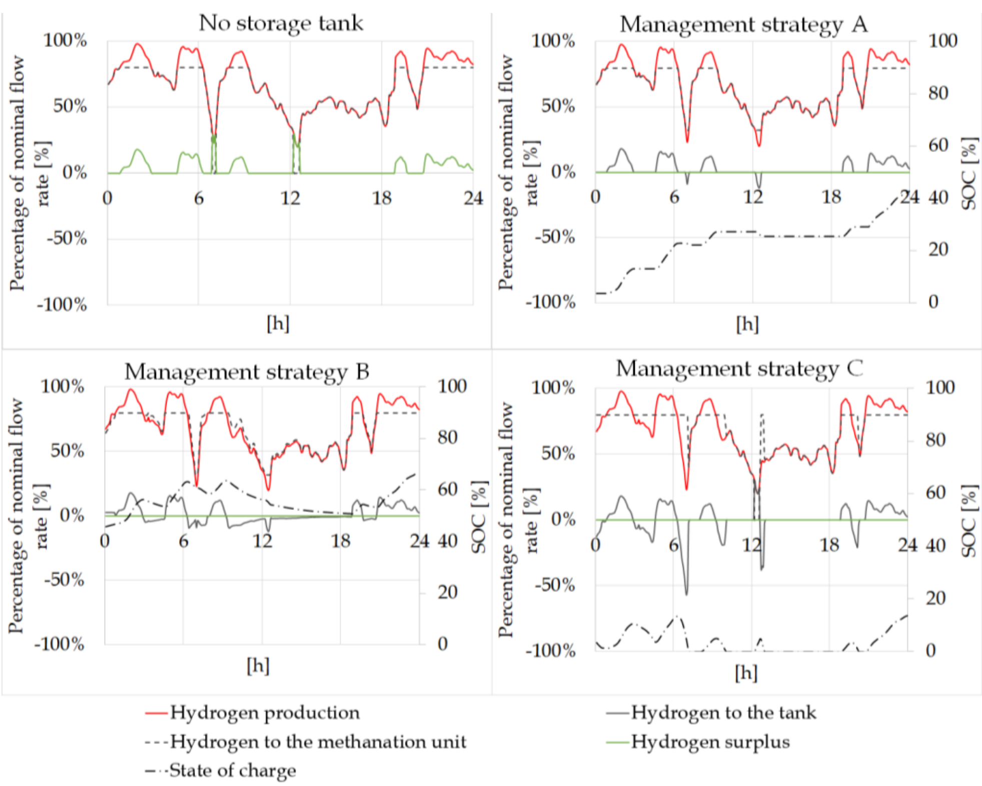

Figure 2. Methanation unit and hydrogen storage system daily operation with different management strategies.

MSB had methane production and methanation unit utilization factor comparable to those of MSA. Nevertheless, MSB had the lowest number of methanation unit shutdowns and the highest average SOC of the hydrogen storage tank (see Table 2). This happens because the setting of the incoming hydrogen flow rate to the methanation unit in MSB is based on the SOC of the hydrogen storage system.

MSC allowed for the highest hydrogen production, but it also considerably increased the number of shutdowns of the methanation unit, which could accelerate its degradation and lower its lifespan. Furthermore, SOC of the storage system remained below the target value during most of the simulations (see Table 2). Therefore, using MSC, the selected storage system resulted highly oversized. Then, this strategy allows the adoption of the smallest size of storage, with the same size of other subsystems.

5 Conclusions

In this study, three MSs for the regulation of operation of the methanation unit and the hydrogen storage tank of a power-to-methane system are proposed. As expected, integrating a hydrogen storage tank upstream of the methanation unit significantly decreases the number of shutdowns and the degradation rate of the methanation unit.

MSA and MSB were similar in terms of methane production and methanation unit utilization factor, but MSB was more effective in managing the methanation unit shutdowns while requiring a higher storage system. MSC provided the highest methane production, but also the highest number of shutdowns while requiring the smallest storage system. However, results show a low average SOC of the storage for all MSs, which suggests a non-optimal sizing of system components. Nevertheless, reducing the size of subsystems could increase the number of shutdowns. Future work should investigate the effect of sizing different subsystems on overall system performance (and, ultimately, costs). Overall, the choice of the MS depends on the purpose for which the power-to-methane system is designed and on the possibility of valorizing surplus hydrogen.

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