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Decision-making methodology for managing photovoltaic surplus electricity through Power to Gas: Combined heat and power in urban buildings

Manuel Bailera[a,*], Begoña Peña[a], Pilar Lisbona[b], Luis M. Romeo[a]

[a] Escuela de Ingeniería y Arquitectura, Universidad de Zaragoza, Campus Río Ebro, María de Luna 3, 50018 Zaragoza, Spain
[b] Escuela de Ingeniería de la Industria Forestal, Agronómica y Bioenergía, Universidad de Valladolid, Campus Duques de Soria, 42004 Soria, Spain

HIGHLIGHTS

- A new cogeneration is proposed and analyzed: PV, Power to Gas, and oxy-fuel boiler.
- A decision-making methodology is developed to manage and size the system.
- A building with 270 kW of PV installed power is analyzed under 9 energy scenarios.
- Low demands allow temporarily displacing the stored methane beyond the month.
- Synthetic methane covers 15.5–86.5% of thermal demand depending on the scenario.

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ABSTRACT

Power to Gas technology, which converts surplus electricity into synthetic methane, is a promising alternative to overcome the fluctuating behavior of renewable energies. Hybridization with oxy-fuel combustion provides the CO_2 flow required in the methanation process and allows supplying both heat and electricity, keeping the CO_2 in a closed loop. The complexity of these facilities makes their management a key factor to be economically viable. This work presents a decision-making methodology to size and manage a cogeneration system that combines solar photovoltaic, chemical storage through Power to Gas, and an oxy-fuel boiler. Up to 35 potential situations have been identified, depending on the surplus electricity, occupancy of the intermediate storages of hydrogen and synthetic methane, and thermal demand. For illustration purposes, the methodology has been applied to a case study in the building sector. Specifically, a building with 270 kW of solar photovoltaic installed power is analyzed under nine energy scenarios. The calculated capacities of electrolysis vary from 65 kW to 96 kW with operating hours between 2184 and 2475 h. The percentage of methane stored in the gas grid varies from 0.0% (no injection) to 30.9%. The more favorable scenarios are those with the lowest demands, showing temporary displacements beyond the month between injection and utilization.

1. Introduction

One of the targets of the European Union for 2020 is the achievement of a 20% of renewable energy in the overall energy mix with a 20% reduction in CO_2 emissions [1]. It is clear that renewables will continue playing a key role in helping the EU reducing pollutant emissions, increasing energy security (using renewable and autonomous energy and diversifying energy sources) and meeting its energy needs beyond 2020. According to the trends to 2050 from the “EU Reference Scenario 2016”, the share of electricity produced from renewables is expected to grow up to 37.2% by 2020, 43% by 2030, and 53% by 2050 [2].

The main barriers associated to renewable energy sources (RES) are related to the management of fluctuations due to the intermittent nature of this kind of power generation. Mainly, the mismatches between supply and electrical demand affect security and stability of the grid and represent an important barrier for the technical and economic feasibility of RES and, in consequence, for their final expansion.

The achievement of the ambitious objectives for RES and the deployment of a diversified energy system, where the energy production fits the instantaneous demand, require the proposal and development of innovative energy storage solutions. Current technologies (pumped hydroelectric storage, compressed air energy storage, flywheels and batteries) present a low energy density and/or narrow growth potential

* Corresponding author.
E-mail address: mbailera@unizar.es (M. Bailera).

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Nomenclature

Variable

A	area [m^2]
E	energy [kWh]
h	hours of operation [h]
n	mol flow [kmol/h]
P	power related to the energy contained in a flow of a chemical product [kW]
Q	thermal power [kW]
W	electric power [kW]
ε	efficiency towards thermal energy production [–]
η	efficiency towards the production of electricity or a chemical product [–]

Subscript

0	nominal operation/optimal point
100	full operation load
40	minimum operation load
ASU	air separation unit
b	buffer of hydrogen
boil	boiler
c	related to a quantity that is consumed
CH_4	methane/methanation process
CO_2	carbon dioxide
d	related to a quantity that is demanded
disc	related to a quantity that is discarded
e	electric energy
elec	electrolyzer
H_2	hydrogen/Electrolysis process
j	index to specify hour j
max	maximum value
meth	methanation
n	gas network
p	related to a quantity that is purchased
part	partial load
PV	solar photovoltaic panels
roof	roof of the building
s	surplus
t	thermal energy
year	accounting an annual period

Superscript

+	surplus
−	deficit

(hundreds of MWh) [3]. These limitations could make Power to Gas (PtG) technology one promising option to overcome these restrictions and increase reserve production ratios. Moreover, it would be very desirable for these new concepts to supply not only electricity but also heat to the final users. In these situations, the usual alternatives for energy storage do not represent a feasible solution. For cogeneration applications, PtG technology represents the only suitable option. Power stations [4], industries [5] and tertiary sector applications, as buildings [6] or transport [7], are representative examples for applying PtG concept to hybrid polygeneration systems.

Under a scenario with massive renewable generation, PtG processes appear as promising alternatives to convert electricity into synthetic natural gas (SNG, renewable methane). The features of this technology allow to chemically store, in the form of CH_4, the surplus electricity of a non-regulated generation system, while reusing CO_2 from a source of pollutant emissions. Different PtG concepts, such as hybridization with air separation plants, biogas plants, biomass gasification, sewage plants, fossil power plants or industrial processes, have been proposed to integrate the source of carbon dioxide [8]. In all cases, the utilization of the residual oxygen produced by electrolysis [9] and the energy consumption to attain a concentrated stream of CO_2 are the key points to reach a competitive technology.

The coupling of hydrogen production by electrolysis fed with RES and the Sabatier reaction (Eq. (1)) is one of the possibilities to produce synthetic methane. The reaction of hydrogen and carbon dioxide produces methane through two consecutive reactions: inverse water–gas shift reaction (Eq. (2)) and CO methanation (Eq. (3)) [10].

$$CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O \qquad \Delta H_{298K} = -164.9\ \text{kJ/mol} \tag{1}$$

$$CO_2 + H_2 \leftrightarrow CO + H_2O \qquad \Delta H_{298K} = +41.5\ \text{kJ/mol} \tag{2}$$

$$CO + 3H_2 \leftrightarrow CH_4 + H_2O \qquad \Delta H_{298K} = -206.4\ \text{kJ/mol} \tag{3}$$

Eq. (2) is an endothermic reaction that requires the presence of a catalyst to take place at low temperature, and promotes conversion to methane in Eq. (3).

Through this process, besides to store electricity surplus, the obtained SNG is nearly neutral in CO_2 emissions if RES are used. Although it has been demonstrated that CO_2 capture and utilization (CCU) is not by itself a useful technology to remarkably mitigate climate change [11], the hybridization of PtG with oxy-combustion [6,9] really avoids additional emissions in the use of natural gas by using CO_2 recycling and RES. This means an actual reduction in CO_2 emissions with respect to conventional combustion facilities.

The surplus electricity storage in the form of methane implies the connection of electric and gas networks in a single energy system introducing high flexibility in the grid balance, with the advantage of not requiring additional infrastructures. He et al. showed that wind power curtailment can be reduced a 97% thanks to Power to Gas under some scenarios [12], Li et al. found that Power to Gas is effective on improving the wind power utilization rate and contributes on the reduction of natural gas consumption [13], while McKenna et al. stated that Power to Methane is expected to be an option in the next decades on a local level due to the restrictions for injecting hydrogen into the gas network [14]. However, the smart management of the intermittent and fluctuating surplus, the variable consumption of power and heat and the storage of intermediate and final species is a very complex challenge to reach an integrated network that guarantees the stability of supply with a positive economic balance.

Smart regulation and scheduling are also crucial and complex for polygeneration systems based in the proposed combination of heat, power and SNG production (and/or even other chemicals), as all the processes are usually simultaneous and fluctuating according to the respective demand [15]. A thorough analysis must be done, as the number of operating hours could be insufficient and the feasibility studies risky. In this scenario, control strategies to manage the excess generation from RES will play an essential role in the feasibility studies of these systems.

Recent studies have presented a simplified methodology for determining the price ratio of the electrical energy sales to the purchase price of electricity to make economically attractive the hydrogen production technology applied to PtG [16]. A power management methodology based on multi-objective optimization techniques has been used in an autonomous hybrid system of RES, energy storages and energy generators in order to optimize the tilt angles of photovoltaic panels and the tower height for wind turbines [17]. Moreover, there are also some probabilistic optimal power flow models to simulate the