Renewable energy and Power-to-gas aided cogeneration for residential uses

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Abstract:

One of the most promising technologies able to manage and storage renewable energy is called Power to Gas (PtG). Power to Gas combines H_2 from electrolysis –run by renewable electricity– with CO_2 to produce synthetic CH_4. This synthetic natural gas (SNG) widens the final uses of the stored energy, potentially enabling greater reconversion efficiencies and economic profits. A suitable option to attain the required CO_2 streams is the integration with carbon capture technologies, in particular oxy-fuel combustion. During oxy-fuel combustion, a mixture of pure oxygen and flue gas is used as comburent instead of air. Thus, the large N_2 content in air is substituted by the combustion products (CO_2 and H_2O), and flue gas can achieve a high CO_2 concentration once steam is condensed. Energy penalty mainly comes from the air separation unit (ASU). Therefore, by using the oxygen from electrolysis, the electrical consumption of the ASU would be removed. The application analysed in this study is a cogeneration system that combines Power to Gas, an oxyfuel boiler and photovoltaic solar production, to be used in buildings with large roof surfaces (e.g., heated indoor pools, shopping malls). Energy efficiency of the system depends on the different cogeneration alternatives selected, on the electric and thermal demands, and on the availability of renewable energy. This paper describes the concept of Power to Gas-Oxyfuel Boiler, explains the applications and shows the energy balances of the whole system. The proper sizes of Photovoltaic Solar and PtG have also been selected as a function of the available irradiation and the profile of electricity demands (350 – 550 MWh/year) and heat (200 – 750 MWh/year).

Keywords:

Energy storage, Power to Gas, Oxyfuel combustion, Renewable energy.

1. Introduction

In Europe, 40% of the final energy demand and 36% of the total CO_2 emitted are connected to the building sector –residential and tertiary sector together [1]. Whereas the residential sector has registered a 9.52% reduction in their final energy consumption since 2000, in the tertiary sector there has been a remarkable 16.48% increase [2].

Tertiary sector has an enormous energy saving potential. Energy efficiency policies under the Energy Performance of Building Directive (EPBD) and the integration of renewable energies shall be continued in order to reach further reduction targets.

Considering that the integration of renewable energy systems in buildings has been demonstrated as a way to reduce GHG emissions, policies must be reinforced together with new technological developments supporting energy-saving strategies especially in the energy demand side. In other words, self-consumption and self-sufficiency levels can be increased by means of new energy demand strategies or energy storage.

From this point of view, solar photovoltaic systems are currently the best option to capture renewable primary energy for applications in the tertiary sector under both isolated and connected operation. Solar photovoltaic (PV) has an average annual growth rate of around 35% [3], the highest rate among the renewable technologies, and could reach the 25% of electrical generation in 2050 if it becomes economically competitive with the conventional power systems [4]. However, given the fluctuating and intermittent nature of solar energy, storage systems at short and long term must be integrated with PV to overcome these drawbacks and to increase the renewable share in electricity and heat consumption of the tertiary sector. A large number of different concepts exists for these purposes, and the most suitable technology will depend on the final application.

The novelty of the present paper is to explore the implementation of new technologies for an environmental friendly energy generation, to cover both electricity and thermal demand. The conventional options for self-consumption, based on batteries for electricity and water tanks for thermal energy, have serious limitations with respect to capacity and medium or long term storage. Hybrid PV panels are more versatile for cogeneration applications, but exhibit similar disadvantages regarding storage timing. Power to Gas (PtG) processes, based in the conversion of surpluses of electricity into gaseous fuels, are promising alternatives for energy storage at long term without capacity limits [5].

PtG technologies have in common a first stage of hydrolysis through which an electrolyser converts electricity into oxygen and hydrogen. The latter is an interesting energy carrier extensively investigated to mitigate energy and environmental problems. The feasibility of self-energy supply through the coupling of PV panels and energy storage through hydrogen production has been investigated in a few published works. On the one hand, hydrogen could be used in fuel cells to produce electricity for periods without solar production [5-7] and for mobility [8]. However, the losses of efficiency in the intermediate processes under the current state of technology make this option not competitive with respect to other alternatives such as the electric vehicle [9]. On the other hand, hydrogen could be burnt in internal combustion machines to produce heat, but its low energy density implies an important energy penalty in compression and only could be injected into the natural gas network in a volume fraction which depends on each country and is very low in general [10].

The conversion of H_2 into Synthetic Natural Gas (SNG) through a methanation process solves the drawbacks of hydrogen as final fuel, as methane does not requires any changes in current energy infrastructure nor current legislation. Methane is produced by means of the well-known Sabatier reaction (Eq. 1) from hydrogen and CO_2, previously captured or produced:

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

The global exothermic mechanism consists of two consecutive reactions, the endothermic water-gas shift (Eq. 2) and the methanation of the CO (Eq. 3), which are respectively:

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

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

As the first process (Eq. 2) requires the availability of CO_2, the present work proposes a hybrid system that combines PtG technology (i.e. electrolysis and methanation) with an oxyfuel boiler where the methane is burnt to produce heat and CO_2. This novel concept [6] has been recently evaluated in district heating sector [7], power production [8], and in an electrochemical industry [9] with promising results from the energy and emissions points of view.

The present work investigates the technical viability of the PV-PtG-oxyfuel boiler system for cogeneration under scenarios of large available area for photovoltaic panels, and different ratios of electrical/thermal demand. Sports centres are taken as application case of the tertiary sector.

Sports centres are equipped with very complex technology which causes considerable electricity consumption mainly for ventilation and electrical engineering. Furthermore, some centres are also equipped with additional energy-intensive installations such as swimming pools, saunas, solariums, wellness area, etc. resulting in a large share of the energy consumption not only for heating the water but also for space heating. Specifically, the selected case study is assumed to be placed in Zaragoza (Spain). Obviously, selected location will influence on PV evaluation.

2. PV production and energy consumptions in sports centres

The combination of photovoltaics and Power to Gas in buildings with large roof areas allows to provide electricity at the same time that surpluses are converted into methane. Thus, facilities with moderate heating demands that use natural gas boilers are potential users of this renewable cogeneration system (e.g., heated indoor pools, shopping malls, resorts). In this study we analyse the application of PtG-Oxyfuel boilers combined with PV panels at sports centres.

2.1. PV production

The available roof has been quantified by means of the Google Maps tool for several sports centres in Zaragoza (722.8 residents/km^2) [10], Spain. The sizes vary between 1300 to 3600 m^2, so we consider in our study a medium building with 2600 m^2 of roof surface. In practice, it is taken as available only the 70% of the roof for installing photovoltaic panels (i.e., 1820 m^2). Thus, the nominal power (Eq. 4) of the PV system that could be installed is 273 kW$_p$ (nominal efficiency of 15%).

$$P_{peak} = Area \cdot \eta_{nom} \qquad (4)$$

The electricity production from PV panels is quantified by using the PVGIS Tool (Photovoltaic Geographical Information System) [11], and calculations are performed for an average day of every month. The annual renewable production in the selected location and roof amounts to 433.8 MWh.

2.2. Electrical demand

In these facilities, most important electrical demands come from dehumidifiers, lighting, and pumps, followed by air conditioners, appliances and computers. The typical total electric consumption, E_d, may span in the range 300 – 700 MWh/y depending on the size of the centre [12,13]. Therefore, we propose three scenarios of electric consumption: (i) E_d is 1.2 times the PV production, (ii) E_d is 1.0 times the PV production and (iii) E_d is 0.8 times the PV production.

The monthly load curve for electricity demand is taken from an energy audit of a Spanish sports centre and then properly scaled to the electric demand scenarios (Fig. 1). A proper scaling refers to the conservation of the monthly pattern of energy distribution while accounting the electric and thermal energy demanded for each specific sports centre. The pattern shows a peak of consumption in June and July due to the cooling necessities, a stable period between October and March, and a drop for April and May. The hourly demand is simplified by considering 100% load when the centre is open, and 55% when it is closed (dehumidifiers keep working).

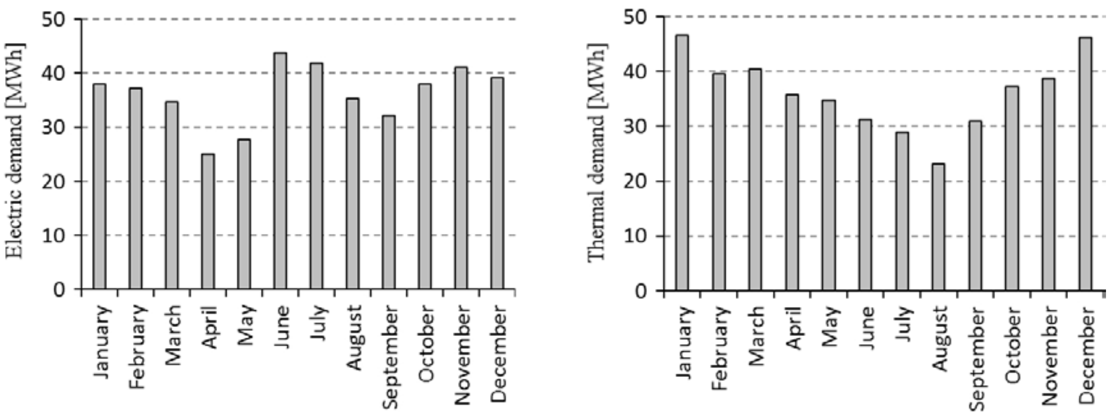

Fig. 1. Monthly electric and thermal demand for $E_d/PV=1$ and $Q_d/E_d=1$

2.3. Thermal demand

Annual thermal demands, Q_d, in sports centres are mainly for indoor pools heating purposes, as well as for producing domestic hot water and heating the building. Typical consumptions widely vary depending on the location and type of facilities (200 – 1000 MWh/y). We consider several scenarios according to the ratios: Q_d/E_d = 1.4, 1.0 and 0.6. Demand is distributed along the year following the profile shown in an energy audit of a sport centre in Zaragoza as model [13]. The load curve (Fig. 1) clearly shows a seasonal behaviour where consumption increases during the coolest months. The hourly demand is simplified by considering 100% load when the centre is open, and 70% when it is closed (pool heating keeps working). In summary, by combining the potential demands of electricity and thermal energy, a total of 9 scenarios arise (Table 1).

3. PV-PtG-Oxyfuel boiler system

The hybrid system proposed in this study to supply the energy requirements of the sport centre includes a combination of photovoltaic panels, PtG and an oxyfuel boiler. The hybridization of PtG with oxyfuel boiler produces a double positive synergy as presented in Fig. 2. On the one hand, oxyfuel boiler acts as a concentrated CO_2 source for methanation and, on the other hand, it takes advantage from the O_2 by-produced during the electrolysis stage. This oxygen serves as comburent in the boiler removing the necessity of using an air separation unit to obtain the oxygen.

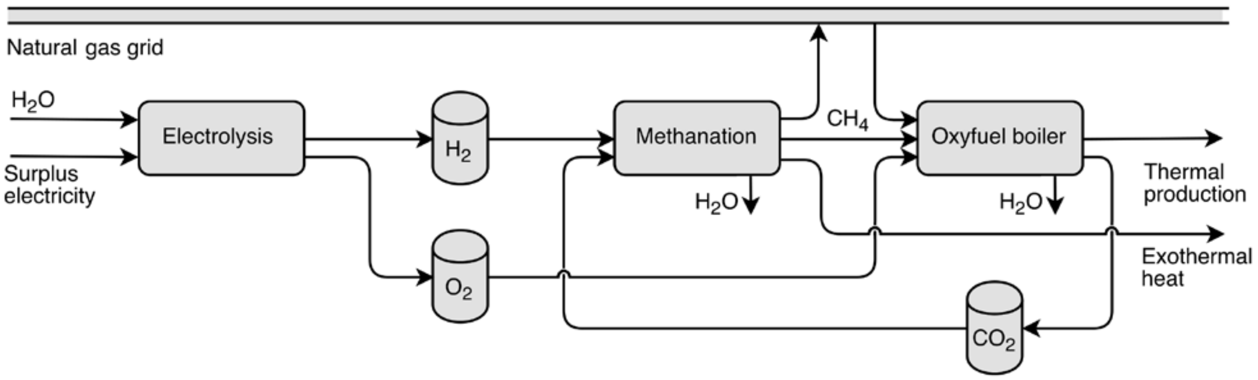

Fig. 2. PtG-Oxyfuel boiler integration scheme

Since several scenarios are studied, the PV-PtG-Oxyfuel system may represent a small share of the thermal supply. Therefore, it will be assumed that sports centres maintain their conventional air-fired boilers to support the thermal demand. Nevertheless, it will be quantified the required ASU for a hypothetic oxyfuel boiler sized to cover the whole demand (O_2 from the electrolysis would be insufficient in that cases).

Excess electricity from PV panels will be chemically stored through the Power to Gas subsystem in the form of methane. Thus, the boiler will cover part of the thermal demand of the analysed facilities together with the exothermal heat from methanation that is also directly integrated as a useful output. Whenever the methane production exceeds thermal demand, it will be injected into the gas grid to displace its consumption to other periods. Then, when recovered from the grid, natural gas will be consumed in the oxyfuel boiler whenever possible; otherwise, methane will be consumed in the air-fired boiler.

Additionally, buffers are required to manage the H_2, O_2 and CO_2 surpluses and deficiencies. Hydrogen will be a surplus when it exceeds the amount that can be treated by the methanation plant, and a lack when it is not enough to convert the CO_2 coming from the oxyfuel boiler. In the case of oxygen, it will be an excess when not all the produced methane is consumed, and a lack when synthetic natural gas is recovered from the network. Carbon dioxide will be a surplus when it is consumed more methane than can be produced, and it will be a shortage when methanation is not operated at full load although there is enough hydrogen.

The PtG-oxyfuel boiler sub-system has been modelled in Aspen Plus® under chemical equilibrium and steady state operation (Fig. 3), in order to evaluate the efficiency of the system. Combustion of SNG fuel, m_f, takes place in the boiler where the chemical equilibrium with comburent flow is reached. The sensible heat of the combustion gas, Q_b, is transferred to produce hot water. A final flue gas temperature of 270 ºC is achieved, which is used to preheat the recycled flue gas up to 180 ºC. The exhaust gas stream is partially recycled into the boiler (79%), $m_{FG,B}$, and partially fed to the methanation system (21%), $m_{FG,m}$. Comburent in the oxyfuel boiler is composed by O_2 from electrolyser, $m_{O2,ele}$, plus partially-dried flue gas.

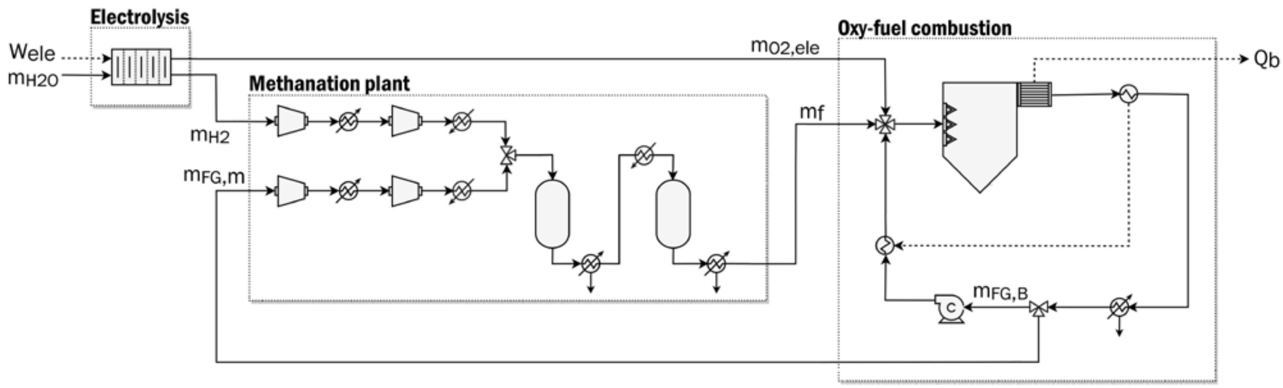

Fig. 3. PtG-Oxyfuel model

Electrolyzer unit splits water in pure oxygen and a mixture of hydrogen and water. Water conversion in this device achieves 99.9%, and the electrical consumption is set at 4.2 kWh/Nm^3H_2 [14]. These operation conditions lead to an electrolysis efficiency of 70.0% (LHV basis). Methanation stage is composed of two isothermal reactors at 10 bar and 350 ºC, with an intermediate water condenser. The final synthetic natural gas achieves a 95% of methane content. Besides, the exothermal heat from methanation is quantified as a useful output of the system.

The thermal efficiency of the methanation stage is 81.1% (energy content ratio between SNG and H_2), and the efficiency of the boiler is 85%. Moreover, the exothermal energy of the methanation reaction is integrated to produce domestic hot water (a 20% loss of the available heat is assumed).

4. Results and discussion

The previously described consumptions have been taken for typical facilities in Zaragoza (Spain), so the results of the study refer to this city. Results quantify the electricity demand that can be replaced with photovoltaic production and the existing surplus electricity for every scenario. The Power to Gas facility is properly sized to maximize the amount of surplus energy that is processed at nominal load in each case. Then, it is calculated the coverage of thermal demand supplied with the energy stored in form of methane.

4.1. Electrical production: Photovoltaics availability and PtG sizing

As stated in section 2.1, the annual renewable production amounts to 433.8 MWh. However, the surplus electricity represents up to the 43.2%, 51.4% and 60.2% of this production, for E_d equal to 1.2, 1.0, and 0.8, respectively. Besides, it can be observed that the larger solar irradiation in the summer does not significantly increase the number of hours in which solar production covers demand, but the electricity surplus (Fig. 4).

The size of the Power to Gas system is optimized by using the load duration curve (Fig. 5). The amount of electricity that is stored at nominal power is maximized with respect to the electrolysis power, in order to increase the overall efficiency of the system. Thus, the electrolysis power that best suits each scenario is 66 kW, 79 kW and 93 kW (Table 1), which allows processing 147.9 MWh/y, 185.4 MWh/y and 227.3 MWh/y. The equivalent operating hours of the electrolyser range between 2241 and 2446 hours, depending on E_d/PV ratio.

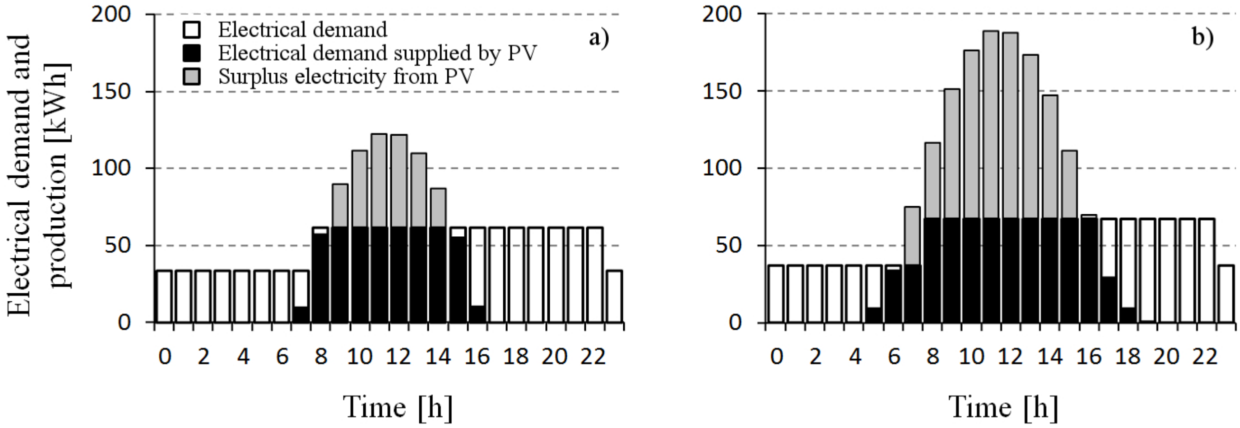

Fig. 4. Electrical demand and production for E_d/PV=1: a) January; b) July

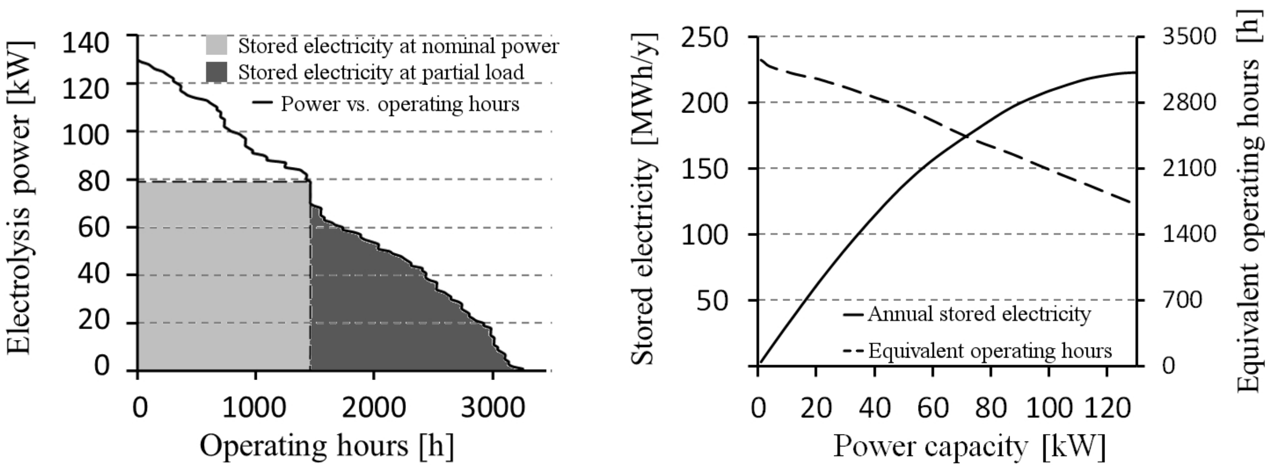

Fig. 5. Left: Sizing of the Power to Gas system (maximization of the stored electricity at nominal power); Right: Stored electricity & equivalent operating hours vs. Power capacity (E_d/PV=1)

4.2. Thermal production: PtG-Oxyfuel boiler operation based on stored surplus electricity

The processed surplus electricity is converted to methane as depicted in Fig. 2 to directly satisfy thermal demand or to store it in the gas network for a later period. The management of the PV-PtG-Oxyfuel boiler system operation follows a complex decision tree of 38 potential cases that may occur while operating the facility. The variables that are compared every hour to characterize the cases are the following:

- Amount of H_2 produced in the electrolyzer
- Amount of H_2 that is stored in the buffer
- Minimum partial load of methanation stage
- Maximum load of methanation stage
- Amount of synthetic natural gas that is stored in the network
- Producible heat by consuming the H_2 from the electrolyzer
- Producible heat by consuming the H_2 from the buffer
- Producible heat by consuming the SNG from the network
- Thermal energy demand

Up to 38 potential cases are identified, from which the most representative are the following:

- Surplus electricity production is not enough to operate the methanation plant (even using the H_2 from the buffer), while the synthetic natural gas previously stored in the network is insufficient to satisfy thermal demand.
- Surplus electricity production allows producing more H_2 than the nominal input of the methanation plant and, therefore, the excess H_2 is stored in the buffer. Besides, thermal demand does not require consuming all the SNG produced, so the remaining is injected in the gas grid.
- Surplus electricity produces less H_2 than the minimum amount required to operate the methanation plant (below minimum partial load). Nevertheless, the utilization of the H_2 coming from the buffer allows starting-up the plant and reaching the nominal load, without depleting the resource of the buffer. Moreover, the thermal energy demand is low, and part of the produced SNG can be injected into the gas grid.

The size of the methanation system is set according to the most limiting factor among the nominal H_2 production and the maximum hourly thermal demand. If the heat production that can be obtained from the nominal hydrogen generation (SNG combustion plus exothermal heat) is lower than the maximum thermal demand, then the methanation nominal input will be sized equal to the nominal H_2 production. Besides, the nominal input of the oxyfuel boiler will be the nominal production of SNG (i.e., the size of a subsystem is set by the preceding one). Conversely, if the nominal hydrogen production allows providing more thermal energy than the maximum thermal demand, the methanation will be scaled down to match producible heat and maximum demand. Otherwise, the methanation system would be oversized. In this case, the air-fired boiler loses its relevance and the oxyfuel boiler should be sized to fulfil maximum demand even when exothermal heat integration is not available (i.e., when SNG is recovered from the gas network).

Under this framework, the percentage of thermal demand that is covered by the PV-PtG-Oxyfuel boiler system ranges between 12.0% and 64.7% depending on the scenario (Table 1). However, in scenarios 1, 2 and 4, the PtG system is only acting as a conversion technology to transform surplus electricity in thermal energy, instead of taking advantage of the capability of storing electricity for long-time periods in form of methane. Similarly, in scenarios 3, 5 and 7, the amount of SNG that is stored in the gas network for its later use is negligible, with percentages lower than the 9%. Only in scenarios 6, 8 and 9, the PtG storage start making sense, with 20 – 30% of the SNG consumption displaced in time. Therefore, it is clear when comparing scenarios 3 and 8 that not only the thermal demand is important to evaluate PV-PtG-Oxyfuel systems, but also the relation between PV, E_d and Q_d.

The minimum costs associated to the air separation unit will be found in scenario 9 with the lowest investment cost - smallest size of the ASU - and the lowest yearly electricity consumption required to run ASU operation.

Regarding the buffer demand, the same trend is observed for the three gases – hydrogen, oxygen and carbon dioxide. That scenario which allows methanation reactors to operate the largest number of hours will be much more demanding of buffering capacity. Thus, scenario 9 is found to demand buffer capacities extremely higher (one order of magnitude above) when compared with the rest of scenarios. These equipment will increase the investments costs of the last scenario and, moreover, will demand the availability of free space to build the gasometers in the nearby of the sport centre which will not probably exist downtown in the city.

Other important aspect of these PV-PtG-Oxyfuel systems is the duration of the storage, i.e., for how long the stored surplus electricity is displaced. In scenario 6, the stored SNG is always consumed during the following 24 hours (Fig. 6). In the case of sport centres, this short delay between surplus energy and thermal demand could be covered by other storage technologies with lower efficiency losses and less expensive (e.g., thermal storage in hot water deposits or batteries). However, when scenario 9 is analysed, it can be seen that SNG is injected in the gas grid throughout August, and then consumed during September and October (Fig. 7). The displacement in this case is in the range of months, so the utilization of Power to Gas technology would be justified. The issue that arise in scenario 9 is the requirement of pressurized storage of oxygen and carbon dioxide. During August, great amounts of CO_2 must be consumed to produce more methane than the introduced into the boiler, while surplus O_2 has to be stored. Conversely, in September and October the stored O_2 will be consumed to operate the oxyfuel boiler since SNG is recovered from the network, and CO_2 will be an excess.

Table 1. Results of the PV-PtG-Oxyfuel boiler model for the defined scenarios

Scenario	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Ratio PV:E_d	1.0:1.2	1.0:1.2	1.0:1.2	1.0:1.0	1.0:1.0	1.0:1.0	1.0:0.8	1.0:0.8	1.0:0.8
Ratio E_d:Q_d	1.0:1.4	1.0:1.0	1.0:0.6	1.0:1.4	1.0:1.0	1.0:0.6	1.0:1.4	1.0:1.0	1.0:0.6
Electric demand (E_d) [MWh/y]	520.6	520.6	520.6	433.8	433.8	433.8	347.0	347.0	347.0
E_d covered by PV [%]	47.3	47.3	47.3	48.6	48.6	48.6	49.8	49.8	49.8
Surplus electricity from PV [MWh/y]	187.7	187.7	187.7	222.9	222.9	222.9	261.0	261.0	261.0
Electrolyser size [kW]	66.0	66.0	66.0	79.0	79.0	79.0	93.0	93.0	93.0
Electrolysis operating hours [h]	2241.4	2241.4	2241.4	2348.5	2348.5	2348.5	2445.7	2445.7	2445.7
Stored surplus electricity [%]	78.8	78.8	78.8	83.2	83.2	83.2	87.1	87.1	87.1
Methanation size (H_2 input) [kW]	46.2	46.2	46.2	55.3	55.3	50.1	65.1	65.1	40.1
Methanation operating hours [h]	2241.3	2241.3	2241.3	2348.2	2348.2	2591.4	2445.3	2445.3	3971.5
Exothermal heat [MWh/y]	16.2	16.2	16.2	20.4	20.4	20.4	25.0	25.0	25.0
Produced SNG [MWh/y]	84.0	84.0	84.0	105.3	105.3	105.3	129.1	129.1	129.1
SNG directly consumed [%]	100.0	100.0	91.4	100.0	96.8	74.1	95.6	78.5	70.7
SNG stored in the network [%]	0.0	0.0	8.6	0.0	3.2	25.9	4.4	21.5	29.3
SNG recovered from network [%]	-	-	100.0	-	100.0	100.0	100.0	100.0	100.0
to the oxyfuel boiler	-	-	99.7	-	99.1	100.0	100.0	100.0	100.0
to the air-fired boiler	-	-	0.3	-	0.9	0.0	0.0	0.0	0.0
Oxy-boiler size (CH_4 input) [kW]	37.5	37.5	37.5	44.8	44.8	49.9	52.8	52.8	39.9
Thermal demand (Q_d) [MWh/y]	728.8	520.6	312.3	607.3	433.8	260.3	485.9	347.0	208.2
Q_d covered by PtG [%]	12.0	16.8	28.0	18.1	25.3	42.2	27.7	38.8	64.7
H_2 buffer size [m^3 (NTP)]	6.1	6.1	6.1	7.3	7.3	10.4	8.7	8.7	58.4
O_2 buffer size [m^3 (NTP)]	3.1	3.1	25.2	3.6	17.4	46.3	25.9	49.1	701.0
CO_2 buffer size [m^3 (NTP)]	-	-	12.8	-	11.8	22.2	13.2	25.0	352.0
Required purchase of NG to complete demand [MWh/y]	754.4	509.4	264.4	585.3	381.1	177.0	413.2	249.8	86.5
Required ASU to run only in oxyfuel [kW]	9.2	6.5	3.9	7.6	5.4	3.3	6.1	4.4	2.6
ASU consumption to run only in oxyfuel [MWh/y]	49.4	33.4	17.3	38.4	25.0	11.6	27.1	16.4	5.7

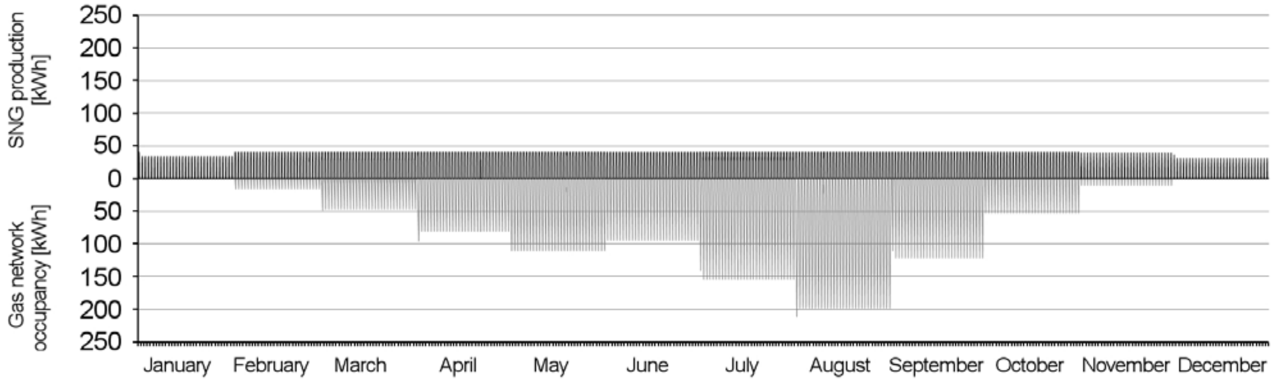

Fig. 6. SNG production and Gas network occupancy for scenario 6

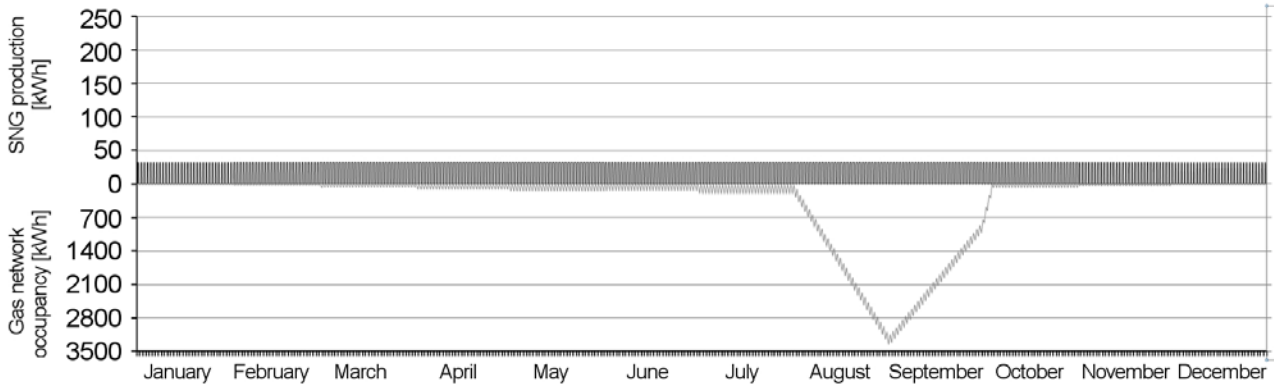

Fig. 7. SNG production and Gas network occupancy for scenario 9

5. Conclusions

The application of PtG-Oxyfuel systems in buildings of the tertiary sector that have photovoltaic panels has been proposed and analysed. The surplus electricity coming from PV is managed and stored through Power to Gas technology in the form of methane to be later used in an oxyfuel boiler and cover thermal demand. The study case has been focused in sports centres given their large roof surfaces and thermal consumptions.

Several scenarios have been proposed depending on the ratio between PV production, electricity demand and thermal demand ($PV:E_d:Q_d$). A complex decision tree of 38 potential cases was followed to characterize the operation of the system. It was found that the percentage of thermal demand covered by the PV-PtG-Oxyfuel system widely varies between 12.0% and 64.7% depending on the scenario. However, not every scenario makes the most of PtG technology in terms of storage. Only for scenarios 6, 8 and 9, the surplus energy is truly displaced to be consumed in other periods. Besides, scenarios 6 and 8 only require displacing the stored energy for time intervals below 24 hours. In these cases, economic comparisons with batteries and thermal storage technologies would determine the best option for surplus electricity management. Nevertheless, in scenario 9 the time displacement goes beyond the month range, so Power to Gas seems to be more suitable than batteries or thermal storage.

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