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Possible role of Power-to-Gas in future energy systems

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Possible role of Power-to-Gas in future energy systems

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***Abstract*—Energy storage can become increasingly important in energy systems dominated by intermittent renewable energy sources. In this paper, the possible opportunities for power-to-gas, as long-term storage option, are compared to the opportunities for short-term storage technologies. A simulation is performed to quantitatively address the difference between both storage options. In this analysis, short-term storage is characterized by a relatively high efficiency but low energy storage capacity. Power-to-gas is characterized by a lower efficiency but a higher energy storage capacity. Results indicate that power-to-gas could play a role in future energy systems with a high imposed share of renewable energy, especially when the renewable energy production profile shows a seasonal trend.**

***Index Terms*--Renewables integration, system flexibility, long-term storage, power-to-gas, synthetic methane.**

I. INTRODUCTION

The amount of installed renewable capacity has grown significantly in recent years and is expected to grow further in the future [1]-[3]. Some of these renewable energy sources (RES), e.g. wind and solar, are characterized by an intermittent nature, i.e. they are highly variable and have a limited predictability. A growing amount of RES in the electricity system therefore leads to an increasing need for flexibility.

This flexibility can be provided by different mechanisms: dynamic operation of conventional generation, extension of the electricity grid, energy storage, demand response and curtailment of the intermittent energy source [4]-[6]. It is clear that not all mechanisms are equivalent in use.

The focus of this paper is electricity storage. Many different types of storage exist, both for short and long time horizons [7]-[10]. Long-term storage is now dominated by pumped hydro [1]. In the future, power-to-gas (P2G) might become an important option [2]. P2G is a technology which uses electricity to produce gas [12]-[15]. The advantage of using P2G for long-term storage is its significantly larger energy storage potential compared to pumped hydro [3]. Next to this, the produced methane can, in first instance, be transported and stored in the existing infrastructure.

The term power-to-gas is used in the literature for both the conversion of electricity to hydrogen and the further conversion to methane. In this paper, only the process which produces methane is investigated. In this process, water is first decomposed in hydrogen and oxygen. In a consecutive step, the obtained hydrogen is used together with carbon dioxide in the Sabatier reaction[1] to produce methane. A schematic representation of the process is given in Fig. 1.

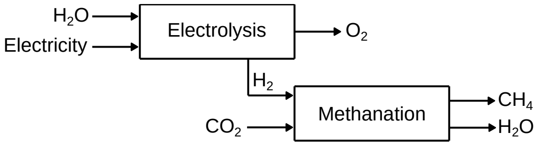

Figure 1. Main components of the P2G process.

The produced methane is often termed ‘Renewable Power Methane’ (RPM) [4]. However, the ‘renewability’ of the produced methane depends on its carbon neutrality, which depends on the system configuration of P2G, i.e. where the electricity and CO_2 comes from and where the produced methane is used.

In this regard, the goal of this paper is to address the opportunities for P2G in future energy systems. The paper starts with a general framework for P2G, to determine which system configurations are possible and to analyze when the produced methane is actually carbon neutral (section 2). In section 3, a technical overview of current P2G technologies is presented and the compatibility of P2G with a high RES/highly volatile residual load environment is determined. Finally, the possible opportunities of P2G are addressed in a quantitative way using a linear program (LP) investment model (section 4).

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[1] The Sabatier reaction is used to denote the chemical reaction in which CO_2 is hydrogenated. This reaction can occur chemically with a catalyst or biochemically with archaea. The existing literature is inconclusive whether the term Sabatier reaction should be reserved for only the catalyzed process or could be used in general. In this paper, the term Sabatier reaction is used for both the chemical and biochemical process.

II. CONCEPTUAL FRAMEWORK

Power-to-gas may be an interesting energy storage technology to cope with the situation of massive intermittent RES injection into the system. In that framework, it is instructive to investigate whether the produced methane is carbon neutral or not. To determine whether P2G is a carbon neutral technology, it is necessary to (i) define the notion carbon neutral and (ii) look at how the methane is produced.

In this paper, energy is regarded as carbon neutral if no carbon is emitted to the environment when the energy is converted from one form to another. Therefore, two conditions should be met. First, the electrical energy used in the production process needs to be carbon neutral. Second, the CO_2 produced when using the synthetic methane should be recycled to produce new methane or should be captured and stored.

An overview of the most common CO_2 sources and methane uses is given in Table I. Based on this overview, it is possible to determine whether the produced synthetic methane can be regard as carbon neutral.

TABLE I. DIFFERENT CO_2 SOURCES AND USES FOR SYNTHETIC METHANE

Possible CO2 sources	**Possible synthetic methane uses**
Carbon capture (CC)	Gas fired power plant (GFPP) + CC
Biogas	GFPP without CC
Atmosphere	Domestic heating
Industrial process + CC	Industrial process + CC
	Industrial process without CC
	Transport
	Chemical feedstock

As an example, two cases are examined and illustrated in Fig. 2. CO_2 is obtained from a carbon capture plant in both cases. In the first case, the synthetic methane is used in a gas fired power plant (GFPP) with carbon capture (CC), resulting in a closed carbon loop. In the second case, the methane is used in a GFPP without CC. As CO_2 is in this case emitted to the environment, the synthetic methane is not carbon-neutral and cannot be regarded as renewable. Only in the first case, the term renewable methane (RM) is applicable to denote the produced gas.

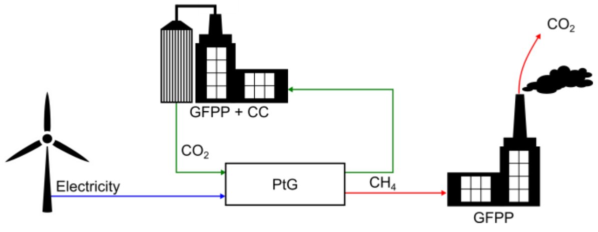

Figure 2. A renewable (closed) and non-renewable (open) methane cycle

For the quantitative analysis in section 4, only GFPP with CC are used, both as CO_2 source and as “sink” to use the produced methane. This way, the produced methane is regarded renewable and can be used to achieve possibly imposed renewable energy targets.

III. TECHNICAL PARAMETERS AND CHARACTERISTICS OF P2G

In this section, an overview of the technical parameters and characteristics of a P2G plant is given together with a range of parameter values found in the literature. The compatibility of P2G with a highly intermittent RES environment is assessed.

Fig. 1 above shows the schematic representation of a P2G plant. The electrolyzer and the methanation reactor shown on the figure are the two main components. For each component, different types exist.

Three different types of electrolyzers are considered: alkaline, Polymer Electrolyte Membrane (PEM) and Solid Oxide Electrolyzers (SOE). Although alkaline electrolyzers were predominantly used for steady state processes, many manufactures can now produce alkaline electrolyzers capable of following the volatile production profile of intermittent renewables [5]. This is due to hot start-up times of the order of seconds and almost unlimited ramping capabilities.

PEM electrolyzers have dynamic characteristics similar to alkaline. PEM electrolyzers appear to be in general slightly less efficient than alkaline but have a bigger operating range [6]. SOE are still in the research phase. Although their reported efficiencies are much higher than those of alkaline and PEM electrolyzers [7], it is yet unclear whether SOE can handle dynamic operation due to the high temperatures at which they operate, which lead to high thermal inertia.

Methanation reactors are less dynamic in operation and will therefore most likely need short-term storage (buffer) of hydrogen to have an economically optimal system configuration. The methanation reaction can take place in a catalytic or biochemical way. Many reactor designs exist for each reaction type [8]. The catalytic process is more mature and controllable, but highly sensitive to impurities in the reactant stream. Impurities form a lesser problem for biological methanation [5].

Next to the electrolyzer and reactor, a lot of auxiliary components need to facilitate the electrolysis and methanation process. A list of the auxiliary components that could be needed, is given (note that the necessary components depend on the specific P2G plant configuration):

- Power electronics for electrolyzer electricity feed-in
- H_2, CO_2, O_2 and CH_4 buffers
- H_2 and CH_4 compressor
- Heat storage tank
- Heat exchangers
- Product strippers for produced H_2, O_2 and CH_4
- H_2O and CO_2 purification unit

To model the P2G unit, it is necessary to determine its key characteristics. In Table 2, these characteristics are divided in two different groups. The first column contains the variables that are chosen when designing the plant’s electrolyzer and methanation reactor, or are determined by the energy system’s requirements. The second column contains the resulting characteristics that follow from a chosen electrolyzer, reactor and necessary auxiliary components.

TABLE 2. DESIGN AND RESULTING P2G PLANT CHARACTERISTICS

Design characteristics	Resulting characteristics
Input power	H_2 and CH_4 output stream
H_2 pressure	H_2O and CO_2 consumption
H_2 purity	Efficiency
CH_4 pressure	Minimum load
CH_4 purity	Ramp-up/down rate
Reactor temperature	Start-up/shut-down rate
	Minimum up/down time
	CAPEX
	OPEX
	Lifetime

In the next section, a P2G unit is modeled to assess the opportunities for P2G in a quantitative way. In this first simulation, only the efficiency, CAPEX, OPEX and lifetime are taken into account.

Numerical values for the necessary characteristics can be found in the literature. An overview of these values is given in Table 3. All cost values in this paper are expressed in €$_{2013}$.

An efficiency of 60% is taken as it is assumed that dynamic operation will lead to higher losses, which decreases the average efficiency compared to steady-state efficiency. A wide range of CAPEX values is found in the literature. An average value of 1500 €/kW is taken. This value results in a similar equivalent annual cost (EAC) as battery storage. The discount rate takes into account the investment risk compared to other generation and storage technologies.

TABLE 3. CHARACTERISTICS OF P2G

Characteristic	Value range	Assumed value	Source
Efficiency[a] [%]	50 - 81	60	[8],[13],[17]
CAPEX [€/kW]	750 – 2950	1500	[13],[16]-[18]
OPEX [€/kW/y]	6 – 88.5	30	[13],[18]
Lifetime [y]	12 – 30	20	[13],[16],[18]
Discount rate [%]		7.5	
EAC [€/kW/y]		177.14	

a. Electricity to methane, expressed in higher heating value

IV. ANALYSIS OF FUTURE OPPORTUNITIES

A. Model description

The model used to assess the possible role of P2G is a linear program which covers the electricity system and incorporates investment decisions. The model objective is to minimize total system cost while meeting the demand at all times and assuring an imposed minimum share of renewable end-electricity.

The total system cost is equal to the cost of all installed generation and battery storage capacity, fixed operating and maintenance cost and the cost of consumed natural gas. Renewable methane can only be produced endogenous. The cost of RM is taken into account through the installation cost of electricity generation technologies. Curtailment is free.

Electricity is generated by RES and combined cycle power plants (CCGT) fueled with renewable methane or natural gas. Electricity can be stored as RM by P2G or in batteries. The energy storage capacity for batteries is limited by their energy-to-power ratio. No energy-to-power ratio is imposed for RM storage. The electric (P2G) power capacity and methane storage capacity are not coupled and can be installed independently.

No dynamic operational constraints, electricity grids or gas grids are taken into account. The time horizon of the model is 1 year, with hourly resolution.

The Belgian electric power system is used as a test case to quantitatively address the opportunities for P2G. Demand data of the Belgian electric power system from 2013 is obtained from the Belgian transmission system operator (TSO) [9]. Renewable generation profiles are obtained separately (solar, onshore and offshore wind) from the TSO and are normalized to a maximum magnitude of 1.

The economic parameters of the RES technology are based on [10] and shown in Table 4. An economic lifetime of 20 years is used for each technology to calculate the equivalent annual cost (EAC).

TABLE 4. ECONOMIC PARAMETERS FOR RES CAPACITY

Technology	CAPX	OPEX	Discount rate	EAC
	[€/kW]	[%CAPEX/y]	[%]	[€/kW/y]
Solar	1600	1	5[b]	144.39
Offshore	4900	3.5	7.5[b]	652.15
Onshore	1700	1.5	5[b]	161.91

b. Discount rates are risk-adjusted

The technical and economic characteristics of battery and CCGT technology are listed in Table 5. The price of natural gas is taken as 30 €/MWh$_p$ [11] and is constant throughout the year. Renewable methane is assumed to be stored with existing infrastructure. Therefore, no extra gas storage cost is taken into account.

TABLE 5. CHARACTERISTICS OF BATTERY AND CCGT TECHNOLOGY

Characteristic		Battery	CCGT+CCS
Efficiency	[%]	81[c]	50[d]
CAPEX	[€/kW]	1500	1900
OPEX	[%CAPEX/y]	1	3.5
Energy-to-power ratio	[h]	7.2	-
Discount rate	[%]	5	5
Economic lifetime	[y]	12	20
EAC	[€/kW/y]	184.24	218.96
Source		[8],[22]	[21],[23]

c. Round-trip electricity to electricity
d. Including efficiency loss due to carbon capture

B. *Results and discussion*

A set of four methodological cases is composed, which differ from each other by the type of RES capacity that is allowed to be installed (i.e. onshore wind, offshore wind or solar). The fourth case allows all three types of RES to be installed. In this case, the installed RES capacities are bound by their yearly electricity production. Each RES technology has to produce an equal amount of electricity. The composed cases are purely methodological.

These four cases are used in different scenarios. For each scenario, two system boundary conditions are set. The first system boundary condition imposes a minimum renewable end-energy share (either 50% or 80%). A second boundary condition determines what type of storage can be installed. This can vary between only P2G, only batteries or both P2G and batteries.

Simulation results indicate that for scenarios with a 50% share of renewable end-energy, storage efficiency is in general more important than energy storage capacity. The first column of Table 6 shows that when 50% of the end-energy needs to be renewable and both storage technologies are allowed, battery storage is each time preferred over P2G.

When the imposed renewable share of end-energy increases, energy storage capacity becomes more important, even at the cost of efficiency loss. In these scenarios, P2G plays an important role. The last column of Table 6 shows a scenario with an imposed renewable end-energy share of 80% and both P2G and batteries as storage option. In this scenario, the energy stored as RM is always significantly higher than the energy stored in batteries.

The role of P2G is, besides by the share of renewable end-electricity, determined by the production profile of RES. When this production profile shows a seasonal trend, P2G can be a valuable storage option. The storage profile of renewable methane in case of an 80% renewable share in end-energy and storage by both batteries and P2G is shown in Fig. 3. When only solar capacity is installed, energy from solar power is stored between 2500h and 6000h, roughly from April until the end of August, and is used during the other part of the year. The necessary energy storage capacity is in this case significantly larger than for cases with RES not showing a seasonal production trend.

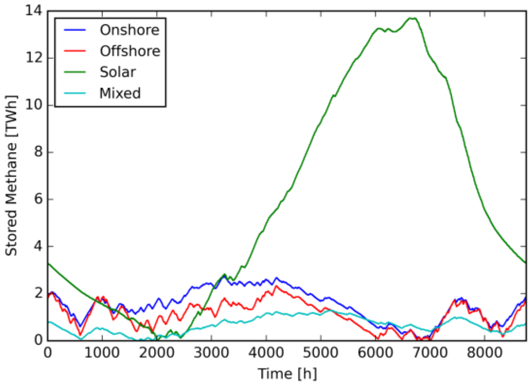

Figure 3. RM storage for different cases, 80% end-energy is renewable and both P2G and battery storage are allowed.

TABLE 6. SIMULATION RESULTS FOR DIFFERENT SCENARIOS: INSTALLED CAPACITIES, AMOUNTS OF ENERGY STORAGE AND AVERAGE END-ELECTRICITY COST (AEEC)

Storage technology	**Both**	**P2G**	**Battery**	**Both**
	50%	***80%***	***80%***	***80%***
		Onshore		
Onshore cap [GW$_e$]	22.88	49.74	57.72	48.48
P2G cap [GW$_e$]	0.00	7.94	-	6.94
RM produced [TWh$_p$]	0.00	14.14	-	12.06
Gas Storage [TWh$_p$]	0.00	3.48	-	2.76
Battery cap [GW$_e$]	1.73	-	8.22	2.30
AEEC [€/MWh$_e$]	108.43	161.59	169.33	155.70
		Offshore		
Offshore cap [GW$_e$]	12.27	26.60	27.14	24.44
P2G cap [GW$_e$]	0.00	14.15	-	9.85
RM produced [TWh$_p$]	0.00	22.37	-	14.96
Gas Storage [TWh$_p$]	0.00	2.11	-	2.33
Battery cap [GW$_e$]	2.28	-	32.38	8.91
AEEC [€/MWh$_e$]	164.60	292.88	325.79	277.13
		Solar		
Solar cap [GW$_e$]	51.47	155.91	163.43	104.62
P2G cap [GW$_e$]	0.00	59.22	-	11.33
RM produced [TWh$_p$]	0.00	61.19	-	15.61
Gas Storage [TWh$_p$]	0.00	17.90	-	13.70
Battery cap [GW$_e$]	13.87	-	35.05	26.10
AEEC [€/MWh$_e$]	182.47	457.79	409.18	310.31
		Mixed		
Onshore cap [GW$_e$]	6.80	13.98	13.30	12.50
Offshore cap [GW$_e$]	4.06	8.34	7.93	7.45
Solar cap [GW$_e$]	14.33	29.49	28.05	26.36
P2G cap [GW$_e$]	0.00	7.81	-	3.38
RM produced [TWh$_p$]	0.00	12.89	-	5.33
Gas Storage [TWh$_p$]	0.00	0.87	-	1.29
Battery cap [GW$_e$]	1.53	-	9.72	6.96
AEEC [€/MWh$_e$]	135.57	211.26	198.95	193.00

The storage profile of a scenario with 80% renewable end-electricity when only solar capacity is installed, is shown in Fig. 4. The figure shows a detailed RM and battery storage profile of one week in April. The battery storage displays a daily charge and discharge profile while the RM storage is filled monotonous during this week. This illustrates the role of long-term storage for P2G and the role of short-term storage for batteries (or other technologies with a limited energy storage capacity).

In all scenarios, the total amount of RM produced is an order of magnitude lower than the total yearly gas use in Belgium (~184 TWh$_p$ [12]). When a high share of renewable energy is imposed and only P2G is allowed as storage option, the amount of produced RM is high as P2G is used for both short and long-term storage.

The available gas storage capacity in Belgium (8.4 TWh_p [12]) is generally sufficient for RM storage. In the scenario with a seasonal RES production profile and high imposed shares of renewable end-energy, the necessary energy storage capacity becomes larger than the current available capacity in Belgium.

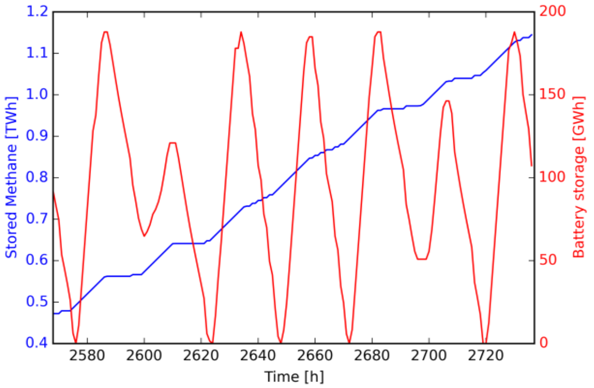

Figure 4. Detailed storage profile of P2G and batteries, 80% end-energy is renewable and both P2G and battery storage are allowed.

V. CONCLUSIONS

Synthetic methane is only regarded as renewable when two conditions are fulfilled. First, the electricity used in the production process should be carbon neutral. Second, the CO_2 produced when using the synthetic methane should be recycled to produce new methane or should be captured and stored.

The overview of technical P2G parameters and discussion of its dynamic characteristics indicate that P2G technology is compatible with a highly volatile residual load environment. Therefore, P2G can be used as storage technology in a future energy system dominated by intermittent RES.

A quantitative analysis is made to assess the difference in possible opportunities for short-term storage and P2G as long-term storage option. Short-term storage is characterized by a relatively high efficiency but a limited energy storage capacity. P2G is characterized by a lower efficiency but a higher energy storage capacity. Simulation results indicate that P2G can play a significant role in scenarios with a high imposed share of renewable end-energy. When the RES production profile shows a seasonal trend (such as solar dominated RES systems), P2G becomes more important as the necessary energy storage capacity increases.

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