



Calculation and analysis of efficiencies and annual performances of Power-to-Gas systems



Elimar Frank, Jachin Gorre*, Fabian Ruoss, Markus J. Friedl

University of Applied Science Rapperswil, Institute for Energy Technology, Oberseestrasse 10, CH-8640 Rapperswil, Switzerland

HIGHLIGHTS

- Comprehensive, universal and unambiguous approach to evaluate the efficiency.
- The approach allows any plant configuration.
- The unambiguous assignment of the efficiency to a system boundary makes comparability easier.
- The plant can be characterized with an annual performance over one year and not with one operating point.

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ABSTRACT

This paper describes a generic and systematic method to calculate the efficiency and the annual performance for Power-to-Gas (PtG) systems. This approach gives the basis to analytically compare different PtG systems using different technologies under different boundary conditions. To have a comparable basis for efficiency calculations, a structured break down of the PtG system is done. Until now, there has not been a universal approach for efficiency calculations. This has resulted in a wide variety of efficiency calculations used in feasibility studies and for business-case calculations. For this, the PtG system is divided in two sub-systems: the electrolysis and the methanation. Each of the two sub-systems consists of several subsystem boundary levels. Starting from the main unit, i.e. the electrolysis stack and/or methanation reactor, further units that are required to operate complete PtG system are considered with their respective subsystem boundary conditions.

The paper provides formulas how the efficiency of each level can be calculated and how efficiency deviations can be integrated which are caused by the extended energy flow calculations to and from energy users and thermal losses. By this, a sensitivity analysis of the sub-systems can be gained and comprehensive goal functions for optimizations can be defined.

In a second step the annual performance of the system is calculated as the ratio of useable output and energetic input over one year. The input is the integral of the annual need of electrical and thermal energy of a PtG system, depending on the different operation states of the plant. The output is the higher heating value of the produced gas and – if applicable – heat flows that are used externally.

The annual performance not only evaluates the steady-state operating efficiency under full load, but also other states of the system such as cold standby or service intervals. It is shown that for a full system operation assessment and further system concept development, the annual performance is of much higher importance than the steady-state system efficiency which is usually referred to.

In a final step load profiles are defined and the annual performance is calculated for a specific system configuration. Using this example, different operation strategies are compared.

1. Introduction

Power-to-Gas (PtG) systems use electric energy to produce hydrogen or methane. The hydrogen is generated in a first step by electrolysis. In an optional second step which is usually referred to as “methanation”,

the hydrogen is mixed with carbon dioxide and converted into methane. If the latter is synthesized as described, it is also referred to as synthetic natural gas (SNG).

With PtG systems, seasonal storage of renewable electrical energy can be achieved. Boer et al. [1] compare the performance of PtG

* Corresponding author.

E-mail address: jachin.gorre@hsr.ch (J. Gorre).

Nomenclature

PtG	Power-to-Gas	0.	System Power-to-Gas
SBL	sub-system boundary level	1.	sub-system electrolysis
TA	temperature adjustment (of methanation)	2.	sub-system methanation
HHV	higher heating value [$\text{kWh}_{\text{ch}}/\text{kg}$]	out	output stream
$p_{x,y}$	pressure [barg]	i	number/name of unit
$\dot{m}_{x,y}$	mass flow [kg/h]	in	input stream
$\dot{E}_{x,y}$	energy flow across the boundaries of SBL x,y [kW]	h	higher (heating value)
$\dot{E}_{\text{th},x,y}$	flow of thermal energy contained in a flow of fluid across the boundaries of SBL x,y [kWh_{th}]	el	electrical
$\dot{E}_{\text{ch},x,y}$	flow of chemical energy expressed with the higher heating value contained in a flow of fluid across the boundaries of SBL x,y [kWh_{ch}]	th	thermal
$P_{x,y}$	electrical demand [kW_{el}]	stack	electrolysis stack
$\dot{Q}_{x,y}$	non-convective flow of thermal energy across the boundaries of SBL x,y [kW_{th}]	ely	electrolyte
$H_{h,z}$	higher heating value of media z . [$\frac{\text{kWh}_{\text{ch}}}{\text{kg}}$]	H_2	hydrogen
$\Delta_{\nu}H$	enthalpy of vaporization of water [$\frac{\text{kWh}}{\text{mol}}$]	O_2	oxygen
T	temperature [$^{\circ}\text{C}$]	H_2O	water
T_{use}	external useable temperature level of waste heat [$^{\circ}\text{C}$]	pr	product gas
T_{ref}	reference temperature set to be $T_{\text{ref}} = 25^{\circ}\text{C}$ [$^{\circ}\text{C}$]	HS	thermal energy supply
$\eta_{x,y,a}$	efficiency with internal heat use	FC	feed gas compressor
$\eta_{x,y,a}^*$	efficiency with internal heat use and the external usage of heat transferred over the boundaries of a sub-system.	MR	methanation reactor
$\eta_{x,y,b}$	efficiency (internal heat use is not possible)	GD	gas drying
η_{HX}	heat recovery efficiency	CM	cooling media
AC	alternating current [kW_{AC}]	pr	product
DC	direct current [kW_{DC}]	IC	SNG compressor before injection
kW_{el}	kilowatt (electrical) [kW_{el}]	HX	heat exchanger
kW_{th}	kilowatt (thermal) [kW_{th}]	SNG	synthetic natural gas
NOH	non-operating hours [h]	ref	reference
		cir	circulation pump of electrolyte
		use	usable
		TA	temperature adjustment (of methanation)
		AC/DC	alternating/direct current rectifier
		EHX	electrical heater
		trans	transformer
		permeate	permeate from the product gas purification membrane
		AC	alternating current
		DC	direct current
		HM	heat management
		grid	electrical grid
		losses	losses of an unit
		gas	gaseous medium at reference temperature (25°C)
		liq	liquid medium at reference temperature (25°C) and ambient pressure
		eva	evaporated medium, which is at reference temperature (25°C) liquid
		ΔH	enthalpy of evaporation
		HS	thermal supply of water
Indices			
x	sub-system electrolyser $x = 1$ or methanation $x = 2$		
y	sub-system boundary level (SBL)		
x, y	variable concerning SBL x, y		
z	third index of efficiency designation describing the internal use of heat/medium		
a	internal use of waste heat of the sub-system		
b	no use of waste heat		
*	additional external use of waste heat, which is not used internally		

systems as a storage technique with the most cost effective storage options at the current time. Aiming at the assessment of the future role of PtG or the transition of national energy supply concepts, Schieber et al. [2] and Gutierrez and Rodriguez [3] show how PtG can be used to store terawatt hours (TWh) of energy for long term.

In addition to the effect of seasonal storage, PtG provides flexibility and stability in the electricity grid due to providing secondary control reserve [4], using surplus electricity [5–7] or due to coupling with energy production facilities directly, as investigated in [8,9]. PtG is also described in literature as an economic alternative to network expansion [10]. All contributions cited so far are based on an average efficiency for the performance of the PtG systems.

A view on techno-economic analysis of different PtG concepts are done by [11,12]. The studies of [13–15], complemented the techno-economic analysis with a life cycle assessment. The key messages of [16,17] are the feasibility of improving the efficiency and reduction of CO_2 emissions with PtG in the electrochemical and steel industry.

Increasing the hydrogen content in the injected gas increases the efficiency of a PtG plant, as more of the gas does not undergo the methanation process with its associated losses. PtG allows to increase the hydrogen content of the natural gas. Hydrogen-rich natural gas reduces emissions of carbon monoxide, nitrogen oxides and unburned hydrocarbons [18–20]. The implication of different gas qualities on end user devices has been investigated by [21,22]. A decreasing energy duty is one negative aspect of hydrogen-rich gases.

Focusing on different PtG applications and different aspects of PtG, the results and conclusions of the currently available publications and studies are difficult to compare with each other. When calculating the efficiency of a PtG system or the amount of gas produced, some publications use values from own equilibrium simulations, e.g., [23], others rely on literature studies and select values from other publications, e.g. [5,13,15,24], which are mostly not deduced from scientific analysis but e.g. specific field experience. Also the description of plant operation are difficult to compare since deviating measuring points and process

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