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

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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. Staring 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

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Nomenclature

PtG	Power-to-Gas
SBL	sub-system boundary level
TA	temperature adjustment (of methanation)
HHV	higher heating value [kWh_{ch}/kg]
$p_{x.y}$	pressure [barg]
$\dot{m}_{x.y}$	mass flow [kg/h]
$\dot{E}_{x.y}$	energy flow across the boundaries of SBL $x.y$ [kW]
$\dot{E}_{th,x.y}$	flow of thermal energy contained in a flow of fluid across the boundaries of SBL $x.y$ [kW_{th}]
$\dot{E}_{ch,x.y}$	flow of chemical energy expressed with the higher heating value contained in a flow of fluid across the boundaries of SBL $x.y$ [kW_{ch}]
$P_{x.y}$	electrical demand [kW_{el}]
$\dot{Q}_{x.y}$	non-convective flow of thermal energy across the boundaries of SBL $x.y$ [kW_{th}]
$H_{h,z}$	higher heating value of media z. [$\frac{kWh_{ch}}{kg}$]
$\Delta_V H$	enthalpy of vaporization of water [$\frac{kWh}{mol}$]
	averaged heat capacity at constant pressure [$\frac{kWh}{kg*K}$]
T	temperature [°C]
T_{use}	external useable temperature level of waste heat [°C]
T_{ref}	reference temperature set to be T_{ref} = 25 °C [°C]
$\eta_{x.y,a}$	efficiency with internal heat use
$\eta^*_{x.y,a}$	efficiency with internal heat use and the external usage of heat transferred over the boundaries of a sub-system.
$\eta_{x.y,b}$	efficiency (internal heat use is not possible)
η_{HX}	heat recovery efficiency
AC	alternating current [kW_{AC}]
DC	direct current [kW_{DC}]
kW_{el}	kilowatt (electrical) [kW_{el}]
kW_{th}	kilowatt (thermal) [kW_{th}]
NOH	non-operating hours [h]

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
0.	System Power-to-Gas
1.	sub-system electrolysis
2.	sub-system methanation
out	output stream
i	number/name of unit
in	input stream
h	higher (heating value)
el	electrical
th	thermal
stack	electrolysis stack
ely	electrolyte
H_2	hydrogen
O_2	oxygen
H_2O	water
pr	product gas
HS	thermal energy supply
FC	feed gas compressor
MR	methanation reactor
GD	gas drying
CM	cooling media
pr	product
IC	SNG compressor before injection
HX	heat exchanger
SNG	synthetic natural gas
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

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 Gutierres 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 contend 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