



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. 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

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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 [kWh _{ch} /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)
$\dot{E}_{th,x,y}$	flow of thermal energy contained in a flow of fluid across the boundaries of SBL x,y [kW _{th}]	el	electrical
$\dot{E}_{ch,x,y}$	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}]	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 . [$\frac{\text{kWh}_{ch}}{\text{kg}}$]	H ₂	hydrogen
$\Delta_{\nu}H$	enthalpy of vaporization of water [$\frac{\text{kWh}}{\text{mol}}$]	O ₂	oxygen
T	temperature [°C]	H ₂ O	water
T_{use}	external useable temperature level of waste heat [°C]	pr	product gas
T_{ref}	reference temperature set to be $T_{ref} = 25$ °C [°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 CO₂ 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

parameter calculations are used. Beilera et al. [25], Gahleitner [26] and Rönsch et al. [23] give an overview of the worldwide existing PtG projects. Especially those approaches with less specific technical details are based on different system boundaries for calculating process parameters and must therefore be interpreted differently since a common method is lacking.

A PtG system consists of the core unit electrolyser and an optional methanation both with their peripheral systems. The latter are referred to as balance of plant and can be treatment units for educt gases, compression stages, storage devices, product gas treatment units for cleaning, drying and upgrading as well as electricity supply units such as transformers and rectifiers. The balance of plant very much depends on the technologies used in the core units and the plant’s respective application and context in the system it is embedded (e.g. sources of CO₂, input of waste heat from another source or usage of the PtG plant’s waste heat).

The problem is that PtG systems require additional energy and produce additional losses for operating the balance of plant. In order to make data from manufacturers, literature and simulations comparable with each other, the boundaries of the systems under consideration must be known and it has to be specified what is included in “balance of plant”. Kotowicz et al. [27] propose characteristics of hydrogen generator efficiency. Furthermore, the operating conditions (steady state or transient, full load or part load, operating strategy during the year, standby operation) also play a role in calculating the efficiency. With the rising number of plants for demonstration and commercial operation, there is an increased necessity to have a clear definition of system boundaries and efficiency calculations to compare PtG systems with each other.

Davis and Martín [28] present in their publication the operational efficiency of optimal year round production of synthetic methane from water electrolysis and carbon dioxide comparing the use of solar PV systems and wind turbines on a monthly basis. Brunner et al. [29] investigated the competitiveness of different operational concepts for PtG. For benchmarking purposes, like technical development of units or feasibility studies of PtG plants, Gahleitner [26] notes, that the operational efficiency of a power-to-gas plant is more crucial than the

nominal efficiency. This is where the paper focuses on and follows a systematic approach to asset valuation. This method ensures that the different PtG systems and applications can be compared. In particular, little attention is paid to the systematic evaluation of the various operating phases, as data from industrial applications are lacking.

This paper establishes assessment criteria to make PtG technologies and PtG plants comparable with each other in order to increase transparency. By using the efficiency, it is possible to compare the stationary operation of a wide variety of plants. The nominal efficiency of a PtG system is not relevant for industrial operation. Annual performance is essential. The evaluation of a technology does not depend on its efficiency, but whether it is economically feasible in its field of application. With the annual performance introduced in this paper, it is possible to compare all operational phases of the plant with other PtG systems and other storage technologies. The annual performance compares the energy expenditure of one year for the operation of the plant with the energetic content of the product and the utilizable by-products. The annual performance is defined as ratio of usable system energy output (gas and heat) to overall system energy input (electricity and possibly heat). This is very much like the annual performance of heating systems.

The annual performance of a PtG plant considers different operation strategies depending on the application and system integration of the PtG plant. For instance, a PtG plant can be operated based on the availability of (renewable) electricity or based on the availability of low cost electricity. On one hand, different operation strategies lead to different sizing of the system and on the other hand to different hours of operation, standby times as well as on/off cycles of the plant. Based on a certain set of input and output conditions and subsequent design and operation of the PtG plant, profitable markets and business models can be investigated [30]. An example is shown in [31], where a highly simplified approach for the technical performance of the PtG plant was assumed.

This paper is intended to simplify the future calculation of the economic efficiency of industrial plants and the assessment of energy consumption in feasibility studies. Decisions on the economic efficiency of PtG plants can be made easier by using the presented key figure.

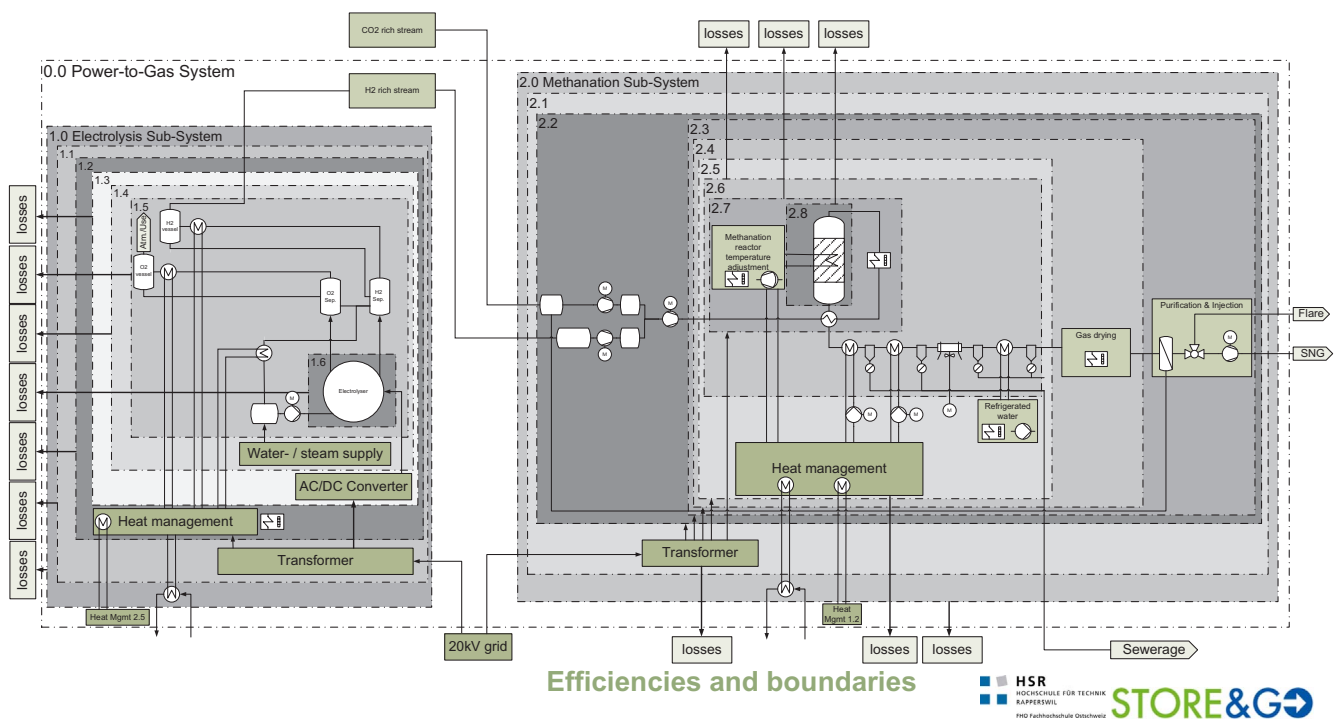


Fig. 1. The efficiency of the PtG system (0) includes the sub-system electrolysis (1) and the methanation (2). Each sub-system is structured into sub-system boundary levels (SBL) to calculate the efficiency of different levels and boundaries.

Section 2

Section 2.1 describes a generic PtG system definition, breaking the system down into the two sub-systems of electrolysis and methanation. Each sub-system has a core process unit and is extended with sub-system boundary levels (SBL) according to an onion-shell principle. The SBLs of the sub-system electrolysis are described in Section 2.2, the SBLs of the methanation in Section 2.3. The overall efficiency of the PtG system is defined in Section 2.4 and the quantities derived from it describing the annual performance are defined in Section 2.5. Section 2.6 lists the parameters required as input data when applying the method.

In Section 3, the method is applied to hypothetical examples of a power-to-gas system. The results of efficiency calculation are presented in Sections 3.1.1–3.1.3 for the sub-system electrolysis, methanation and the PtG system. With the efficiency calculation of the entire system and the definition of different energetic operation modes of the system over a year, the annual performances is calculated in Section 3.2.

With the results of this paper, a complete analysis and assessment of techno-economic indicators are possible and make them comparable with the values of other plants.

2. Methods

2.1. System description and efficiencies

In this paper “Power-to-Gas system” refers to a complete PtG plant as shown in Fig. 1. It comprises two sub-systems: electrolysis denoted by index $x = 1$ and methanation denoted by index $x = 2$. Within both of these main parts, sub-system boundary levels (SBL x, y) are defined, which include different parts of the plant equipment. The SBLs contain balance of plant units required for its operation. Each time a new sub-system boundary level is added to the core, the efficiency is labelled with new indices and an asterisk. Through this procedure, the notation indicates systematically which units are included in the respective efficiency calculation. By defining these numbering and system boundaries within a sub-system, it is possible to compare any system design, despite the complexity and individuality of each system. It starts with the electrolyser and all its balance of plant denoted as SBL 1.0 down to its core component the bare electrolyser stack denoted as SBL 1.6. The methanation with the entire balance of plant is SBL 2.0 and the methanation reactor only is SBL 2.8. The structure is also shown in Table 3.

All efficiencies η of the entire system, of the sub-systems and of the SBLs are defined as quotients of flows of usable output power \dot{E}_{out} to input power \dot{E}_{in} .

$$\eta = \frac{\dot{E}_{out}}{\dot{E}_{in}} \quad (1)$$

The efficiency $\eta_{x,y,z}$ has three indexes. The first two identify the SBL according to Fig. 1 and Table 3. The third index is $z = a$ if the efficiency includes heat used somewhere else in the same sub-system or PtG system 0.0. This is for instance the case when looking at efficiencies of the Methanation Sub-System, if the thermal energy flow of the hot methane from SBL 2.8 is used to preheat any of the media in the same sub-system. If the output of thermal energy is not used inside the power-to-gas system, it can't be considered in the efficiency which is indicated by the third index being $z = b$. An additional asterisk to the efficiency variable $\eta_{x,y,z}^*$ indicates that heat leaving the SBL is used outside the sub-system considered or the PtG system. An overview on how efficiencies are denominated depending on whether heat used internal or external of the power-to-gas system is given in Table 1.

The primary output of a PtG plant is the chemical energy contained in the gas produced calculated according to Eq. (4). The first priority of a PtG plant is to provide as much chemical energy as possible. To increase the efficiency, the part of the heat ejected by one component, which is above the usable temperature T_{use} can be used internal of the PtG plant in a heat sink as a second priority. If a relevant amount of rejected heat is still available above the useable temperature T_{use} , it can

be used external of the plant as a third priority. This increases the efficiency according to the previous definitions. The temperature T_{use} , above which heat is considered useable, is determined specifically for each specific system concept.

In the PtG system and its SBLs x, y , we consider four different forms of power and energy flows: Electric power $P_{x,y}$, flow of chemical energy $\dot{E}_{ch,x,y}$, convective flow of thermal energy $\dot{E}_{th,x,y}$ and non-convective flow of thermal energy $\dot{Q}_{x,y}$. Flows into the system boundaries are indicated with the index “in” and flows out of the system are indicated with index “out”. Further indices indicate the fluid containing the chemical or thermal energy flow.

The output power is the sum of all flows of chemical energy $\dot{E}_{ch,x,y,out}$ and usable thermal energies $\dot{E}_{th,x,y,out}$ and $\dot{Q}_{x,y,out}$. The input power is the sum of all flows of electricity $P_{x,y}$, chemical energy $\dot{E}_{ch,x,y,in}$ and thermal energies $\dot{E}_{th,x,y,in}$ and $\dot{Q}_{x,y,in}$.

$$\dot{E}_{x,y,in} = \dot{E}_{ch,x,y,in} + \dot{E}_{th,x,y,in} + \dot{Q}_{x,y,in} + P_{x,y} \quad (2)$$

$$\dot{E}_{x,y,out} = \dot{E}_{ch,x,y,out} + \dot{E}_{th,x,y,out} + \dot{Q}_{x,y,out} \quad (3)$$

The flows of chemical energy $\dot{E}_{ch,x,y}$ are calculated in using the higher heating value H_h .

$$\dot{E}_{ch,x,y} = \dot{m}_{x,y} \cdot H_h \quad (4)$$

Convective flows of thermal energy into the system boundary $\dot{E}_{th,x,y,in}$, contained thermal energy of gaseous, liquid or evaporated media. The flow of the non-condensable gases N_2, O_2, H_2, CO_2 and CH_4 , are calculated in using the heat capacity $\bar{c}_{p,gas}$ averaged over the temperature range between $T_{ref} = 25^\circ C$ and the temperature T of the gas according to equation (5). Linear regressions for averaged heat capacities $\bar{c}_{p,gas}$ are given in Table 2.

$$\dot{E}_{th,x,y,gas,in} = \dot{m}_{gas} \cdot \bar{c}_{p,gas} \cdot (T - T_{ref}) \quad (5)$$

For liquid media the convective flow of the thermal energy $\dot{E}_{th,liq,in}$ is calculated according to Eq. (6) in using the heat capacity $\bar{c}_{p,liq}$ of the liquid averaged over the temperature range between its temperature T and the reference temperature $T_{ref} = 25^\circ C$. If the liquid medium is evaporated, i.e. liquid water to steam, the heat capacity $\bar{c}_{p,liq}$ of the liquid is averaged over the temperature range between T_{ref} and the evaporation temperature $T_{\Delta H}$, the heat of evaporation ΔH at $T_{\Delta H}$ as well the heat capacity $\bar{c}_{p,liq,eva}$ of the evaporated medium averaged over the temperature range between $T_{\Delta H}$ and the media temperature T have to be considered to calculate the flow of thermal energy $\dot{E}_{th,liq,eva,in}$ according to Eq. (7). Linear regressions for averaged heat capacities $\bar{c}_{p,liq}$ and $\bar{c}_{p,liq,eva}$ and the heat of evaporation of water are given in Table 2.

$$\dot{E}_{th,x,y,liq,in} = \dot{m}_{liq} \cdot \bar{c}_{p,liq} \cdot (T - T_{ref}) \quad (6)$$

$$\dot{E}_{th,x,y,liq,eva,in} = \dot{m}_{liq} \cdot (\bar{c}_{p,liq} \cdot (T_{\Delta H} - T_{ref}) + \Delta H + \bar{c}_{p,liq,eva} \cdot (T - T_{\Delta H})) \quad (7)$$

When flows of thermal energy $\dot{E}_{th,x,y,out}$ out of the SBL are used external of the sub-system considered or PtG system, they are not calculated in using the range between the medium's temperature T and the reference temperature T_{ref} but only the range between the medium's temperature T and the temperature T_{use} above which heat can be used.

Table 1
Definition of efficiency denomination.

	Heat is used internal of the PtG system	
	Yes 3rd index is a	No 3rd index is b
Excess heat is used outside of the sub-system or PtG system	Yes η^* No η	$\eta_{x,y,a}^*$ $\eta_{x,y,b}$

Table 2

Values and linear regressions for averaged heat capacities proposed for the calculation of thermal energy flows according Eqs. (5)–(11) and (13).

Oxygen O ₂ for	$\bar{c}_{p,O2} \approx 885.4 \frac{J}{kg \cdot K} + 0.071 \frac{J}{kg \cdot K^2} \cdot (T - 273.15 \text{ K})$
Hydrogen H ₂ for	$\bar{c}_{p,H2} \approx 13973.4 \frac{J}{kg \cdot K} + 1.256 \frac{J}{kg \cdot K^2} \cdot (T - 273.15 \text{ K})$
Carbon dioxide CO ₂ for	$\bar{c}_{p,CO2} \approx 617.3 \frac{J}{kg \cdot K} + 0.950 \frac{J}{kg \cdot K^2} \cdot (T - 273.15 \text{ K})$
Methane CH ₄ for	$\bar{c}_{p,CH4} \approx 1282.4 \frac{J}{kg \cdot K} + 2.828 \frac{J}{kg \cdot K^2} \cdot (T - 273.15 \text{ K})$
Liquid water for 1 °C < T < 286 °C	$\bar{c}_{p,H2O,l} \approx 4075 \frac{J}{kg \cdot K} + 0.806 \frac{J}{kg \cdot K^2} \cdot (T - 273.15 \text{ K})$
Steam for 1 °C < T < 1000 °C	$\bar{c}_{p,H2O,g} \approx 1864 \frac{J}{kg \cdot K} + 0.295 \frac{J}{kg \cdot K^2} \cdot (T - 273.15 \text{ K})$
Evaporation enthalpy of water at 100 °C	$\Delta_v H (100 \text{ °C}) = 2.26 \cdot 10^6 \text{ J/kg}$

For a gas, the flow of thermal energy $\dot{E}_{th,x,y,gas,out}$ is calculated according to Eq. (8).

$$\dot{E}_{th,x,y,gas,out} = \dot{m}_{gas} \cdot \bar{c}_{p,gas} \cdot (T - T_{use}) \quad (8)$$

The thermal energy in the flow of a liquid media in its liquid or evaporated state are given in Eqs. (9) and (10) respectively.

$$\dot{E}_{th,x,y,liq,out} = \dot{m}_{liq} \cdot \bar{c}_{p,liq} \cdot (T - T_{use}) \quad (9)$$

$$\dot{E}_{th,x,y,liq,eva,out} = \dot{m}_{liq} \cdot (\bar{c}_{p,liq} \cdot (T_{\Delta H} - T_{use}) + \Delta_v H (T_{\Delta H}) + \bar{c}_{p,liq,eva} \cdot (T - T_{\Delta H})) \quad (10)$$

According to Eqs. (4)–(12), a fluid flow has neither chemical nor thermal energy if the fluid has no heating value (N₂, O₂, CO₂ and H₂O), its temperature is $T_{ref} = 25 \text{ °C}$ and in the case of water, it is in its liquid state. This represents the origin in the enthalpy scale chosen in this paper. $\dot{Q}_{th,x,y}$ denotes the non-convective heat transfer in or out of a SBL. Assuming a fluid, that do not change the phase, the change in the material density, due to temperature and pressure variation can be neglected, the heat capacity is calculated with the equations from Table 2. The non-convective heat transfer into the system

$\dot{Q}_{th,x,y,in}$ and out of the system are given in Eqs. (12) and (11) respectively.

$$\dot{Q}_{th,x,y,out} = \dot{m}_{x,y} \cdot \bar{c}_p \cdot (T - T_{use}) \quad (11)$$

and

$$\dot{Q}_{th,x,y,in} = \dot{m}_{x,y} \cdot \bar{c}_p \cdot (T - T_{ref}) \quad (12)$$

If heat is transferred from one medium to another with the same properties, the heat recovery efficiency η_{HX} can be used for calculating the transferred heat.

$$\eta_{HX} = \frac{T_2 - T_1}{T_3 - T_1} \quad (13)$$

Summarized for each SBL, sub-system and the whole PtG system the potential energy flows for calculating an efficiency are listed in Table 3. Eqs. (2), (3) and (14) define the calculation of the efficiency of a PtG system, sub-system or SBL. Each energy flow is described for the electrolyser sub-system in Section 2.2 and for the methanation sub-system in Section 2.3. The potential energy flows have to be checked for each project individually

$$\eta_{x,y,z}^* = \frac{\dot{E}_{x,y,out}}{\dot{E}_{x,y,in}} \quad (14)$$

2.2. Sub-System 1 electrolysis

The electrolysis sub-system 1 can be described starting with the sub-system boundary levels electrolysis stack, electrolyte circuit and product gas treatment (SBL 1.6 and 1.5 in Fig. 1) which represent the procedural levels. Additionally, the heat management and the supply of

water or steam is considered and are included when applying the calculation method. On the electrical side the transformer and the rectifier are considered. Both have to be integrated in the calculation of the efficiency of an electrolysis sub-system. This section covers conventional technologies as the alkaline electrolyser and the PEM electrolyser both fed with liquid water. It also covers the Solid Oxide Electrolyser Cell (SOEC) using hot steam.

2.2.1. SBL 1.6: Electrolysis stack

The core element of the electrolysis sub-system is the electrolysis stack. Depending on the connected load several electrolysis stacks can be operated in parallel mode. The efficiency $\eta_{1.6,a}^*$ is a quotient with the numerator containing the chemical power $\dot{E}_{ch,1.6,out}$ in the hydrogen flow and the thermal power $\dot{E}_{th,1.6,out}$ above T_{use} in the flows of hydrogen ($\dot{E}_{th,1.6,H2,out}$), oxygen ($\dot{E}_{th,1.6,O2,out}$) and electrolyte ($\dot{E}_{th,1.6,ely,out}$). The denominator is the electrical input power ($P_{el,1.6}$) and thermal energy $\dot{E}_{th,1.6,in}$ in the electrolyte ($\dot{E}_{th,1.6,ely,in}$).

If none of the heat rejected by the electrolyser stack is used externally, the efficiencies of SBL 1.6 $\eta_{1.6,a}$, internal heat use only, and $\eta_{1.6,b}$, non heat use internal either external are lower.

$$\dot{E}_{th,1.6,in} = \dot{E}_{th,1.6,ely,in} \quad (15)$$

$$P_{1.6} = P_{stack,DC} \quad (16)$$

$$\dot{E}_{ch,1.6,out} = \dot{m}_{1.6,H2} \cdot H_{h,H2} \quad (17)$$

$$\dot{E}_{th,1.6,out} = \dot{E}_{th,1.6,H2,out} + \dot{E}_{th,1.6,O2,out} + \dot{E}_{th,1.6,ely,out} \quad (18)$$

2.2.2. SBL 1.5: Electrolyte or water circuit

In an electrolysis process, the flow of electrolyte has to be maintained, controlled and circulated requiring the electric power P_{cir} . In most cases, this is done with a pump. During start-up and during operation both in part-load as well as full-load the temperature of the electrolyte has to be kept at operation temperature. Therefore depending on the insulation thermal power $\dot{Q}_{1.5,in}$ has to be supplied thermal ($\dot{Q}_{1.5,in}$) or electrical (P_{HS}), rejected thermal power is described with $\dot{Q}_{1.5,out}$. The thermal power is rejected from gaseous products of the electrolysis process and the electrolyte. The gases have to be conditioned depending on the downstream processes or use. The heat from cooling the gas and the electrolyte is transferred to a cooling circuit medium, again with losses depending on insulation. The amount of thermal energy $\dot{E}_{th,H2O}$ in the water supplied to the process is given by its temperature T and whether the water is liquid or gaseous according Eqs. (6) and (7).

$$\dot{E}_{th,1.5,in} = \dot{E}_{th,1.5,H2O,in} \quad (19)$$

$$\dot{Q}_{1.5,in} = \dot{Q}_{1.5,Ely,in} \quad (20)$$

$$P_{1.5} = P_{1.6} + P_{cir} + P_{HS} \quad (21)$$

$$\dot{E}_{th,1.5,out} = \dot{E}_{th,1.5,H2,out} + \dot{E}_{th,1.5,O2,out} \quad (22)$$

$$\dot{Q}_{1.5,out} = \dot{Q}_{1.5,H2,out} + \dot{Q}_{1.5,O2,out} + \dot{Q}_{1.5,Ely,out} \quad (23)$$

2.2.3. SBL 1.4: Water/steam supply

The inputs for the electrolysis are electricity and water. The supply of water can be liquid or gaseous depending on the electrolysis process design. The thermal energy to fulfil the process parameter for the upstreaming processes is provided from the heat management in SBL 1.2 ($\dot{Q}_{1.4,TS,in}$), electrical (P_{TS}) or is already part of the fresh water stream $\dot{E}_{1.4,H2O,in}$. Electricity P_{H2O} is needed to transport water or steam to the process upstream of this SBL or for electrical supply of thermal energy, while the output stays the same as on SBL 1.5.

$$\dot{E}_{th,1.4,in} = \dot{E}_{1.4,H2O,in} \quad (24)$$

Table 3
Breakdown of Power-to-Gas system 0.0 into two sub-systems and sub-system boundary levels (SBLs), 1.0–1.6 and BLs 2.0–2.8.

SBL	Components	Input flows				Output flows			
		$\eta_{x,y,z}^*$	$\dot{E}_{ch,x,y,in}$	$\dot{E}_{th,x,y,in}$	$\dot{Q}_{x,y,in}$	$P_{x,y,in}$	$\dot{E}_{ch,x,y,out}$	$\dot{E}_{th,x,y,out}$	$\dot{Q}_{x,y,out}$
<i>Sub-system 1 Electrolysis</i>									
1.6	Electrolysis Stack	$\eta_{1,6,a}^*$		$\dot{E}_{th,1,6,in}$		$P_{1,6}$	$\dot{E}_{ch,1,6,out}$	$\dot{E}_{th,1,6,out}$	
		$\eta_{1,6,a}$		$\dot{E}_{th,1,6,in}$		$P_{1,6}$	$\dot{E}_{ch,1,6,out}$		
		$\eta_{1,6,b}$		$\dot{E}_{th,1,6,in}$		$P_{1,6}$	$\dot{E}_{ch,1,6,out}$		
1.5	1.6 + Electrolyte circuit and product gas treatment, i.e. H ₂ and O ₂ purification	$\eta_{1,5,a}^*$		$\dot{E}_{th,1,5,in}$	$\dot{Q}_{1,5,in}$	$P_{1,5}$	$\dot{E}_{ch,1,6,out}$	$\dot{E}_{th,1,5,out}$	$\dot{Q}_{1,5,out}$
		$\eta_{1,5,a}$		$\dot{E}_{th,1,5,in}$	$\dot{Q}_{1,5,in}$	$P_{1,5}$	$\dot{E}_{ch,1,6,out}$		
		$\eta_{1,5,b}$		$\dot{E}_{th,1,5,in}$	$\dot{Q}_{1,5,in}$	$P_{1,5}$	$\dot{E}_{ch,1,6,out}$		
1.4	1.5 + Water/steam supply	$\eta_{1,4,a}^*$		$\dot{E}_{th,1,4,in}$	$\dot{Q}_{1,4,in}$	$P_{1,4}$	$\dot{E}_{ch,1,6,out}$	$\dot{E}_{th,1,5,out}$	$\dot{Q}_{1,5,out}$
		$\eta_{1,4,a}$		$\dot{E}_{th,1,4,in}$	$\dot{Q}_{1,4,in}$	$P_{1,4}$	$\dot{E}_{ch,1,6,out}$		
		$\eta_{1,4,b}$		$\dot{E}_{th,1,4,in}$	$\dot{Q}_{1,4,in}$	$P_{1,4}$	$\dot{E}_{ch,1,6,out}$		
1.3	1.4 + AC/DC rectifier	$\eta_{1,3,a}^*$		$\dot{E}_{th,1,4,in}$	$\dot{Q}_{1,4,in}$	$P_{1,3}$	$\dot{E}_{ch,1,6,out}$	$\dot{E}_{th,1,5,out}$	$\dot{Q}_{1,3,out}$
		$\eta_{1,3,a}$		$\dot{E}_{th,1,4,in}$	$\dot{Q}_{1,4,in}$	$P_{1,3}$	$\dot{E}_{ch,1,6,out}$		
		$\eta_{1,3,b}$		$\dot{E}_{th,1,4,in}$	$\dot{Q}_{1,4,in}$	$P_{1,3}$	$\dot{E}_{ch,1,6,out}$		
1.2	1.3 + Heat management	$\eta_{1,2,a}^*$		$\dot{E}_{th,1,4,in}$	$\dot{Q}_{1,2,in,a}$	$P_{1,2,a}$	$\dot{E}_{ch,1,6,out}$	$\dot{E}_{th,1,5,out}$	$\dot{Q}_{1,2,out}$
		$\eta_{1,2,a}$		$\dot{E}_{th,1,4,in}$	$\dot{Q}_{1,2,in,a}$	$P_{1,2,a}$	$\dot{E}_{ch,1,6,out}$		
		$\eta_{1,2,b}$		$\dot{E}_{th,1,4,in}$	$\dot{Q}_{1,2,in,b}$	$P_{1,2,b}$	$\dot{E}_{ch,1,6,out}$		
1.1	1.2 + Power supply	$\eta_{1,1,a}^*$		$\dot{E}_{th,1,4,in}$	$\dot{Q}_{1,2,in,a}$	$P_{1,1,a}$	$\dot{E}_{ch,1,6,out}$	$\dot{E}_{th,1,5,out}$	$\dot{Q}_{1,2,out}$
		$\eta_{1,1,a}$		$\dot{E}_{th,1,4,in}$	$\dot{Q}_{1,2,in,a}$	$P_{1,1,a}$	$\dot{E}_{ch,1,6,out}$		
		$\eta_{1,1,b}$		$\dot{E}_{th,1,4,in}$	$\dot{Q}_{1,2,in,b}$	$P_{1,1,b}$	$\dot{E}_{ch,1,6,out}$		
1.0	1.1 + External heat usage	$\eta_{1,0,a}^*$		$\dot{E}_{th,1,4,in}$	$\dot{Q}_{1,2,in,a}$	$P_{1,1,a}$	$\dot{E}_{ch,1,6,out}$	$\dot{E}_{th,1,5,out}$	$\dot{Q}_{1,0,out}$
		$\eta_{1,0,a}$		$\dot{E}_{th,1,4,in}$	$\dot{Q}_{1,2,in,a}$	$P_{1,1,a}$	$\dot{E}_{ch,1,6,out}$		
		$\eta_{1,0,b}$		$\dot{E}_{th,1,4,in}$	$\dot{Q}_{1,2,in,b}$	$P_{1,1,b}$	$\dot{E}_{ch,1,6,out}$		
<i>Sub-system 2 Methanation</i>									
2.8	Methanation Reactor	$\eta_{2,8,a}^*$	$\dot{E}_{ch,2,8,in}$	$\dot{E}_{th,2,8,in}$	$\dot{Q}_{2,8,in}$		$\dot{E}_{ch,2,8,out}$	$\dot{E}_{th,2,8,out}$	$\dot{Q}_{2,8,out}$
		$\eta_{2,8,a}$	$\dot{E}_{ch,2,8,in}$	$\dot{E}_{th,2,8,in}$	$\dot{Q}_{2,8,in}$		$\dot{E}_{ch,2,8,out}$		
		$\eta_{2,8,b}$	$\dot{E}_{ch,2,8,in}$	$\dot{E}_{th,2,8,in}$	$\dot{Q}_{2,8,in}$		$\dot{E}_{ch,2,8,out}$		
2.7	2.8 + Temperature adjustment	$\eta_{2,7,a}^*$	$\dot{E}_{ch,2,8,in}$	$\dot{E}_{th,2,7,in}$	$\dot{Q}_{2,7,in,a}$	$P_{2,7}$	$\dot{E}_{ch,2,8,out}$	$\dot{E}_{th,2,7,out}$	$\dot{Q}_{2,7,out}$
		$\eta_{2,7,a}$	$\dot{E}_{ch,2,8,in}$	$\dot{E}_{th,2,7,in}$	$\dot{Q}_{2,7,in,a}$	$P_{2,7}$	$\dot{E}_{ch,2,8,out}$		
		$\eta_{2,7,b}$	$\dot{E}_{ch,2,8,in}$	$\dot{E}_{th,2,7,in}$	$\dot{Q}_{2,7,in,b}$	$P_{2,7}$	$\dot{E}_{ch,2,8,out}$		
2.6	2.7 + Product gas treatment	$\eta_{2,6,a}^*$	$\dot{E}_{ch,2,8,in}$	$\dot{E}_{th,2,7,in}$	$\dot{Q}_{2,7,in,a}$	$P_{2,7}$	$\dot{E}_{ch,2,8,out}$	$\dot{E}_{th,2,6,out}$	$\dot{Q}_{2,6,out}$
		$\eta_{2,6,a}$	$\dot{E}_{ch,2,8,in}$	$\dot{E}_{th,2,7,in}$	$\dot{Q}_{2,7,in,a}$	$P_{2,7}$	$\dot{E}_{ch,2,8,out}$		
		$\eta_{2,6,b}$	$\dot{E}_{ch,2,8,in}$	$\dot{E}_{th,2,7,in}$	$\dot{Q}_{2,7,in,b}$	$P_{2,7}$	$\dot{E}_{ch,2,8,out}$		
2.5	2.6 + Heat management	$\eta_{2,5,a}^*$	$\dot{E}_{ch,2,8,in}$	$\dot{E}_{th,2,7,in}$	$\dot{Q}_{2,5,in,a}$	$P_{2,5,a}$	$\dot{E}_{ch,2,8,out}$	$\dot{E}_{th,2,6,out}$	$\dot{Q}_{2,5,out}$
		$\eta_{2,5,a}$	$\dot{E}_{ch,2,8,in}$	$\dot{E}_{th,2,7,in}$	$\dot{Q}_{2,5,in,a}$	$P_{2,5,a}$	$\dot{E}_{ch,2,8,out}$		
		$\eta_{2,5,b}$	$\dot{E}_{ch,2,8,in}$	$\dot{E}_{th,2,7,in}$	$\dot{Q}_{2,5,in,b}$	$P_{2,5,b}$	$\dot{E}_{ch,2,8,out}$		
2.4	2.5 + Product gas drying	$\eta_{2,4,a}^*$	$\dot{E}_{ch,2,8,in}$	$\dot{E}_{th,2,7,in}$	$\dot{Q}_{2,5,in,a}$	$P_{2,4,a}$	$\dot{E}_{ch,2,8,out}$	$\dot{E}_{th,2,4,out}$	$\dot{Q}_{2,5,out}$
		$\eta_{2,4,a}$	$\dot{E}_{ch,2,8,in}$	$\dot{E}_{th,2,7,in}$	$\dot{Q}_{2,5,in,a}$	$P_{2,4,a}$	$\dot{E}_{ch,2,8,out}$		
		$\eta_{2,4,b}$	$\dot{E}_{ch,2,8,in}$	$\dot{E}_{th,2,7,in}$	$\dot{Q}_{2,5,in,b}$	$P_{2,4,b}$	$\dot{E}_{ch,2,8,out}$		
2.3	2.4 + Purification and injection	$\eta_{2,3,a}^*$	$\dot{E}_{ch,2,8,in}$	$\dot{E}_{th,2,7,in}$	$\dot{Q}_{2,5,in,a}$	$P_{2,3,a}$	$\dot{E}_{ch,2,3,out}$	$\dot{E}_{th,2,4,out}$	$\dot{Q}_{2,5,out}$
		$\eta_{2,3,a}$	$\dot{E}_{ch,2,8,in}$	$\dot{E}_{th,2,7,in}$	$\dot{Q}_{2,5,in,a}$	$P_{2,3,a}$	$\dot{E}_{ch,2,3,out}$		
		$\eta_{2,3,b}$	$\dot{E}_{ch,2,8,in}$	$\dot{E}_{th,2,7,in}$	$\dot{Q}_{2,5,in,b}$	$P_{2,3,b}$	$\dot{E}_{ch,2,3,out}$		
2.2	2.3 + Feed gas preparation	$\eta_{2,2,a}^*$	$\dot{E}_{ch,2,2,in}$	$\dot{E}_{th,2,2,in}$	$\dot{Q}_{2,5,in,a}$	$P_{2,2,a}$	$\dot{E}_{ch,2,2,out}$	$\dot{E}_{th,2,2,out}$	$\dot{Q}_{2,5,out}$
		$\eta_{2,2,a}$	$\dot{E}_{ch,2,2,in}$	$\dot{E}_{th,2,2,in}$	$\dot{Q}_{2,5,in,a}$	$P_{2,2,a}$	$\dot{E}_{ch,2,2,out}$		
		$\eta_{2,2,b}$	$\dot{E}_{ch,2,2,in}$	$\dot{E}_{th,2,2,in}$	$\dot{Q}_{2,5,in,b}$	$P_{2,2,b}$	$\dot{E}_{ch,2,2,out}$		
2.1	2.2 + Energy supply from grid	$\eta_{2,1,a}^*$	$\dot{E}_{ch,2,2,in}$	$\dot{E}_{th,2,2,in}$	$\dot{Q}_{2,5,in,a}$	$P_{2,1,a}$	$\dot{E}_{ch,2,2,out}$	$\dot{E}_{th,2,2,out}$	$\dot{Q}_{2,5,out}$
		$\eta_{2,1,a}$	$\dot{E}_{ch,2,2,in}$	$\dot{E}_{th,2,2,in}$	$\dot{Q}_{2,5,in,a}$	$P_{2,1,a}$	$\dot{E}_{ch,2,2,out}$		
		$\eta_{2,1,b}$	$\dot{E}_{ch,2,2,in}$	$\dot{E}_{th,2,2,in}$	$\dot{Q}_{2,5,in,b}$	$P_{2,1,b}$	$\dot{E}_{ch,2,2,out}$		
2.0	2.1 + Heat Usage	$\eta_{2,0,a}^*$	$\dot{E}_{ch,2,2,in}$	$\dot{E}_{th,2,2,in}$	$\dot{Q}_{2,0,in,a}$	$P_{2,1,a}$	$\dot{E}_{ch,2,2,out}$	$\dot{E}_{th,2,2,out}$	$\dot{Q}_{2,0,out}$
		$\eta_{2,0,a}$	$\dot{E}_{ch,2,2,in}$	$\dot{E}_{th,2,2,in}$	$\dot{Q}_{2,0,in,a}$	$P_{2,1,a}$	$\dot{E}_{ch,2,2,out}$		
		$\eta_{2,0,b}$	$\dot{E}_{ch,2,2,in}$	$\dot{E}_{th,2,2,in}$	$\dot{Q}_{2,0,in,b}$	$P_{2,1,b}$	$\dot{E}_{ch,2,2,out}$		

(continued on next page)

Table 3 (continued)

SBL	Components	Input flows				Output flows		
		$\eta_{x,y,z}^*$	$\dot{E}_{ch,x,y,in}$	$\dot{E}_{th,x,y,in}$	$\dot{Q}_{x,y,in}$	$P_{x,y,in}$	$\dot{E}_{ch,x,y,out}$	$\dot{E}_{th,x,y,out}$
PtG System 0								
0.0	PtG System	$\eta_{0,0,a}^*$	$\dot{E}_{th,1,4,in}$	$\dot{Q}_{1,2,in,a} + \dot{Q}_{2,0,in,a}$	$P_{1,1,a} + P_{2,1,a}$	$\dot{E}_{ch,2,2,out}$	$\dot{E}_{th,2,2,out}$	$\dot{Q}_{1,0,out} + \dot{Q}_{2,0,out}$
		$\eta_{0,0,a}$	$\dot{E}_{th,1,4,in}$	$\dot{Q}_{1,2,in,a} + \dot{Q}_{2,0,in,a}$	$P_{1,1,a} + P_{2,1,a}$	$\dot{E}_{ch,2,2,out}$		
		$\eta_{0,0,b}$	$\dot{E}_{th,1,4,in}$	$\dot{Q}_{1,2,in,b} + \dot{Q}_{2,0,in,b}$	$P_{1,1,b} + P_{2,1,b}$	$\dot{E}_{ch,2,2,out}$		

$$\dot{Q}_{1,4,in} = \dot{Q}_{1,4,TS,in} + \dot{Q}_{1,5,ELY,in} \quad (25)$$

$$P_{1,4} = P_{1,5} + P_{TS} + P_{H_2O} \quad (26)$$

2.2.4. SBL 1.3: AC/DC rectifier

For the production of hydrogen and oxygen the electrolysis needs direct current $P_{stack,DC}$. The alternating current $P_{stack,AC}$ coming from the transformer is converted to DC in a rectifier with losses in form of heat. The losses are described by a converting efficiency $\eta_{AC/DC}$. The losses $\dot{Q}_{1,3,AC/DC,out}$ can be rejected partly from the unit and used in the heat management.

$$P_{1,3} = P_{stack,AC} + P_{cir} + P_{TS} + P_{H_2O} + P_{HS} \quad (27)$$

$$P_{stack,AC} = \frac{P_{stack,DC}}{\eta_{AC/DC}} \quad (28)$$

$$\dot{Q}_{1,3,out} = \dot{Q}_{1,5,out} + \dot{Q}_{1,3,AC/DC,out} \quad (29)$$

2.2.5. SBL 1.2: Heat management

A part of the waste heat $\dot{Q}_{1,3,out}$ can be used to reduce the internally thermal power demand ($\dot{Q}_{1,4,in}$), e.g. for heating of the feed water of the electrolysis. Then, the system losses (waste heat) are reduced, but also the necessary input of energy $\dot{Q}_{1,2,in,a}$ or $P_{1,2,a}$ is reduced, e.g. at part load. If a suitable external heat sink is available, the residual waste heat can be changed into useable heat $\dot{Q}_{1,2,out}$ within the heat management and could be used externally. The chemical output stays the same as on SBL 1.5.

$$\dot{Q}_{1,2,out} = (\dot{Q}_{1,3,out} - \dot{Q}_{1,4,in}) * \eta_{HX} \quad (30)$$

$$P_{1,2,a} = P_{1,3} + P_{HM,a} \quad (31)$$

$$P_{HM,a} = \sum P_{CM,i} \quad (32)$$

If there is no internal use of heat foreseen or possible because of the temperature level, the thermal energy $\dot{Q}_{1,4,in}$ to fulfil the process parameter for the upstreaming processes is provided electrical $P_{HM,b}$ or from external heat sources ($\dot{Q}_{1,2,in,b}$).

$$P_{1,2,b} = P_{1,3} + P_{HM,a} + P_{HM,b} \quad (33)$$

$$P_{HM,b} = \frac{\dot{Q}_{1,4,in}}{\eta_{EHX}} \quad (34)$$

$$\dot{Q}_{1,2,in,b} = \frac{\dot{Q}_{1,4,in}}{\eta_{HX}} \quad (35)$$

There are two variants for the removal of heat from a system when the further use of the dissipated heat is intended.

2.2.6. SBL 1.1: Energy supply

Beside the electrolysis stack all other consumers need AC power supply. Usually, a transformer supplies electric energy from the grid (e.g. 20 kV) to the sub-system units and the specific voltage level for the electrolysis. If it is expected, that the internal heat requirement is

supplied electrical the electrical consumption of power is $P_{1,1,b}$. With internal heat use the electrical power is $P_{1,1,a}$.

$$P_{1,1,a} = \frac{P_{stack,AC} + P_{cir} + P_{TS} + P_{H_2O} + P_{HM,a}}{\eta_{trans}} \quad (36)$$

$$P_{1,1,b} = \frac{P_{stack,AC} + P_{cir} + P_{TS} + P_{H_2O} + P_{HM,a} + P_{HM,b}}{\eta_{trans}} \quad (37)$$

2.2.7. SBL1.0 Sub-system electrolysis: overall efficiency

The overall sub-system efficiency depends on the use of the transferred heat. The heat can be recovered partly with an optimized heat management system and be supplied for external use ($\eta_{1,0,a}^*$). Depending on the heat recovery factor of the transferred heat to the external heat sink, the heat term is reduced ($\dot{Q}_{1,0,out}$).

$$\dot{Q}_{1,0,out} = \dot{Q}_{1,2,out} * \eta_{HX} \quad (38)$$

The efficiencies without use of surplus heat correspond to the values of SBL 1.1, where no external heat use is considered but still an internal heat management optimization can be applied ($\eta_{1,0,a}$) or not ($\eta_{1,0,b}$). In equation (39)–(41) the overall efficiency of the sub-system electrolysis is shown.

$$\eta_{1,0,a} = \frac{\dot{E}_{ch,1,6,out}}{\dot{E}_{th,1,4,in} + \dot{Q}_{1,2,in,a} + P_{1,1,a}} \quad (39)$$

$$\eta_{1,0,a}^* = \frac{\dot{E}_{ch,1,6,out} + \dot{Q}_{1,0,out} + \dot{E}_{th,1,5,out}}{\dot{E}_{th,1,4,in} + \dot{Q}_{1,2,in,a} + P_{1,1,a}} \quad (40)$$

$$\eta_{1,0,b} = \frac{\dot{E}_{ch,1,6,out}}{\dot{E}_{th,1,4,in} + \dot{Q}_{1,2,in,b} + P_{1,1,b}} \quad (41)$$

2.3. Sub-system 2 methanation

The units of the methanation sub-system can be described starting with the methanation reactor (SBL 2.8) and the methanation reactor temperature adjustment (SBL 2.7) which together form the core process of methanation. Additionally, product gas cooling, internal heat management, product gas drying, purification and injection, feed gas preparation and external heat use have to be evaluated (cf. SBL 2.6 to 2.2). The supply of energy for all units has to be integrated in the efficiency calculation. With this generalized description, for different process technologies it is possible to define the heat input and output accordingly.

2.3.1. SBL 2.8: Methanation reactor

When producing methane, the second main unit of a PtG plant is the methanation reactor. The hydrogen of the chemical energy flow $\dot{E}_{ch,2,8,in}$ reacts to methane and water. The product gas stream includes chemical energy $\dot{E}_{ch,2,8,out}$ and thermal energy $\dot{E}_{th,2,8,out}$. To protect the catalyst from degradation the whole feed gas stream should be preheated ($\dot{E}_{th,2,8,in}$). The heat of the reaction of the methane production $\dot{Q}_{2,8,out}$ is transferred to the methanation temperature adjustment unit (TA). Run-

up needs additional thermal energy $\dot{Q}_{2.8,in}$, which is transferred from the TA to the reactor to reach the process parameter.

$$\dot{E}_{ch,2.8,in} = \dot{E}_{ch,2.2,in} + \dot{E}_{ch,Permeate} \quad (42)$$

$$\dot{E}_{th,2.8,in} = \dot{E}_{th,2.8,Feed,in} \quad (43)$$

$$\dot{Q}_{2.8,in} = \dot{Q}_{2.8,MR,in} \quad (44)$$

$$\dot{E}_{ch,2.8,out} = \dot{E}_{ch,2.8,pr,out} \quad (45)$$

$$\dot{E}_{th,2.8,out} = \dot{E}_{th,2.8,pr,out} \quad (46)$$

$$\dot{Q}_{2.8,out} = \dot{Q}_{2.8,MR,out} \quad (47)$$

2.3.2. SBL 2.7: Temperature adjustment

The temperature of the methanation reactor is controlled to follow specific process properties. The additional heat ($\dot{Q}_{2.7,TA,in}$) for run-up and thermal power to reach the essential input temperature of the feed gas ($\dot{Q}_{2.7,Feed,in}$) is provided by the heat management in SBL 2.5 ($\dot{Q}_{2.7,in}$) or electrical (P_{TA} and P_{Feed}). The steady operation usually needs heat dissipation out of the TA ($\dot{Q}_{th,2.7,out}$).

$$\dot{E}_{th,2.7,in} = \dot{E}_{th,2.7,Feed,in} \quad (48)$$

$$\dot{Q}_{2.7,in} = \dot{Q}_{2.7,TA,in} + \dot{Q}_{2.7,Feed,in} \quad (49)$$

$$P_{2.7} = P_{TA} + P_{Feed} \quad (50)$$

$$\dot{E}_{th,2.7,out} = \dot{E}_{th,2.7,pr,out} \quad (51)$$

$$\dot{Q}_{2.7,out} = \dot{Q}_{2.7,TA,out} \quad (52)$$

$$\dot{Q}_{2.7,Feed,in} = \dot{m}_{2.3} * \bar{c}_{p,2.7} * T_{2.8,in}^{T_{2.7,in}} (T_{2.8,in} - T_{2.7,in}) \quad (53)$$

2.3.3. SBL 2.6: Product gas treatment

After reaction of feed gas to methane and water the products have to be conditioned (active cooling and condensation of water) so that the product gas methane can be separated ($\dot{E}_{th,2.6,pr,out}$). The latent and the sensitive heat are received by cooling media $\dot{Q}_{2.6,CM,out}$.

$$\dot{E}_{th,2.6,out} = \dot{E}_{th,2.6,pr,out} \quad (54)$$

$$\dot{Q}_{2.6,out} = \sum \dot{Q}_{CM,i,out} + \dot{Q}_{2.7,TA,out} \quad (55)$$

2.3.4. SBL 2.5: Heat management

The heat of the product gas treatment processes and the reaction is prepared to be used internally, combined internally and externally or not at all. The surplus usable heat ($\dot{Q}_{th,2.5,out}$) is available in the heat management for externally use and increase the efficiency of the sub-system. The cooling media are circulated by pumps ($P_{HM,a}$) and run at a specific load. For run-up or specific loads the thermal energy can be supplied from an external heat source ($\dot{Q}_{2.5,in}$) or electrical $P_{2.5,b}$

$$\dot{Q}_{2.5,in} = \frac{\dot{Q}_{2.7,in}}{\eta_{HX}} \quad (56)$$

$$P_{2.5,a} = P_{2.7} + P_{HM,a} \quad (57)$$

$$P_{HM,a} = \sum P_{CM,i} \quad (58)$$

$$P_{2.5,b} = P_{2.7} + P_{HM,a} + P_{HM,b} \quad (59)$$

$$P_{HM,b} = \frac{\dot{Q}_{2.7,in}}{\eta_{EHX}} \quad (60)$$

$$\dot{Q}_{2.5,out} = (\dot{Q}_{2.6,out} - \dot{Q}_{2.7,in}) * \eta_{HX} \quad (61)$$

2.3.5. SBL 2.4: Product gas drying

After cooling of the product gas an additional drying unit may be used to reach the required dew point for the injection into the gas grid. For this, additional energy is needed.

$$P_{2.4,a/b} = P_{2.5,a/b} + P_{GD} \quad (62)$$

$$\dot{E}_{th,2.4,out} = \dot{E}_{th,2.4,pr,out} \quad (63)$$

2.3.6. SBL 2.3: Purification

If the gas quality of the non-condensational products of the methanation reactor does not fulfil the quality for an injection in the gas grid, an additional purification can be installed. The purification can be done with a membrane. The product stream is split in the injectable SNG stream and the permeate stream. If the gas has to be compressed for the designated application the electrical demand P_{PC} has to be provided.

$$P_{2.3,a/b} = P_{2.4,a/b} + P_{PC} \quad (64)$$

$$\dot{E}_{ch,2.3,out} = \dot{E}_{ch,SNG} + \dot{E}_{ch,Permeate} \quad (65)$$

2.3.7. SBL 2.2: Methanation sub-system from feed gas preparation to injection

After purification permeate can be returned and mixed with the feed ($\dot{E}_{ch,2.2,in}$). The quality of the gaseous output, $\dot{E}_{ch,2.2,out}$ and $\dot{E}_{th,2.2,out}$, is conform to the injection requirement or designated application.

$$\dot{E}_{ch,2.2,in} = \dot{E}_{ch,Feed,in} \quad (66)$$

$$\dot{E}_{th,2.2,in} = \dot{E}_{th,Feed,in} \quad (67)$$

$$P_{2.2,a/b} = P_{2.3,a/b} + \sum P_{FC,i} \quad (68)$$

$$\dot{E}_{ch,2.2,out} = \dot{E}_{ch,SNG,out} \quad (69)$$

$$\dot{E}_{th,2.2,out} = \dot{E}_{th,SNG,out} \quad (70)$$

2.3.8. SBL 2.1: Methanation sub-system with energy supply from grid

Heating and cooling of the sub-system needs electrical units. The supply for all units of the methanation is summarized in $P_{2.1}$. The equation includes the losses of the transformer from network level to the consumer level.

$$P_{2.1,a} = \frac{P_{TA} + P_{Feed} + P_{HM,a} + P_{GD} + P_{PC} + \sum P_{FC,i}}{\eta_{trans}} \quad (71)$$

$$P_{2.1,b} = \frac{P_{TA} + P_{Feed} + P_{HM,a} + P_{HM,b} + P_{GD} + P_{PC} + \sum P_{FC,i}}{\eta_{trans}} \quad (72)$$

2.3.9. Sub-system Methanation: Overall efficiency

The overall sub-system efficiency depends on the use of the transferred heat. The heat can be recovered partly with an optimized heat management system and be supplied for external use ($\eta_{2.0,a}^*$). Depending on the use of heat, the heat term in the efficiency calculation has to be multiplied by a heat recovery factor for heat exchanger.

$$\dot{Q}_{2.0,out} = \dot{Q}_{2.5,out} * \eta_{HX} \quad (73)$$

Excess energy has to be rejected. The efficiencies without external use of surplus heat correspond to the values of SBL 2.1, where no external heat use is considered but still an internal heat management optimization can be applied ($\eta_{2.0,a}$). A sub-system methanation without internal and external use of heat is also possible ($\eta_{1.0,b}$). In equation (74)–(76) the overall efficiency of the sub-system methanation is shown.

$$\eta_{2.0,a} = \frac{\dot{E}_{ch,2.2,out}}{\dot{E}_{ch,2.2,in} + \dot{E}_{th,2.2,in} + \dot{Q}_{2.0,in,a} + P_{2.1,a}} \quad (74)$$

$$\eta_{2.0,a}^* = \frac{\dot{E}_{ch,2.2,out} + \dot{Q}_{2.0,out} + \dot{E}_{th,2.2,out}}{\dot{E}_{ch,2.2,in} + \dot{E}_{th,2.2,in} + \dot{Q}_{2.0,in,a} + P_{2.1,a}} \quad (75)$$

$$\eta_{2.0,b} = \frac{\dot{E}_{ch,2.2,out}}{\dot{E}_{ch,2.2,in} + \dot{E}_{th,2.2,in} + \dot{Q}_{2.0,in,b} + P_{2.1,b}} \quad (76)$$

2.4. Power-to-Gas System 0

The Power-to-Gas System 0 comprises the whole sub-system electrolyser and the sub-system methanation. The energy flows for calculating the PtG system efficiency include all thermal, electrical, and convective energy flows that cross the outer system boundary of the power-to-gas system. The overall System efficiency depends on the use of the transferred heat from both sub-systems. The heat can be recovered partly with an optimized heat management system and be transferred between both sub-systems. The exchange of heat for the internal heating use takes place within the system boundary and is not contained in the output energy flow, but leads to a reduction in the amount of energy supplied. The excess heat of the heat management can be supplied for external use.

The efficiency calculation of a system with several sub-systems depends on the structure of the concerned sub-systems. If a system has several sub-systems, the efficiency of each sub-system can only be multiplied for calculating the system efficiency, if the output of sub-system A corresponds to the input sub-system B, e.g. paddle wheel of a turbine and a connected generator. For the PtG system this does not apply. Each sub-system has additional auxiliary energies or auxiliary media that are added to the subsystem. Therefore, if further inputs are added to sub-system B (e.g. methanation, input of A is the hydrogen, but in addition there is electricity for the consumption of the cooling units and pumps to sub-system B), then the efficiency of the sub-systems cannot be multiplied. A new efficiency balance of the entire system has to be drawn.

$$\eta_{0.0,a} = \frac{\dot{E}_{ch,2.2,out}}{\dot{E}_{th,1.4,in} + \dot{Q}_{1.2,in,a} + \dot{Q}_{2.0,in,a} + P_{1.1,a} + P_{2.1,a}} \quad (77)$$

$$\eta_{0.0,a}^* = \frac{\dot{E}_{ch,2.2,out} + \dot{Q}_{2.0,out} + \dot{E}_{th,2.2,out}}{\dot{E}_{th,1.4,in} + \dot{Q}_{1.2,in,a} + \dot{Q}_{2.0,in,a} + P_{1.1,a} + P_{2.1,a}} \quad (78)$$

$$\eta_{0.0,a}^* = \frac{\dot{E}_{ch,2.2,out} + \dot{Q}_{1.0,out} + \dot{E}_{th,2.2,out}}{\dot{E}_{th,1.4,in} + \dot{Q}_{1.2,in,a} + \dot{Q}_{2.0,in,a} + P_{1.1,a} + P_{2.1,a}} \quad (79)$$

$$\eta_{0.0,a}^* = \frac{\dot{E}_{ch,2.2,out} + \dot{Q}_{1.0,out} + \dot{Q}_{2.0,out} + \dot{E}_{th,2.2,out}}{\dot{E}_{th,1.4,in} + \dot{Q}_{1.2,in,a} + \dot{Q}_{2.0,in,a} + P_{1.1,a} + P_{2.1,a}} \quad (80)$$

$$\eta_{0.0,b} = \frac{\dot{E}_{ch,2.2,out}}{\dot{E}_{th,1.4,in} + \dot{Q}_{1.2,in,b} + \dot{Q}_{2.0,in,b} + P_{1.1,b} + P_{2.1,b}} \quad (81)$$

2.5. Annual performance

While a first and rough estimation of a PtG plant performance can be based on stationary (full load) efficiencies, the annual efficiency has to consider more detailed specifications. In addition to the more detailed calculation of the performance in different load states (as described in the previous section), the distribution of full and part load conditions throughout the year has to be assessed. Furthermore, the plant will not always be operated in full load or part load (i.e. production modes) but also in two other states: Hot standby (idle) or cold standby (see Fig. 2).

The annual performance represents the distribution and sequence of all different operation states over the year and calculates the overall

energy demand which is compared to the energetic output, consisting of the product gas and possibly also a usage of the heat rejected from the processes.

In order to be able to calculate the distribution and sequence of the operation states several parameters have to be defined that are necessary to control the system operation accordingly:

1. Energy consumption for the states “Cold Standby”, “Hot standby” and “Production”
2. Energy consumption during transition from “Cold Standby” to “Hot Standby”
3. System reaction times for changing the operation state

In status “Cold Standby” all reaction processes are stopped and the gas-bearing pipes are flushed with nitrogen. If necessary, a freezing protection has to be applied for pipes filled with water. All safety-relevant process units are kept in operation. The energy consumption for the state “Cold Standby” is the demand of all parts keeping the system in a useable mode: control, communication and safety feature and equipment, pumps of cooling media and electrolyte.

From the status “Hot Standby” the production of methane can start immediately. To enter the status “Hot Standby”, first of all the sub-system methanation has to be heated up to the required process temperatures. The temperature control limit is 50 K/h to reduce thermal stress within the reactor. The electrolysis sub-system can be operated very dynamic with fast “cold-start” ability. In this paper it was assumed that the temperature control of both subsystems would take the same time. In addition, the maximum hydrogen product rate of the electrolysis corresponds to the maximum input of methanation. The system could be optimized by a hydrogen buffer tank to operate the sub-systems separately. This was not implemented here. The system has to be flushed with hydrogen to be ready for production. The electrolyzer is heated indirectly electrically, as a higher voltage than the thermo-neutral decomposition voltage of water is required for splitting water. This leads to heat generation and heats up the electrolyser. The methanation gets its heat from electrical heating of the media, tempering the methanation reactor. The duration of ramping up depends on the system configuration. The status change from cold standby into hot standby can take several hours.

If the PtG system remains in status “Hot Standby” the losses of heat have to be compensated. Almost all heat losses of the two sub-systems should originate from circulated media. For the electrolysis this is the electrolyte and for the methanation the reactor temperature adjustment media.

Considering this, the annual performance factor can be defined as quotient of the energy output (gas heating value and usable heat) of one year and the necessary electrical and thermal energy input to operate the system or to keep it in standby mode. The output is defined as the produced mass of SNG and the external used heat from the sub-systems electrolyser and methanation. The input can be defined as the electrical input and heat requirement for the whole system operation over one year. It is possible that the heat requirement of the system is delivered electrical.

Annual performance factor F_{PtG} :

$$F_{0.0,a}^* = \frac{\int \dot{E}_{ch,2.0,out}(t)dt + \int \dot{Q}_{1.0,out}(t)dt + \int \dot{Q}_{2.0,out}(t)dt}{\int \dot{E}_{th,1.4,in}(t)dt + \int \dot{Q}_{1.2,in,a}(t)dt + \int \dot{Q}_{2.0,in,a}(t)dt + \int P_{1.1,a}(t)dt + \int P_{2.1,a}(t)dt} \quad (82)$$

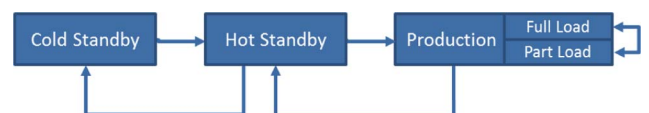


Fig. 2. Different states of a PtG-plant and the possible changeover between these states.

$$F_{0,0,a} = \frac{\int \dot{E}_{ch,2,0,out}(t)dt}{\int \dot{E}_{th,1,4,in}(t)dt + \int \dot{Q}_{1,2,in,a}(t)dt + \int \dot{Q}_{2,0,in,a}(t)dt + \int P_{1,1,a}(t)dt + \int P_{2,1,a}(t)dt} \tag{83}$$

2.6. Calculation data

In order to compare the results of all unit efficiencies presented in Sections 2.2 and 2.3, representative input data for the calculation of a PtG system were defined. Properties of gaseous compounds were calculated at standard condition (T = 273.15 K, p = 101325 Pa).

3. Results

For the exemplary calculation of SBL, sub-system and system efficiencies and annual performance presented in this section, an alkaline electrolysis and a catalytic methanation has been assumed. The example is hypothetical but based on real case assumptions. All relevant data are listed in Section 2.6.

3.1. Efficiency

A PtG plant may be operated in part load. Then, some units of the sub-equipment will still run at full load since a power control of the unit is not necessary, too expensive or not applicable. For instance, the electrical heating of the drying unit only runs at full load operation mode. The electrolyte pump and the cooling unit should be adapted to the load, to have an optimal heat recovery value. For calculating the energy demand of the circulation pumps, however, a constant operation at full load may be expected.

The specific energy demand of the electrolysis may also change with part load conditions, as well as the operation of the methanation. Therefore, if part load operation is considered, the dependency of the sub-system and system efficiencies has to be considered in the calculations. In this paper, the dependency of efficiencies on part-load operation is neglected since currently almost all PtG plants will be operated with 0/100% load conditions.

The calculation of the efficiency shows that the use of waste heat to cover internal heat sinks results in an increase of efficiency, since the energy input of the sub-system is reduced. If waste heat is still available after internal heat use, the efficiency can be increased once more. The coverage of internal and external heat sinks is useful when the temperature levels of the two heat sinks do not overlap or the proportion of

waste heat is much greater than the proportion of internal heat. Then: $\eta_{x,0,a}^* > \eta_{x,0,a} > \eta_{x,0,b}$.

3.1.1. Efficiency Sub-System 1 electrolysis

In Fig. 3 the results of efficiency calculations are presented for the sub-system boundary levels of electrolysis. The efficiency of each level of the electrolysis sub-system is illustrated with the maximum possible internal and external heat use and with internal use of heat coming from the processes. The temperature level of useable heat has been set to be 60 °C, however, can be changed for calculating other conditions.

The input heat flow is calculated based on a reference temperature of 25 °C. SBL 1.6 is not shown because it only describes the electrolyser stack. From a system perspective, this is not relevant because the units to close the electrolyte circle are not part of it. The functionality of the electrolyser sub-system is given, when the circulation of electrolyte is closed.

Fig. 3 shows that the difference between the efficiencies with heat use (black bars) and without (grey bars) is significant and in the range of about 30% (absolute) for all SBL of the electrolyser. The values of $\eta_{1,y,a}^*$ depend on the temperature level of useable heat. With 60 °C as used in this specific calculation, the whole heat of reaction of the separation of water into hydrogen and oxygen can be used. Analysing the drop of efficiencies from SBL 1.5 to SBL 1.1, the greatest loss of efficiency in the electrolyser system is due to the transformer (SBL 1.4 to SBL 1.3). With increasing plant capacity of the PtG-system, the efficiency of the transformation also increases, depending on the type of transformer unit. The decrease in efficiency decreasing is the compensation of the power factor cos(phi).

The quantification in the calculated example reveals that, in order to increase overall efficiency of a PtG system, the use of heat from the electrolyser and/or the methanation sub-system (see Fig. 4) have the highest influence. For the electrolyser sub-system we have three opportunities to handle the heat. The overall electrolyser sub-system efficiencies are calculated with the parameter described in Tables 4 and 5 and the different uses of surplus heat. They are shown in Table 6.

Since the amount of internal heat demand is very low compared to the excess heat of the process, the internal heat use does not have a significant influence on the efficiency. Using a high temperature electrolyser with steam, more energy would be needed internal for tempering and evaporating the water.

In the case with $T_{use} = 60\text{ °C}$ or 80 °C , the results show that the efficiency increase with the external use of heat. Furthermore, the results show how the maximum possible efficiency drops when the external useable temperature level is higher than the output of the sub-system.

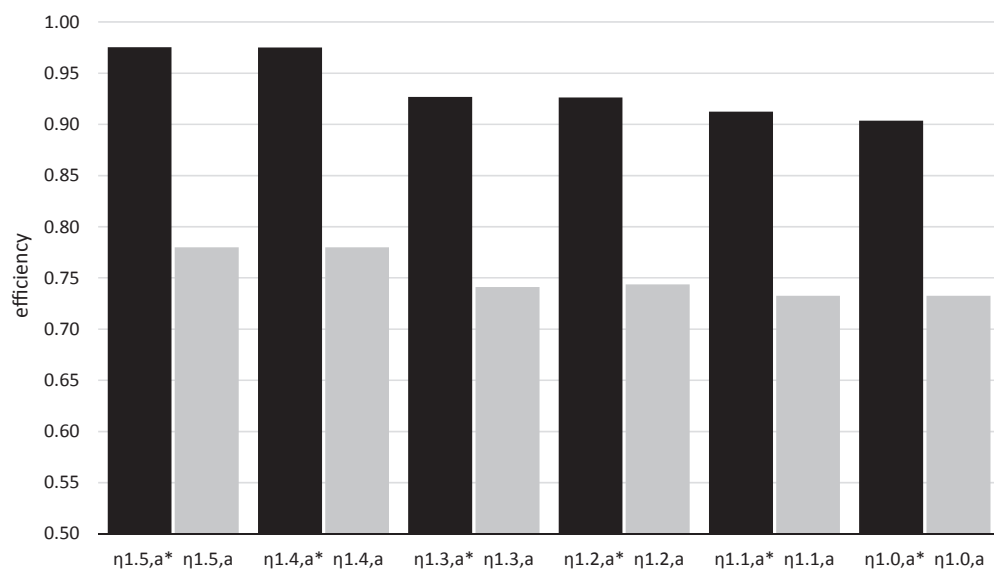


Fig. 3. Exemplary efficiencies of the sub-system boundary level of the electrolysis with technical assumptions disclosed in Tables 4 and 5. For each SBL an efficiency is calculated with heat recovery (black bars) for external and internal heat use and without heat use (grey bars). For this specific electrolyser sub-system the greatest reduction of efficiency is the transformer of alternating current into direct current.

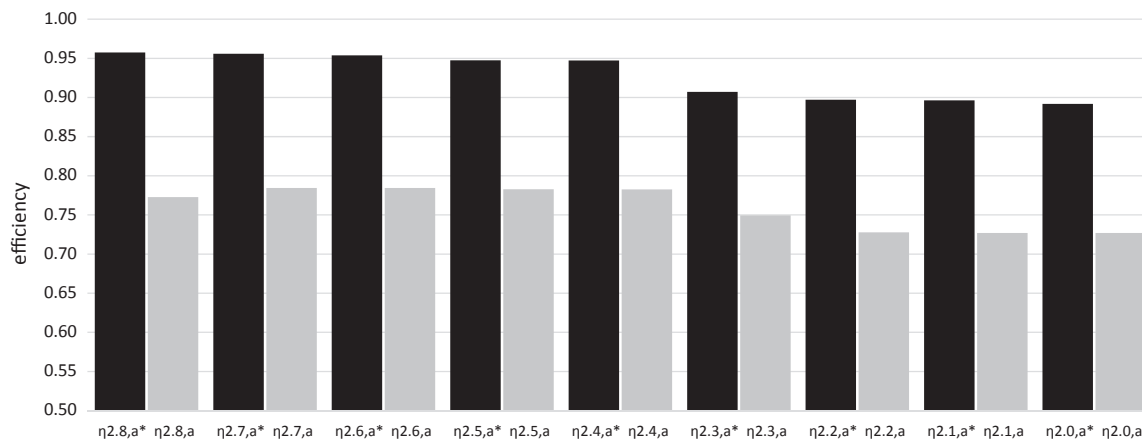


Fig. 4. Exemplary efficiencies of the sub-system boundary level of the electrolysis with technical assumptions disclosed in Tables 4 and 5. For each SBL an efficiency is calculated with internal and external heat recovery (black bars) and with internal heat use (grey bars). For the methanation sub-system the circulation of permeate reduces the output in η2.3,a and takes effect on the efficiency. The efficiency of SBL 2.7 compared with 2.8 is higher because of the internal heat use.

Table 4 Representative input data for the calculation of a 1 MW PtG plant.

Description	Unit	Value
Capacity power-to-hydrogen	kW _{el,AC}	1000
Safety infrastructure power	kW _{el,AC}	2
Electrical heat tracing methanation	kW _{el,AC}	300–625
Operation temperature Electrolysis	°C	55
Operation temperature methanation	°C	280
Minimal level of useable Heat	°C	60
Losses hot standby over circulating heating-cooling media	kW _{th}	74

3.1.2. Efficiency Sub-System 2 methanation

Fig. 4 shows the efficiencies for the methanation sub-system, again with external and internal heat use (η_{2,y,a}^{*}, black bars) and with internal (η_{2,y,a}, grey bars). The temperature level of useable heat has been set to be 60 °C, however, can be changed for calculating other conditions. Similar to the electrolysis, using the excess heat changes the efficiency for all SBL by about 20% (absolute) in this case. The most significant drops of efficiencies are from SBL 2.4 to 2.3 and (without heat use) from 2.3 to 2.2. The reduction of the efficiency from the sub-system boundary level 2.4 to 2.3 depends on the energy consumption of the compressor to increase the pressure of the SNG from sub-system pressure of the methanation to the injection pressure of the gas network.

Between SBL 2.3 and 2.2 the input and output are changed caused

Table 5 Exemplary hourly energy consumption for different states and change of states of a PtG plant with 1000 kW_{el,AC} electrolyser and downstream sub-system methanation.

State	Hourly energy consumption	Operation condition
Cold standby	12 kW	Electrolyser energy consumption: 5 kW _{el,AC} (0% relative production rate) Methanation energy consumption: 5 kW _{el,AC} Methanation flow load of H ₂ and CO ₂ : 0% Safety infrastructure power consumption: 2 kW _{el,AC}
Bringing into service	1328–1650 kW	Electrolyser energy consumption: 1074 kW _{el,AC} (100%) Methanation energy consumption: 316 – 638 kW _{el,AC} (depending on the function of temperature ramp up gradient and duration) Methanation flow load of H ₂ and CO ₂ : 0% Safety infrastructure power consumption: 2 kW _{el,AC}
Hot standby	387 kW	Electrolyser energy consumption: 39 kW _{el,AC} (0%) Methanation energy consumption: 47 kW _{el,AC} (pumps, compensation thermal losses) Methanation flow load of H ₂ and CO ₂ : 0% Safety infrastructure power consumption: 2 kW _{el,AC}
Full load operation	1195 kW	Electrolyser energy consumption: 1074 kW _{el,AC} (100%) Methanation energy consumption: 60 kW _{el,AC} (compressor, pumps) Methanation flow load of H ₂ and CO ₂ : 100% Safety infrastructure power consumption: 2 kW _{el,AC}

Table 6 Efficiency of the electrolyser sub-system depending on the use of heat and the minimum temperature level of the external usage. If the usable temperature level increase, the efficiency of the sub-system decreases.

Description	T _{use} = 60 °C	T _{use} = 80 °C	T _{use} = 100 °C
η _{1.0,a} [*] Use of surplus heat internally and externally	0.904	0.733	0.733
η _{1.0,a} Use of surplus heat internally	0.733	0.733	0.733
η _{1.0,b} No use of surplus heat	0.728	0.728	0.728

Table 7 Efficiency of the methanation sub-system depending on the use of heat.

Description	T _{use} = 60 °C	T _{use} = 80 °C	T _{use} = 100 °C
η _{2.0,a} [*] Use of surplus heat internally and externally	0.892	0.881	0.870
η _{2.0,a} Use of surplus heat internally	0.727	0.727	0.727

by shifting the sub-system boundary: from hydrogen and permeate of product gas purification to pure hydrogen, and from SNG and permeate to injectable SNG. The input contents the hydrogen from the electrolyser, the output is SNG, the circulated permeate is located within the sub-system boundary.

Theoretically, a complete conversion of hydrogen to methane (and water) would lead to a methanation efficiency (without heat usage) of 83%. If the conversion is not complete, the efficiency is higher because the calorific value of hydrogen that is not converted to methane is higher than the formed methane.

The overall efficiencies of the sub-system methanation, which are calculated with the parameter described Tables 4 and 5 and the different uses of surplus heat, are shown in Table 7. Also for the sub-system methanation an internal and external heat usage can be analysed. We only present calculations of two options: The combined use of heat for internal and external sinks ($\eta_{2,0,a}^*$) and the use of heat for internal heat sinks only ($\eta_{2,0,a}$).

Considering the whole PtG system by combining $\eta_{1,0}$ and $\eta_{2,0}$ we have several cases with and without different heat use concepts for electrolysis and/or methanation which lead to varying results based on specific boundary conditions.

3.1.3. Efficiency Power-to-Gas System 0

In Fig. 5 the overall efficiency of the PtG-system is presented based on the conditions described in Tables 4 and 5 for the following cases: Internal usage of heat of both sub-systems (electrolyser and methanation), external and internal usage of heat of both sub-systems, and the two cross combinations.

Again, Fig. 5 clearly shows the benefit of using the excess heat of the two main processes on the system efficiency ($\eta_{0,0,a}^*$ vs. $\eta_{0,0,a}$). Because of the higher amount of surplus heat against the amount of internal heat necessity the greatest increase of efficiency can be reached if the surplus heat is used internally and externally. If no excess heat is used at all, the highest overall system efficiency that can be reached is as low as 54.3%, whereas the highest system efficiency with a comprehensive usage of excess heat and technical assumptions as described in Tables 4 and 5 is 85.9%.

It has to be noted again that the results and conclusions presented in this section are only valid for the specific assumptions that were introduced. For other process technologies or heat use concepts, etc., all efficiencies can be calculated accordingly and related conclusions can be drawn from the results.

3.2. Annual performance

In the following several exemplary calculations of annual efficiencies are presented, based on the theoretical system described in Section 2 and theoretical load profiles (see Fig. 6 and Table 9). Calculation is performed with a stationary Excel system model and calculated with a time step of one hour. The results are presented in Table 10.

For real operation, the plant control would have to decide on the operation state (production, hot standby or cold standby). This includes the integration of the reaction (or heating-up) time of the system and the ability to foresee optimal operation state for a certain number of hours, e.g. whether the system should remain in hot standby since the production should be started again soon. For the latter, a new parameter “Hot Standby duration equivalent” is introduced which describes the number of hours for which it is worthwhile (from an energetic point of view) to keep the plant in hot standby instead of switching to cold standby. Obviously, hot standby will be applied if the time until the next predicted production starts is expected in a shorter time than the calculated “Hot Standby duration equivalent”. The hourly energy consumption of the sequence “bringing into service” depends on the gradient of the temperature ramp-up. For the system specification assumed here, the gradient should not be higher than 50 K/h since thermal strain could damage the material.

Table 8 shows the consumption of energy during “bringing into service” dependent of the duration of heating and compares the energy consumption with the possible hours of “Hot Standby” using the same energy demand. It is supposed that the losses of the electrolysis sub system as well as the methanation sub system are 5% based on the

energy in the circulated media.

The decision to change from hot standby to cold standby depends on the forecast of the upcoming electricity price for the next few days. For the calculations presented in this paper, the prediction accuracy was assumed to be perfect. In real applications, the prediction accuracy will be better the smaller the time range of the prediction is.

In the following, calculations of the annual performance of a PtG system for different cases are presented (see Fig. 6). The states “operation”, “hot standby” and “cold standby” have been taken into account for the calculation of the annual performance (see Table 9). Changing the states, only the bringing into service procedure is calculated in detail. A cooling of the system has not been considered. The assumption is that the change from cold standby to operating condition always takes the full duration of 12 h. The operation mode of all five cases is only in full-load mode.

Following assumption applies to case 1 to 4: For a certain number of hours in the year (here 4000) the electricity price is below the (calculated) threshold to turn the plant on for 100% production. All these production hours are in one sequence.

For case 1 to 3 the plant starts already in production mode. In case 4 the plant starts from or cold standby mode and one bringing into service sequence has to be done.

For case 1 there is no hot standby required but the plant is turned on once, runs 4000 h and is then turned off again. The electricity price distribution above the threshold does not matter, as well as the hour of the year when the production starts.

For case 2 the plant is turned into hot standby after 4000 h operation.

In case 3 the plant is also turned into cold standby for a certain time after hot standby.

In case 5 the complexity is increasing. Changes to the first cases are an elaborated electricity function that reflects the variation of the electricity price over the year (on an hourly basis). Different operation states of the plant have to be applied, including hot and cold standby.

4. Discussion

The investigations reveal that for the assessment of a PtG plant it is necessary to specify appropriate system boundaries. If two sub-systems (electrolysis and methanation) are applied, the sub-system efficiencies

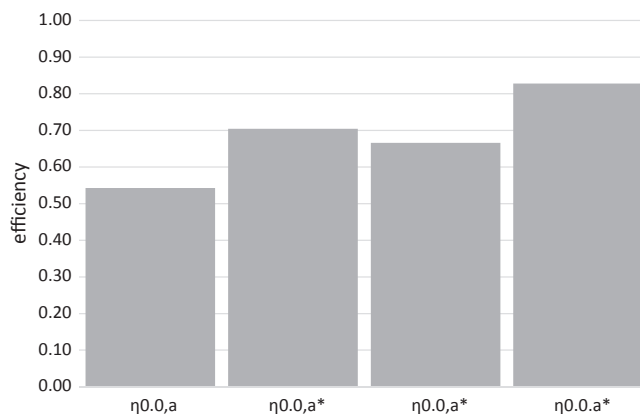


Fig. 5. PtG system efficiency for the specific system configuration described in Tables 4 and 5 with different heat use strategies. The overall efficiency of a PtG system is the energy balance for the whole system, including the sub-system electrolyser and methanation and the heat use strategy for each sub-system. The calculated efficiencies are from left to right: internal heat use in both sub-systems electrolyser and methanation ($\eta_{0,0,a}$), additional external heat use of surplus heat of the electrolyser, additional external heat use of surplus heat of the methanation, additional external heat use of surplus heat of the electrolyser and the methanation.

Table 8
Calculated hot standby duration with the equivalent amount of energy for bringing the plant once into service.

Duration of ramp-up “Cold Standby” to “Hot Standby” in h	“Hot Standby” duration for equivalent energy consumption as ramp up in h
5	17.6
6	19.8
7	22.0
8	24.2
9	26.4
10	28.6
11	30.8
12	33.0
24	59.4

cannot be multiplied to obtain the efficiency of the whole plant. The reason for this are additional flows of auxiliary energy or auxiliary media that are added to each of them. Therefore, the concept of efficiency calculations presented in this paper is a relevant basis for the investigation of PtG systems.

The biggest efficiency decrease of the electrolysis sub-system results from the conversion of AC to DC. The need for internal heat use in alkaline or PEM electrolyzers is restricted to preheating fresh

Table 9
Overview of the operation cases for calculating the annual performance.

Case	Operation/h	Cold standby/h	Bringing into service/–	Hot standby/h
1	4000	4760	–	–
2	4000	–	–	4760
3	4000	1760	–	3000
4	4000	–	1	4748
5	4000	1580	15	3000

Table 10
Annual performance of the specifically selected cases.

Case	With heat usage	Without heat usage
1	0.825	0.508
2	0.540	0.332
3	0.619	0.380
4	0.539	0.332
5	0.589	0.363

demineralized water and has a minor influence on the efficiency. Due to the low temperature level (approx. 60–90 °C), external heat use is restricted to building heating and hot water supply.

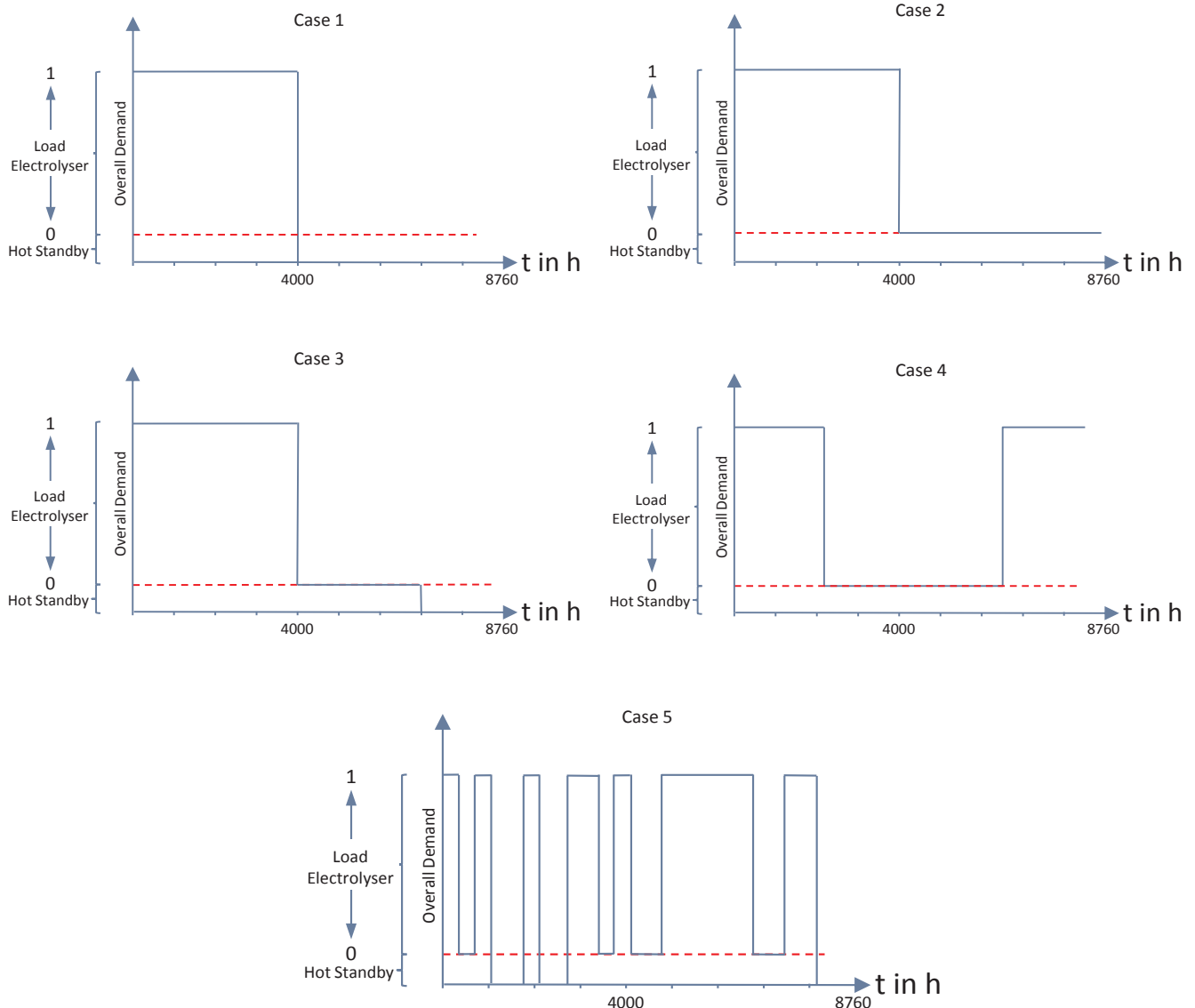


Fig. 6. Symbolic graphs of the five operating cases for the calculation of the annual performance.

In the methanation process the compression of SNG from system pressure to grid pressure can result in a significant decrease of efficiency. In the case of chemical methanation, heat is available at a medium temperature level (approx. 200–300 °C) and can be used for internal heat recovery or external applications.

For increasing the overall system efficiency by using waste heat for appropriate heat sinks, waste heat should preferably be used internally since the primary output of a PtG plant is SNG. The efficiency might further be increased if waste heat from the system can be used for an external application. Yet, from an efficiency perspective internal heat recovery should be prioritized because it reduces the required energy input.

The electrolysis can be operated dynamically with fast “cold-start” ability. In contrast, the methanation unit is slow due to the maximum temperature increment of 50 K per hour. E.g. the electrolysis can operate and store hydrogen, while the methanation reactor is still heating up. Even with changes in load during operation, electrolysis can react faster than methanation. The different load change abilities and the requirement to keep the product quality constant results in the necessity to integrate a hydrogen storage, which allows a more independent operation of the two subsystems.

In addition to the efficiency calculation in Section 3.1, the calculation of the annual performance (Section 3.2) shows new aspects for the evaluation of PtG systems and their application. The annual performance does not only consider the steady-state operation at full load but also changes between the states and the time spent in the respective state during one year. If the PtG system is operated with a high number of operating hours, it makes sense to keep the system in hot standby between production cycles, as the losses in cold standby and start-up procedure use more energy depending on the duration of the system downtime. During change from cold standby to operating mode, a large quantity of bad gas is produced and the duration of synthetic natural gas production is shortened. This reduces the annual performance.

To calculate the annual performance the time dependent energy requirements of the plant as well as the energetically usable products have to be taken into consideration for each state. Then, it can indicate whether it is energetically worthwhile to run the plant in the “Hot Standby” phase between two operating phases or to shut it down and restart it at a later point (see Fig. 7). The duration of the two operation phases as well as the time interval between the two phases must be known in advance. In general, the calculation of the annual performance is a parameter which allows to determine the specific efficiency

of a particular application of the PtG system precisely. Section 3.2 and Table 11 reveal, for instance, a decreasing annual efficiency with increasing numbers of run-downs and start-ups. In addition, with the method presented it is possible to evaluate the influence of part-load operation, e.g. continuing to operate the methanation process while electrolysis is in standby due to temporarily high electricity costs.

While this paper can only present exemplary calculations for the application of the method, PtG system configurations and technical and economic boundary conditions will be very different for future plants. Therefore, especially operating costs have to be calculated specifically for each case. Efficiency has a major influence on the operating costs of a system. The presented calculation of annual performance can now be used for calculating annual cost performance for different PtG plant specifications as a basis for the economic evaluation which can then be compared. This should lay the basis for further techno-economic improvements of plant layouts and operation strategies that include not only the production of renewable gas but also e.g. ancillary services for electricity grids.

5. Conclusions

A systematic method to calculate efficiencies of PtG systems was developed and is described in this paper. The method considers all energy flows to and from the two sub-systems electrolysis and methanation of a PtG system. Based on this, annual performances can be derived which are an important measure to analyse and further develop PtG systems, especially for techno-economic upscaling.

As part of the method, sub-system efficiencies have been defined. The method presented can be applied for electrolysis and/or methanation processes. In exemplary calculations, the biggest efficiency drop of the electrolysis sub-system resulted from the conversion of AC to DC, whereas in the methanation process the compression of SNG from system pressure to grid pressure lead to a significant decrease of efficiency.

It was shown that when combining electrolysis and methanation, the sub-system efficiencies cannot simply be multiplied, For a specific system configuration, exemplary calculations were carried out and parameter sensitivities were identified which are important for a deeper understanding of optimal system concepts. It was found that a precise specification of the boundaries of the individual sub-system levels is necessary. The exemplary calculations show that the method is capable to lay out the basis for a deeper understanding of PtG system efficiency

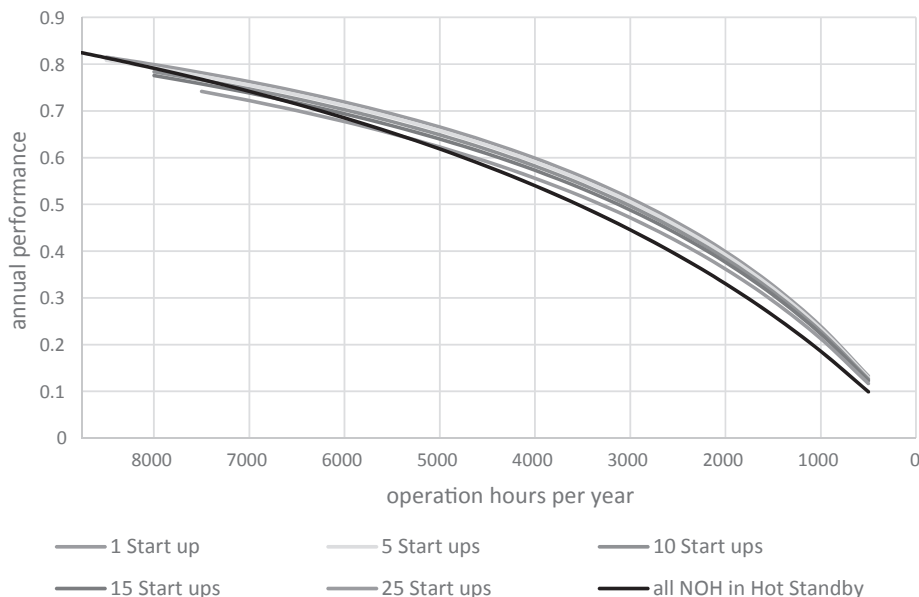


Fig. 7. Graphical representation of the results from Table 11.

Table 11

Annual performances depending on operation hours, duration of standby and ramp ups. In all cases, the system is operated in hot-standby mode for 70% of the non operation hours. The third column shows the annual performance in case all non operative hours are in hot standby mode. It can be seen that only a certain number of bringing into service processes are energetically useful.

operation hours	Non operating hours (NOH)	all NOH in Hot Standby	70 % of NOH in Hot Standby, x *10h per bringing into service, rest of time off																		
			1 Start up	3 Start ups	5 Start ups	8 Start ups	10 Start ups	15 Start ups	20 Start ups	25 Start ups	30 Start ups	50 Start ups									
8760	0	0.8246																			
8500	260	0.8136	0.8151	0.8118	0.8084																
8000	760	0.7913	0.7991	0.7957	0.7923	0.7872	0.7839	0.7758													
7500	1260	0.7675	0.7816	0.7782	0.7747	0.7696	0.7662	0.7579	0.7498	0.7418	0.7340										
7000	1760	0.7420	0.7626	0.7591	0.7556	0.7503	0.7469	0.7384	0.7302	0.7221	0.7142										
6500	2260	0.7146	0.7418	0.7382	0.7346	0.7293	0.7258	0.7172	0.7088	0.7006	0.6926	0.6844	0.6763	0.6683	0.6603	0.6523	0.6443	0.6363	0.6283	0.6203	0.6123
6000	2760	0.6851	0.7189	0.7152	0.7116	0.7062	0.7027	0.6939	0.6854	0.6771	0.6690	0.6608	0.6526	0.6444	0.6362	0.6280	0.6198	0.6116	0.6034	0.5952	0.5870
5500	3260	0.6532	0.6936	0.6899	0.6862	0.6807	0.6771	0.6683	0.6597	0.6513	0.6431	0.6349	0.6267	0.6185	0.6103	0.6021	0.5939	0.5857	0.5775	0.5693	0.5611
5000	3760	0.6186	0.6655	0.6617	0.6580	0.6525	0.6488	0.6399	0.6313	0.6228	0.6146	0.6064	0.5982	0.5900	0.5818	0.5736	0.5654	0.5572	0.5490	0.5408	0.5326
4500	4260	0.5811	0.6341	0.6303	0.6265	0.6210	0.6173	0.6084	0.5997	0.5912	0.5830	0.5748	0.5666	0.5584	0.5502	0.5420	0.5338	0.5256	0.5174	0.5092	0.5010
4000	4760	0.5401	0.5988	0.5950	0.5912	0.5856	0.5820	0.5730	0.5644	0.5559	0.5478	0.5397	0.5316	0.5235	0.5154	0.5073	0.4992	0.4911	0.4830	0.4749	0.4668
3500	5260	0.4951	0.5588	0.5550	0.5512	0.5457	0.5421	0.5332	0.5246	0.5163	0.5083	0.4999	0.4919	0.4839	0.4759	0.4679	0.4599	0.4519	0.4439	0.4359	0.4279
3000	5760	0.4457	0.5131	0.5094	0.5057	0.5002	0.4967	0.4880	0.4796	0.4715	0.4637	0.4559	0.4481	0.4403	0.4325	0.4247	0.4169	0.4091	0.4013	0.3935	0.3857
2500	6260	0.3910	0.4604	0.4568	0.4532	0.4480	0.4446	0.4362	0.4282	0.4205	0.4130	0.4055	0.3980	0.3905	0.3830	0.3755	0.3680	0.3605	0.3530	0.3455	0.3380
2000	6760	0.3303	0.3989	0.3955	0.3922	0.3873	0.3841	0.3763	0.3689	0.3617	0.3548	0.3479	0.3410	0.3341	0.3272	0.3203	0.3134	0.3065	0.2996	0.2927	0.2858
1500	7260	0.2624	0.3263	0.3233	0.3203	0.3159	0.3131	0.3062	0.2997	0.2934	0.2874	0.2814	0.2754	0.2694	0.2634	0.2574	0.2514	0.2454	0.2394	0.2334	0.2274
1000	7760	0.1859	0.2392	0.2368	0.2344	0.2309	0.2286	0.2231	0.2179	0.2129	0.2082	0.2034	0.1986	0.1938	0.1890	0.1842	0.1794	0.1746	0.1698	0.1650	0.1602
500	8260	0.0992	0.1328	0.1313	0.1299	0.1277	0.1263	0.1230	0.1198	0.1168	0.1140	0.1112	0.1084	0.1056	0.1028	0.1000	0.0972	0.0944	0.0916	0.0888	0.0860

and performance. Based on this, more realistic feasibility studies and business case calculations can be carried out which make use of the efficiencies by calculating the annual performance.

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